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Structural behavior of perforated web elements of cold-formed steel flexural members subjected to web crippling and a combination of web crippling and bending

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STRUCTURAL BEHAVIOR OF PERFORATED WEB ELEMENTS OF COLD-FORMED STEEL FLEXURAL MEMBERS SUBJECTED TO WEB CRIPPLING AND A COMBINATION OF WEB CRIPPLING AND BENDING

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PREFACE

A study of structural behavior was conducted and design equations were developed that account for the degradation in web crippling capacity caused by web openings for single web cold-formed steel flexural members. The sections were subjected to a concentrated load applied to one flange. The load application satisfied the AISI definition for either End-One-Flange or Interior-One-Flange loading. The research findings enable the current design provisions for sections without web openings to be modified by a reduction factor equation to obtain the web crippling capacity for sections with web openings. The modified capacity is considered for the web crippling capacity in the absence of bending moment. For situations of combined bending and web crippling, the current AISI provisions for interaction are used based on the web opening modified bending moment and web crippling capacities.

Simple and practical web reinforcement configurations using material from the same cross section as the member are provided. Use of the web reinforcement configurations, for single web members having web openings, will ensure that the web crippling strength for the same cross section without web openings is obtained for the same key parameters defining the design situation.

This report is based on the dissertation of the same title presented to the Faculty of the Graduate School of the

University of Missouri-Rolla (UMR) in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering. This investigation was sponsored by the American Iron and Steel Institute (AISI) and the Metal Lath/Steel Framing Association (ML/SFA) Division of the National Association of Architectural Metal Manufacturers (NAAMM). Technical guidance was provided by the ML/SFA-AISI Joint Task Force: J.E. Sullivan (chairman), C. Bissey, R.L. Brockenbrough, C.R. Clauer, E.R. diGirolamo, S.J. Errera, E.R. Estes, Jr., L. Hernandez, A.L. Johnson, K.H. Klippstein, J.P. Matsen, W.R. Midgley, T.B. Pekoz, N. Peterson, G.S. Ralph, R.M. Schuster, T.W. Trestain, and R.A. LaBoube. Thanks are also extended to R.B. Haws, K.L. Cole, AISI staff, and A.L. Sisco, NAAMM staff, for their assistance.

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I. INTRODUCTION

A. GENERAL REMARKS

Since 1946 the use and the development of thin-walled cold-formed steel construction in the United States have been accelerated by the issuance of the various editions of the Specification for the Design of Cold-Formed Steel Structural Members of the American and Iron Steel Institute (AISI). Each subsequent edition incorporates investigation results which have improved the completeness and surety of the Specification. For example, based on a study conducted by Hetrakul and Yu (1978), the 1980 edition underwent expansive refinement in the design of beam webs subjected to web crippling and the combination of bending and web crippling. However, the web crippling provisions and combined bending and web crippling provisions of the 1980 and subsequent revised editions of the Specification pertain strictly to flexural members without web openings.

Since 1990, the University of Missouri-Rolla has conducted a comprehensive study of the behavior of web elements of flexural members with web openings subjected to forces causing bending, shear, and web crippling, and combinations thereof. The current AISI ASD Specification (1986) and AISI LRFD Specification (1991a) have no provisions for the possible degradation in strength for the various limit states of flexural members caused by the presence of web openings.

The foremost reason for conducting this investigation was the concern that the presence of a web opening(s) would have a degrading effect on the web crippling behavior and the combined bending and web crippling behavior of flexural members. Therefore the effect of a web opening must be defined, and if necessary, recognized in the AISI Specification provisions.

The primary measure of the two behaviors is the ultimate or nominal capacities for these two limit states. The fundamental intent of the investigation was to study these behaviors and subsequently to quantify the magnitude of the load capacity degradation caused by the web openings for inclusion in future editions of the AISI Specification.

The use of members with pre-punched web openings spaced at intervals along the longitudinal axis of the section provides the convenience of providing passage for services without the considerable expense, delay, and need for quality control associated with creating web openings at the work site. Sections with web openings are frequently used in floors, ceilings, and walls to maximize occupancy volume by reducing the need for visible conduits. Cold-formed steel members with web openings are used extensively in practice, and, in relation to their cold-formed steel solid web counterparts, commonly comprise a majority of the cold-formed steel members used in light-steel construction.

Web openings will influence the overall capacity of flexural members by influencing each of the limit states applicable to flexural members, which are bending, shear, web crippling, and combinations thereof. Furthermore, under most design situations, it is probable that the influence of the web openings is a reduction in the load capacity for each of the limit states, and hence a reduction in the overall capacity of the flexural member.

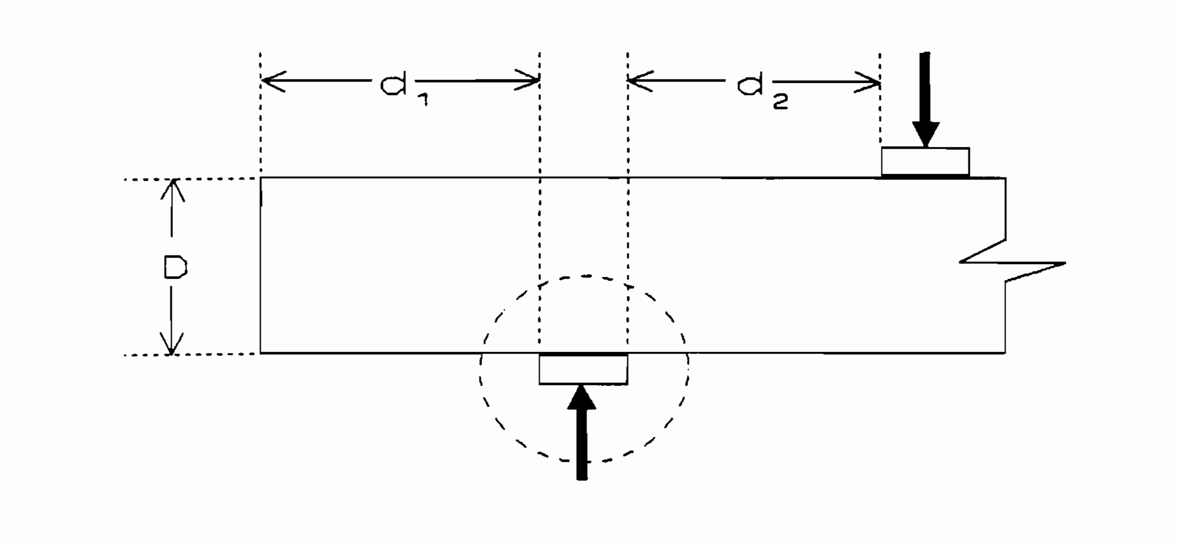
It is unlikely that the capacity reduction effect of the web openings can be eliminated by specifying the location and size of each of the web openings while simultaneously allowing web openings of sufficient size and required location to provide passage of services. Modifying the size, locations, and spacing of the web openings cannot be accomplished for most design situations using industry standard cold-formed steel sections.

Two factors limit the versatility required to accomplish these modifications. First, sections with web openings have an industry standard web opening spacing of 24 inches, center to center, and secondly, each of the web openings are of uniform size. Acquiring sections with a different web opening spacing, gagged or suppressed web openings, or reduced size of specified web openings can be achieved only at additional cost and with extensive prior coordination. This is because the fabrication equipment used for creating pre-punched web openings generally does not possess the flexibility to allow deviations from 24 inch spacing of uniform size openings. For economy, modification to the web opening properties of sections should only be performed if a tremendous number of sections with identically modified web opening properties are needed. It is unlikely that this need will occur in practice. Modification to the web opening properties would require the high cost associated with converting the fabrication equipment to produce the required configurations of the modified sections.

During the design process for the limit state of web crippling, the presence of several concentrated loads and multiple 24 inch spaced web openings of uniform size may make it impossible to adjust the location of the web opening, which is in closest proximity to the concentrated load under consideration, to adequately reduce its degrading effect on web crippling strength. For industry standard sections with web openings, a concentrated load will always be in proximity to a web opening. The bearing region for a concentrated load cannot be at a distance from a web opening greater than 12 inches minus the sum of one-half the length of the bearing and one-half the length of the web opening.

In practice, the location of all web openings in a member is established by specifying the distance between one end of the section and a selected web opening, thereby fixing the location of all other web openings. Therefore, under most design situations, the degrading effect of web openings must be considered for uniform size web openings at prescribed locations. Hence, these prescribed locations establish the relative positions of each concentrated load and its closest uniform size web opening.

The results of this investigation can be used to accomplish this design with safety, economy, and serviceability for the limit states of web crippling and combined bending and web crippling for the End-One-Flange, EOF (Fig. 1), and Interior-One-Flange, IOF (Fig. 1), loading conditions for unreinforced single webs.



$h = D - 2(R+t)$

Loading Condition	End or Interior d_1	One or Two Flange d_2
End-One-Flange, EOF	< 1.5h	> 1.5h
Interior-One-Flange, IOF	≥ 1.5h	> 1.5h
End-Two-Flange, ETF	< 1.5h	≤ 1.5h
Interior-Two-Flange, ITF	≥ 1.5h	≤ 1.5h

Figure 1: AISI Web Crippling Loading Definitions

B. PURPOSE OF INVESTIGATION

This investigation had the following three purposes:

1. The primary purpose of this investigation was to study the structural behavior of single web cold-formed steel flexural members with web openings subjected to web crippling and a combination of bending and web crippling. As appropriate, design recommendations were developed which consider these limit states. The End-One-Flange, EOF (Fig. 1), and Interior-One-Flange, IOF (Fig. 1), loading conditions were considered separately. The primary consideration of structural behavior was the failure load of the tests specimens. This failure load quantified the web crippling behavior, and in the case of significant bending and web crippling interaction, quantified the combined bending and web crippling behavior.

2. The secondary purpose of the investigation was to evaluate the adequacy of the current AISI provisions for single web sections based on the results of the unreinforced EOF and IOF tests performed during the investigation. This evaluation consisted of two tasks and objectives. First, comparison of test results for specimens with no web openings was performed to ensure good correlation with the existing provisions. Second, comparison of test results for specimens with web openings was performed to determine if the existing provisions could adequately predict the web crippling capacity of sections with web openings.

3. The tertiary purpose was to develop optimal EOF and IOF web reinforcement configurations, for single web sections with web openings, which ensure the web crippling strength attains that of the section without web openings for the same cross section and bearing length. The web reinforcement configuration study included development of the requirements for attachment of the web reinforcement to the reinforced section using screw connectors.

Purposes 1 and 2 pertain to both Section III, End-One-Flange Unreinforced Web Opening Study and, Section IV, Interior-One-Flange Unreinforced Web Opening Study. Purpose 3 pertains to Section V, End-One-Flange and Interior-One-Flange Reinforced Web Opening Study. The division of the three studies into separate sections, III, IV, and V of this document, is necessitated by the largely well-defined distinctness of the character of these three topics and their implementation in practice. Correspondingly each of these three sections generally has its own self-contained format associated with an investigation report. Summarized design recommendations for the three topics are in Section VI, Design Recommendations. Section VI is provided in a format intended for inclusion into the AISI Specification.

C. OVERVIEW OF INVESTIGATION AND RESULTS

This paragraph describes the rational and sequence of steps used to accomplish the three previously stated purposes of the investigation and their outcomes.

Therefore, this paragraph provides a brief overview of the entire problem solving process used in this investigation, to include: the procedures, conclusions, and recommendations of the investigation. This is provided in general terms without the use of the specific nomenclature used in the following sections of this document.

Initially, the primary purpose of the investigation was to study the web crippling behavior of single unreinforced cold-formed steel web elements of flexural members with web openings subjected to web crippling only. This purpose did not explicitly include the behavior, or interaction, of combined bending and web crippling. The following discussion justifies the expansion of the scope of the primary purpose of the investigation to include the combined behavior of bending and web crippling.

The interaction of bending and web crippling required consideration because of the requisite configuration of the tests specimens as simply supported flexural members. The magnitude of the resulting bending moment present in the test specimens, specifically in the interior region of the simple span, was often significant and caused degradation in the web crippling capacity for the interior region. Hence, when the bending moment was significant, web crippling behavior could not be studied without consideration of the combined bending and web crippling behavior.

The bending moment of the simply supported test specimens was greatest at mid-span of the test specimens, and was considered zero at the ends of the test specimens. Therefore, the bending interaction affected the IOF (Fig. 1) web crippling capacity, and was considered to have no effect on the EOF (Fig. 1) web crippling capacity of the test specimens. However, in general, EOF web crippling may not be devoid of bending interaction. For example, this situation could exist when the value of d_1 (Fig. 1) approaches the value of 1.5h for the EOF loading condition. Therefore, subsequent discussion of both the EOF and IOF web crippling design procedures state requirements for the general case of bending interaction. The case of insignificant bending moment is considered as a special and simplified situation.

As a result, the scope of the primary purpose of the investigation was expanded to include the combined effect of bending and web crippling. The consideration of bending interaction on the web crippling behavior is a valuable augmentation to the investigation, because in practice, high bending moment often exists at locations of applied concentrated load. Therefore, for sections with web openings, web crippling capacity is reduced by two factors in the region of the web crippling concentrated load: significant bending moment and web openings.

By using an established relationship in the current AISI Specification (1986) and LRFD Specification (1991a) to account for bending interaction on web crippling behavior, the isolated behavior of web crippling for sections with web openings was successfully achieved. The isolated web crippling capacity therefore quantifies the web crippling behavior in the absence of bending moment. The isolated web crippling capacity would have been the failure capacity of the test specimens if the bending moment magnitude in the interior region of the specimens could have been limited to a small value. As discussed herein, this limiting value is approximately 30 percent of the ultimate or nominal bending moment capacity of the sections.

The primary measure of structural behavior was the failure loads of the test specimens. The failure loads quantified the web crippling behavior, and in cases of significant bending moment, the combined bending and web crippling behavior. To quantify the effect of the web openings on the web crippling behavior in the absence of bending moment, relationships were sought between the web crippling strength of sections with web openings and the web crippling strength of sections without web openings, in the absence of bending moment, for the same cross section, bearing length, and loading configuration. The relationships, which were developed as design equations, were based on distinct behavioral trends, and provide the degradation of the web crippling strength in the absence of bending moment caused by the presence of web openings.

As a result of this investigative procedure, the equations developed herein can be applied to the existing AISI Specification web crippling provisions, which apply strictly to sections without web openings, to reduce the allowable or nominal web crippling capacity as appropriate for sections with web openings. The current AISI ASD and LRFD Specification web crippling provisions provide the solid web allowable and nominal capacities, respectively, in the absence of bending moment. Furthermore, this value of web crippling capacity, in the absence of bending moment, from the current AISI web crippling provisions is a required entry into the Specification provisions for combined bending and web crippling interaction.

Hence, for sections with web openings, the web crippling allowable or nominal capacity entry into the interaction equations is affected by the relationships developed during this investigation. Likewise, the bending moment allowable or nominal capacity entry into the interaction equations for sections with web openings is also affected by the relationships developed during the concurrent UMR study of the effect of web openings on flexural behavior. Therefore, the AISI interaction equations for combined bending and web crippling are not changed by the findings of the current UMR investigations; however, the capacity entries into the interaction equations are affected by the findings of the UMR investigations.

The EOF, Section III, and IOF, Section IV, equations developed during the investigation possess the flexibility of being used with any design provisions which provide the web crippling capacity of single web sections without web openings, to include any possible future changes to the AISI provisions for single web sections without web openings. Specifically, the relationships determined during this investigation do not, by themselves, provide the strength of a section with web openings. They provide the relationship between the strength of a section with web openings, as compared to the strength of its solid web counterpart in the absence of bending moment. The term 'solid web counterpart' implies three characteristics: the same cross section, bearing length, and loading condition. The current AISI Specification web crippling provisions had no role in the development of the equations of this investigation. The equations developed herein were developed without regard to the predicted capacity of the solid web strength from the existing web crippling design provisions.

Because of the aforementioned rational used to develop the equations, all previous research performed on sections without web openings, to include the extensive research performed to establish the existing design provisions, is still valid. The existing provisions and their basis investigations are augmented by the findings discussed herein and are not superseded in any manner.

The equations developed herein to provide the reduction in web crippling capacity, in the absence of bending moment, for single webs for sections with web openings act as a coefficient multiplier for the existing AISI Specification web crippling provisions for single web sections in the absence of bending moment. Furthermore, this coefficient multiplier achieves a constant value, which is less than or equal to unity, for the given conditions of the design situation.

The achieved form of the EOF and IOF relationships for the degradation of web crippling strength, in the absence of bending moment, caused by the presence of web openings includes two non-dimensional measures relating to the web opening. These non-dimensional measures are constant values for a given design situation, given as a function of: the depth of the web opening, and the longitudinal location of the web openings with respect to the concentrated load under consideration. Hence, the mathematical relationships developed herein for web crippling capacity reduction, in the absence of bending moment, are expressed as functions only of these two non-dimensional measures of web opening properties. The resulting equations do not include parameters intrinsic to sections without web openings, on which the capacity provided by the current AISI provisions depend.

As demonstrated by the behavior of the test specimens, these two measures of web opening properties are the critical factors relating to the degradation caused by the presence of a web opening(s). The depth of the web opening is proportional to the degradation of web crippling strength caused by the web opening, and the distance between the closest web opening from the concentrated web crippling load under consideration is inversely proportional to the degradation of web crippling strength caused by the presence of a web opening.

A major effort of this phase of the investigation was to quantify the tested behavior of the degradation in web crippling strength, in the absence of bending moment, caused by the presence of web openings. This was accomplished by performing statistical analysis on the tested failure loads of the EOF and IOF specimens after computing the equivalent web crippling capacity of the test specimens in the absence of bending moment. The developed equations therefore quantify the demonstrated behavior of the test specimens, specifically the web crippling strength of test specimens with web openings as compared to the web crippling strength of their solid web counterparts in the absence of bending moment. The equations developed herein are probabilistic models which are based on the results of a sufficient number of tests performed on a wide range of cross-section parameters, to include the opening depth, and the clear distance between the load plate and the web opening.

Separate equations were developed for the EOF and IOF loading conditions. Extensive use, as described herein, was also made of an equation developed by Sivakumaran and Zielonka (1989) to account for the web crippling strength reduction caused by the web openings in the absence of bending moment. The equation developed by Sivakumaran and Zielonka was used for comparison with the equations developed herein. Also, under specific circumstances, the equation developed by Sivakumaran and Zielonka (1989) is recommended for use.

Satisfactory correlation existed between the test results for specimens without web openings and the predicted web crippling capacities computed from the existing AISI provisions for sections without web openings (AISI, 1986, and AISI, 1991a). Therefore no changes are recommended in the current design provisions. The provisions were applicable to all cross sections used in the investigation.

The existing AISI provisions were found to be inadequate to predict the web crippling capacity of sections with web openings. The failure load of the test specimens with web openings did not acceptably achieve the nominal capacity predicted by the existing AISI web crippling provisions.

The failure load of the test specimens with web openings consistently exceeded the allowable capacity predicted from the existing AISI ASD Specification provisions. However, this occurred with a remaining factor of safety significantly less than the factor of safety incorporated into the current AISI ASD web crippling provisions. The factor of safety incorporated into the existing provisions is used to account for uncertainties. The ASD factor of safety is not intended to account for a probable cause of strength degradation caused by a mechanical alteration to a section such as the creation of web openings.

Similarly, the LRFD resistance factor based on the test results of this investigation was less than the web crippling resistance factor of the current AISI LRFD Specification (1991a). This is because the test results for sections with web openings of this investigation had a higher variance than the variance of the test results for the solid web tests performed during the development of the current AISI provisions. The increase in variance is a measure of the uncertainty of the strength prediction equations.

The results of tests without web openings for several cross sections which had high yield strengths exceeding 54 ksi were also compared to the web crippling capacities predicted from additional web crippling equations (Santaputra, Parks, and Yu, 1989) which are not in either AISI (1986) or AISI (1991a).

Optimal web reinforcement configurations were developed which successfully accomplished the previously stated purpose for the web reinforcement configurations. The test parameters were chosen such that the web reinforced specimens were tested under conditions which had the worst case scenario for strength if the web reinforcement was not present, i.e. the least possible web crippling strength as compared to their solid web unreinforced counterparts for the same value of the bearing length. The underlying concept is that if the full strength of the solid web unreinforced section could be obtained under these worst case conditions, then the results could be generalized to all possible conditions for single web sections subjected to EOF and IOF loading which otherwise meet the requirements of the AISI provisions.

The selection of test parameters was based on two principal factors influencing the strength of the section prior to attachment of the web reinforcement: large web openings which approached the maximum permitted in practice, and most critical location of the web opening for the general region of the web opening locations being considered. Furthermore, the tests were performed with the fewest reasonable number of screw connectors used to attach the web reinforcement to the reinforced member.

Four web reinforcement configurations were developed. Two web reinforcement configurations are provided for both the EOF loading and IOF loading conditions. For both loading conditions, separate web reinforcement configurations were developed for the two general situations of possible web opening locations. Specifically, these two situations are when any portion of a web opening, or when no portion of a web opening, is located below or above the load plate.

Requirements for attachment of the web reinforcement to the section are provided using self-drilling screw connectors. These requirements include equations for computing the forces in the connection. The connection requirements were developed in accordance with the AISI provisions (CCFSS, 1993).

Web reinforcement configurations that achieved the strength of the no web opening section were evaluated on their economy and accessibility of the web opening for passage of services, and the four optimal web reinforcement configurations are recommended as design provisions.

D. TERMINOLOGY

The following terminology is used extensively in the subsequent sections of this document.

1. Commonly Used Synonyms. The terms 'solid web', 'no web opening(s)', and 'without web opening(s)' are used synonymously.

2. Cross Section and Cross-Section Properties. In addition to the usual definition of cross section as a set of geometric dimensions, herein, the term cross section also implies a defined and constant set of cross-section properties or parameters which include the material properties and the size and geometry of the web openings. The definitions of the geometric cross-section parameters are shown in Figure 2.

The solid web test specimens possess the same set of cross-section parameters as their web opened counterparts with the exception of the web opening parameters. Although web opening size is a cross-section parameter, and hence

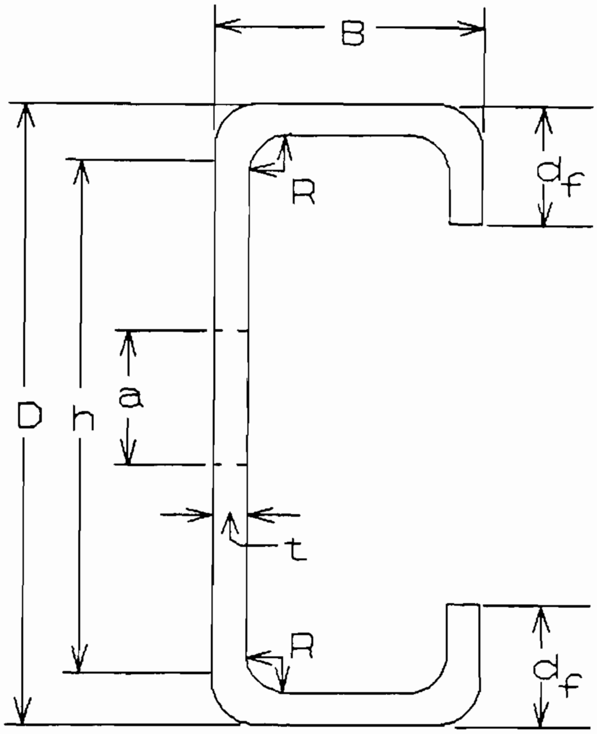


Figure 2: Specimen Cross-Section Parameters

invariant for a specified cross section, solid web test specimens were fabricated from cross sections with web openings. This was accomplished by cutting the two ends of the specimen at locations between two adjacent web openings.

The web opening parameters of size, shape, and mid-height location are invariant for a given cross section because all test specimens were fabricated from manufacturer provided members which were factory produced in the manner discussed in the Section I.A, General Remarks.

3. Loading Configurations. Figure 1 shows the definitions of the four different loading conditions addressed by the web crippling provisions of the AISI ASD

(1986) and LRFD (1991a) Specifications. These loading conditions are named End-One-Flange, EOF, Interior-One-Flange, IOF, End-Two-Flange, ETF, and Interior-Two-Flange, ITF. These definitions are distinct to web crippling, and a discussion of these definitions is provided in Section II.F.

4. Orientation of Specimens and Sections. All references to the relative position of different points on a section or specimen imply that the specimen or section is oriented with its longitudinal axis being situated in a horizontal plane and its web in a vertical plane (Fig. 2).

Correspondingly, the terms 'above' or 'below' and 'not above' or 'not below' are used frequently in describing the relative position of a web opening and the load plate of the concentrated load under consideration. Therefore, if any portion of a web opening and a load plate can both be intersected by a line in the plane of the web which is perpendicular to the flanges, the web opening is considered to be above or below the load plate. Otherwise the web opening is not above or not below the load plate.

The web crippling structural behavior is not dependent on the direction of the concentrated load applied towards the section. For a horizontally oriented member, the concentrated load may be applied upwards towards the member as a reaction, or downwards as a gravity load with the same effect on web crippling behavior. The terms 'above' and 'below' are only distinguished by whether or not the load plate applies the load as a reaction from below the section, such as for the EOF tests (Fig. 3) or the load plate applies the load from above the section, such as for the IOF tests (Fig. 4). Many vertically oriented flexural members or beam-columns, such as wind influenced wall studs, are subjected to concentrated loads at the supports, and therefore must meet the AISI provisions for web crippling. For this situation, the orientation of the sections must be visualized as having their longitudinal axis in a horizontal plane, and web in a vertical plane.

5. Web Opening Aspect Ratio for Opening Position. The non-dimensional parameter α is a measure of the location of a web opening in relation to the location of the concentrated web crippling load. Alpha is equal to the longitudinal clear distance between the load and the web opening, x, divided by the height of the flat portion of the web, h. Alpha is shown in Figures 3 and 4 for the EOF and IOF loading conditions, respectively. Herein, the value of α is computed using the minimum x distance of all web openings, and therefore strictly applies to the uniform size web opening closest to the concentrated load.

6. Percent of Solid Web Strength. The Percent of Solid Web strength, PSW, is the percent of the strength exhibited by a specimen with a web opening as compared to the average strengths for the solid web specimens; for the computation of PSW values, the tests were performed with: i. the same cross section; ii. the same bearing length, N, and; iii. the same loading condition. Hence, the average strength of all

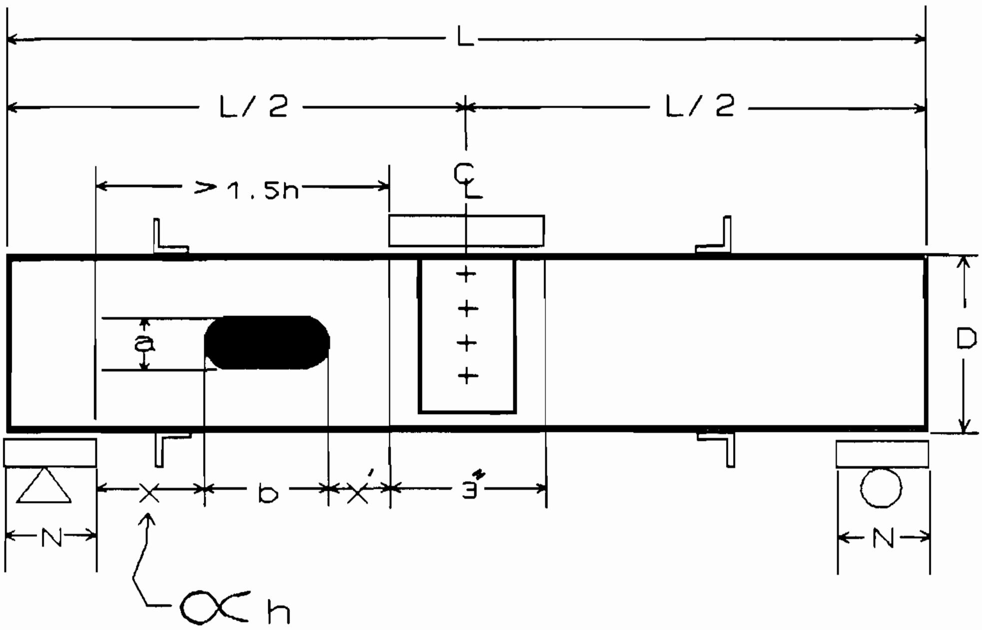


Figure 3: EOF Specimen Parameters

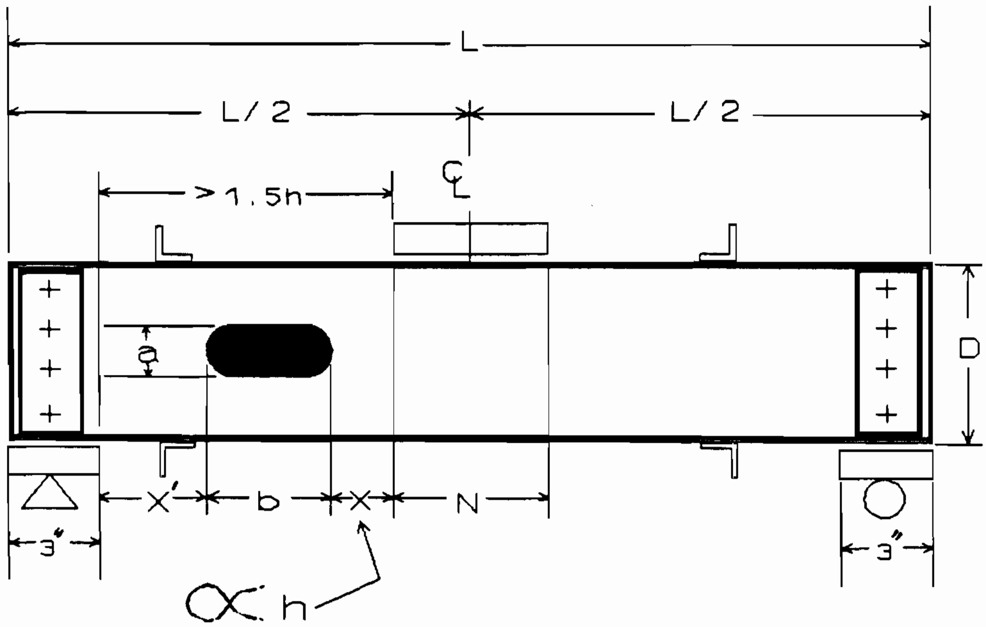


Figure 4: IOF Specimen Parameters

solid web tests for a given cross section, N value, and loading condition is considered a PSW value of 100 percent. For situations of significant bending moment, the strength is not equal to the web crippling strength.

The PSW value of the test specimens with web openings is a measure of the strength degradation caused by the web opening under conditions i, ii, and iii which are common to their solid web counterparts. However, PSW values have no consideration for the degradation in strength simultaneously caused by the interaction of bending. Therefore, PSW is a function of: the size of the web opening; the location of the web opening, and; the magnitude of the bending degradation on web crippling capacity.

Each PSW value has an unique corresponding Bending Moment Adjusted PSW value, PSW_{adj}, which is determined by an established relationship, provided herein, which governs the interaction of bending and web crippling. Use of this relationship eliminates the degradation caused by bending moment, and therefore isolates the effect of degradation caused by the presence of the web opening(s). The bending and web crippling interaction relationship was applied to all test results for specimen failure loads, including those of the solid web, to provide the capacity that would have ideally been realized in the absence of bending moment. Subsequently, the PSW_{adj} values were computed based on the requirements i, ii, and, iii stated above. Therefore, PSW_{adj}

is a function only of the following two factors: the depth of the web opening, and the location of the web opening.

7. Reduction Factor. In general, a reduction factor equation is a probabilistic model which includes pertinent parameters which are related to some strength degrading phenomenon associated with a physical or mechanical alteration to a section. Based upon the design situation, the reduction factor equation yields a numerical value, or reduction factor, RF. Specifically, for this investigation, the web crippling reduction factor equations provide the predicted decrease in web crippling strength caused by the presence of a web opening as compared to the strength of a solid web section, $P_{solid\ web}$, in the absence of bending moment, for the same cross section, bearing length, and loading condition.

The reduction factor equations are therefore the previously mentioned relationships stated to accomplish the primary purpose of the investigation to quantify the web crippling structural behavior, most notably the expected degradation caused by web openings. Furthermore, the reduction factor equations, and their associated ranges of applicability, serve as design recommendations.

Each reduction factor equation was developed from a regression analysis performed on all PSW_{adj} values from the same loading condition. Therefore, for a given loading condition, the PSW_{adj} values were developed from test results from the same cross section, and the reduction factor equations subsequently developed from all PSW_{adj} values.

For the regression analysis used to develop the reduction factor equations, PSW_{adj} was used as the dependent variable, and the aforementioned measures of the web opening size and location were the independent variables. The reduction factor equation does not directly predict the web crippling capacity of a section with web openings; it only predicts the degradation from the solid web capacity.

A reduction factor, RF, is an unique numerical value between zero and unity computed from a reduction factor equation. Use of a reduction factor provides the adjusted capacity, $P_{web\ opening}$, for sections with web openings. Therefore, $P_{web\ opening}$ is less than or equal to the capacity of the solid web section. The use of the reduction factor equation is illustrated by the form:

$$P_{web\ opening} = RF \times P_{solid\ web} \tag{1}$$

Both $P_{web\ opening}$ and $P_{solid\ web}$ can either represent the allowable or nominal loads as appropriate. Therefore, if applied to the nominal capacities:

$$(P_n)_{comp,\ web\ opening} = RF \times (P_n)_{comp,\ solid\ web} \tag{2}$$

where $(P_n)_{comp,\ solid\ web}$ is the nominal web crippling capacity of the solid web section. Or, if applied to the allowable capacities:

$$(P_a)_{comp,\ web\ opening} = RF \times (P_a)_{comp,\ solid\ web} \tag{3}$$

where, $(P_a)_{comp,\ solid\ web}$ is the allowable web crippling capacity of the solid web section.

For example, if the existing AISI ASD Specification web crippling provisions indicate a solid web allowable load, $(P_a)_{comp,\ solid\ web}$, of 1200 lbs, and the reduction factor equation yields a reduction factor value of 0.85, or 85 percent, then, from Equation 3, the allowable capacity for the section with web openings, $(P_a)_{comp,\ web\ opening}$, for the same cross section, bearing length, and loading condition, is the product of 1200 and 0.85 which yields 1020 pounds. Furthermore, the commonly used term of 'reduction' is a misrepresentation because the actual reduction in the above example was 0.15, or 15 percent, which equals the reduction factor equation result subtracted from unity.

For this investigation, three specific reduction factor equations were considered. These are the separate EOF and IOF reduction factor equations, and the reduction factor equation provided by Sivakumaran and Zielonka (1989).

8. <u>Web Opening Size Parameters.</u> The size of a web opening is determined by the parameters a and b (Figs. 3 and 4) which are the maximum web opening dimensions perpendicular and parallel, respectively, to the longitudinal axis of the section and in the plane of the web. Herein, based on the previously stated orientation of specimens, a and b are considered to be the height and length, respectively, of a web opening. Both a and b are

cross-section properties, hence invariant for a given cross section.

For sections with irregularly shaped web openings, the value of a and b are shown in Figure 5. Furthermore, to expand the usefulness of the results of the investigation, which were strictly based on sections with web openings at mid-height of the web, conservative measures are provided for sections with web openings eccentric about mid-height of the web. For eccentric web openings, the value of a is defined in Figure 6. For a combination of irregular and eccentric web openings, a combination of the definitions of Figures 5 and 6 may be used.

A non-dimensional measure of the size of a web opening is the ratio of the height of a web opening, a, divided by the height of the flat portion of the web, h. Therefore, the ratio a/h is a cross-section property. The a/h ratio is therefore a non-dimensional aspect ratio related to the depth of a web opening, and is a parameter of all three reduction factor equations used in this investigation.

For the reduction factor equations developed during the investigation, consideration of the length of a web opening, b, is given as a maximum allowable value for use of the EOF and IOF reduction factor equations and the web reinforcement configurations. A discussion of the effect of b on the PSW and PSW_{adj} values is contained herein, which specifically addresses the exclusion of b from the reduction factor equations developed during the current investigation.

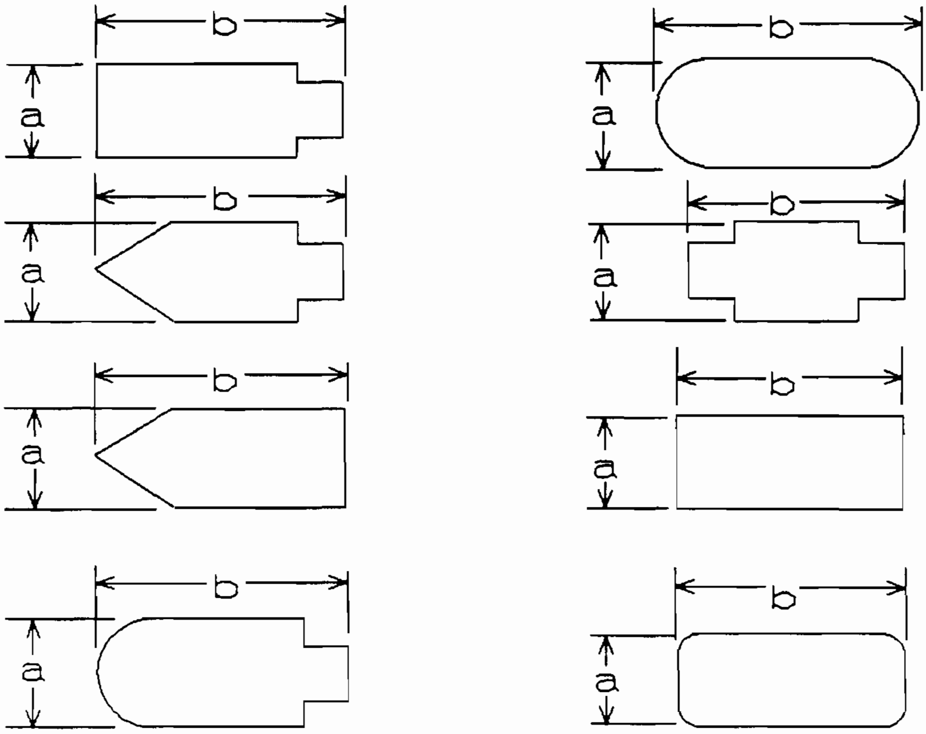


Figure 5: Definitions for Irregularly Shaped Web Openings

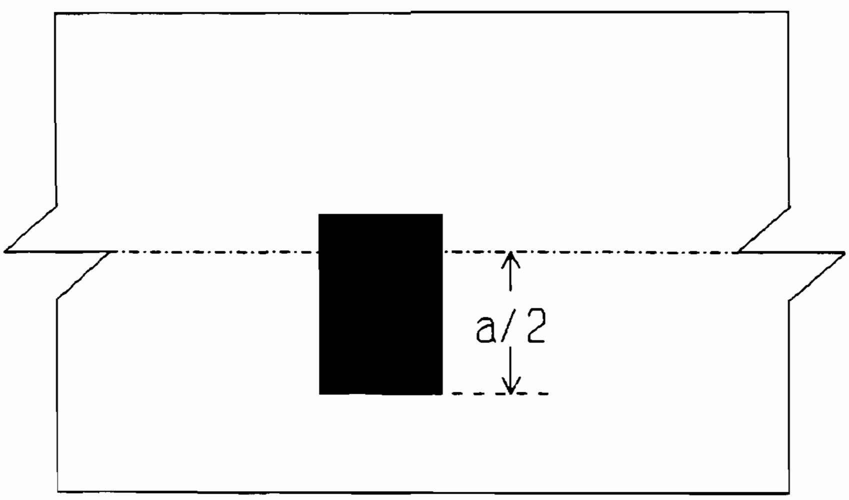


Figure 6: Definition of Parameter a for Eccentric Web Openings

E. SCOPE OF INVESTIGATION

The elements of the scope of the investigation can be grouped into the following four areas: 1. loading conditions, 2. cross-section types, 3. cross-section properties, and 4. range of α values. The characteristics of each test specimen enable categorizing into one of the four areas.

The scope of the investigation is a major factor in providing the ranges of applicability for the reduction factor equations of Sections III and IV and the web reinforcement configurations of Section V. An important consequence of the scope of the investigation was its usefulness as an aid in developing explicit statements of all requirements for applying the reduction factor equations and the web reinforcement configurations. It was intended that major situations that practitioners may confront in assessing the applicability of the recommendations of the investigation be clearly addressed.

Exhaustive and specific requirements of the applicability of the recommendations of the investigation are discussed in Sections III, IV, and V, and are summarized in Section VI, Design Recommendations. A general overview of the implications for the four elements of the scope of the investigation are provided in this paragraph, with the specifics provided in subsequent sections.

1. Loading Conditions. The loading conditions used were EOF and IOF (Fig. 1). The separate reduction factor

equations developed for both the EOF loading condition, Section III, and IOF loading condition, Section IV, are valid for only their respective loading condition. Web reinforcement configurations which accomplished the third purpose of the investigation were developed separately for both the EOF and IOF loading conditions, Section V. The EOF and IOF loading conditions comprise all types of one-flange loading for concentrated loading. Therefore, reduction factor equations and web reinforcement configurations are provided for all cases of concentrated one-flange loading for single web sections.

2. Cross-Section Types. All cross sections tested were C-shaped sections with edge-stiffened flanges. However, the same web crippling behavior will exist for other single web sections. Therefore, the recommendations for the separate EOF and IOF reduction factor equations and the web reinforcement configurations are valid for other single web cross-section shapes, with or without stiffened flanges, which otherwise meet the requirements stated herein for applicability of the AISI Specification provisions for web crippling as given herein in Section II.F.

3. Cross-Section Properties. Tables I, II, and III provide the properties of the EOF unreinforced web, IOF unreinforced web, and EOF and IOF web reinforced configuration tests, respectively. Tables IV and V give the ranges of parameters for the unreinforced web EOF and IOF tests, respectively. The specific ranges of applicability

Table I: Unreinforced EOF Cross-Section Properties

Cross Section	D (in.)	t (in.)	R (in.)	h (in.)	B (in.)	d_f (in.)	a (in.)	b (in.)	F_y (ksi)	F'_y (ksi) see note 3	h/t	a/h	R/t
EOF-SU-1	11.97	0.060	0.156	11.54	1.63	0.52	1.50	4.00	60	60	192	0.130	2.604
EOF-SU-2	3.62	0.044	0.156	3.22	1.64	0.51	1.50	4.00	53	53	73	0.466	3.551
EOF-SU-3	3.61	0.036	0.156	3.22	1.63	0.47	1.50	4.00	64	64	90	0.465	4.340
EOF-SU-4	3.63	0.071	0.156	3.18	1.63	0.51	1.50	4.00	81	66.5	45	0.472	2.201
EOF-SU-5	2.46	0.059	0.156	2.03	1.62	0.49	1.50	4.00	54	54	34	0.738	2.648
EOF-SU-6	2.42	0.033	0.156	2.05	1.63	0.46	1.50	4.00	67	66.5	62	0.732	4.735
EOF-SU-7	2.52	0.062	0.156	2.08	1.62	0.43	0.75	2.00	37	37	34	0.361	2.520
EOF-SU-8	2.50	0.039	0.156	2.11	1.60	0.41	0.75	2.00	34	34	54	0.355	4.006
EOF-SU-9	3.67	0.044	0.156	3.27	1.58	0.56	1.50	4.00	47	47	74	0.459	3.551
EOF-SU-10	3.71	0.077	0.156	3.24	1.63	0.54	1.50	4.00	64	64	42	0.462	2.029
EOF-SU-11	3.65	0.044	0.156	3.25	1.64	0.49	0.00	0.00	63	63	74	0.000	3.551
EOF-SU-12	5.92	0.033	0.156	5.54	1.58	0.44	1.50	4.00	93	66.5	168	0.271	4.735
EOF-SU-13	7.94	0.045	0.156	7.54	1.59	0.47	1.50	4.00	72	66.5	168	0.199	3.472

Table I: Unreinforced EOF Cross Section Properties (cont.)

Notes:
1. See Figures 2 and 3 for definition of dimensions.
2. Cross-Section designations:
   EOF: End-One-Flange loading condition, SU: Single Unreinforced web
   EOF-SU-cross section number-specimen designation
3. AISI Equation C3.4-1 (Eqs. 30 and 31) obtains a maximum value at F_y = 66.5 ksi. The F'_y value was used for computation of web crippling capacity.

Table II: Unreinforced IOF Cross-Section Properties

Cross Section	D (in.)	t (in.)	R (in.)	h (in.)	B (in.)	d_f (in.)	a (in.)	b (in.)	F_y (ksi) see note 4	F'_y (ksi) see note 3	h/t	a/h	R/t	$(M_n)_{comp}$ (K-in.) see note 4
IOF-SU-1	12.05	0.098	0.156	11.54	1.65	0.64	1.50	4.00	36	36	118	0.130	1.594	179.7
IOF-SU-2	2.51	0.032	0.156	2.12	1.57	0.41	0.75	4.00	55	55	66	0.354	4.883	7.58
IOF-SU-3	2.55	0.055	0.156	2.12	1.65	0.47	0.75	4.00	55	55	39	0.354	2.841	15.53
IOF-SU-4	2.42	0.033	0.156	2.05	1.63	0.46	1.50	4.00	67	67	62	0.732	4.735	9.12
IOF-SU-5	3.62	0.033	0.156	3.23	1.62	0.44	1.50	4.00	59	59	98	0.464	4.735	14.06
IOF-SU-6	3.67	0.045	0.156	3.26	1.63	0.47	1.50	4.00	53	53	72	0.460	3.472	18.75
IOF-SU-7	3.65	0.044	0.156	3.25	1.64	0.49	0.00	0.00	63	63	74	0.000	3.551	21.36
IOF-SU-8	3.69	0.067	0.156	3.22	1.63	0.49	1.50	4.00	48	48	48	0.466	2.332	28.21
IOF-SU-9	5.92	0.033	0.156	5.54	1.58	0.44	1.50	4.00	93	91.5	168	0.271	4.735	31.01
IOF-SU-10	7.94	0.045	0.156	7.54	1.59	0.47	1.50	4.00	72	72	168	0.199	3.472	58.17

Notes:
1. See Figures 2 and 4 for definition of dimensions.
2. Cross-Section designations:
   IOF: Interior-One-Flange loading condition, SU: Single Unreinforced web
   IOF-SU-cross section number-specimen designation
3. AISI Equation C3.4-4 (Eqs. 34 and 35) obtains a maximum value at F_y = 91.5 ksi. The F'_y value was used to compute web crippling capacity.
4. $(M_n)_{comp}$ was determined using AISI (1986, and 1991a) Section C3.1.1, Nominal Section Strength, Paragraph (a) Procedure I - Based on Initiation of Yielding. The F_y value was used to compute bending moment capacity.

Table III: Web Reinforced EOF and IOF Cross-Section Properties

Cross Section	D (in.)	t (in.)	R (in.)	h (in.)	B (in.)	d_f (in.)	a (in.)	b (in.)	F_y (ksi)	F_u (ksi)	F_u/F_y	h/t	a/h	$(M_n)_{comp}$ (K-in.)
1	3.62	0.033	0.156	3.23	1.62	0.44	1.50	4.00	59	74	1.25	98	0.464	14.06
2	3.67	0.045	0.156	3.26	1.63	0.47	1.50	4.00	53	70	1.32	72	0.460	18.75
3	3.69	0.067	0.156	3.22	1.63	0.49	1.50	4.00	48	59	1.23	48	0.466	28.21

Notes: 1. See Figures 2, 3, and 4 for definition of dimensions.
2. Web opening dimensions, a and b, were 1.50 x 4.00 inches, respectively.

Table IV: Unreinforced Web EOF Cross-Section Property Ranges

	h (in.)	t (in.)	F_y (ksi)	N (in.)	α	a (in.)	b (in.)	a/h	h/t	R/t
minimum	2.03	0.033	34	1.00	0.00	0.75	2.00	0.13	34	2.03
maximum	11.54	0.077	93	6.00	1.50	1.50	4.00	0.74	192	4.74

Note: See Figures 2 and 3 for definition of dimensions.

Table V: Unreinforced Web IOF Cross-Section Property Ranges

	h (in.)	t (in.)	F_y (ksi)	N (in.)	α	a (in.)	b (in.)	a/h	h/t	R/t	$(M_n)_{comp}$ (K-in.)
minimum	2.05	0.032	36	3.00	0.00	0.75	4.00	0.13	39	1.59	7.58
maximum	11.54	0.098	93	6.00	1.50	1.50	4.00	0.73	168	4.88	179.7

Note: See Figures 2 and 4 for definition of dimensions.

of the cross-section parameters of both the EOF, Section III, and the IOF, Section IV, reduction factor equations and the web reinforcement configurations, Section V, are stated in the appropriate sections. Based on engineering judgement, the range of cross-section parameters tested during the investigation were extrapolated to the industry maximum allowable values for the web opening parameters, and to the full range of applicability of the AISI Specification provisions for web crippling (Section II.F). The only exception is the load bearing length, N. As stated in Sections III, IV, and V, and summarized in Section VI, minimum values for N were specified for applicability of the recommended design provisions.

All web openings were located at mid-height of the web, as usually exists in industry practice. All web openings were rectangular with fillet corners. As stated previously in Section I.D, Terminology, consideration is provided herein for sections with eccentric or irregularly shaped web openings (Figs. 5 and 6).

4. Range of α Values. The value of α (Figs. 3 and 4) varied from zero to 1.5 for the unreinforced EOF and IOF tests. The value of α was zero or an undetermined negative value for the EOF and IOF web reinforcement configuration tests, i.e. α is considered negative when any portion of the web opening is above or below the load plate. For the recommended design provisions of the investigation, the

allowable range of α is not constrained by the tested limits as specifically stated herein for the separate recommendations of the study.

II. REVIEW OF LITERATURE

A. GENERAL

The literature pertinent to this investigation is presented and discussed under the following topical headings:

1. Theoretical analysis of web crippling for cold-formed steel flexural members.
2. Previous research on web crippling behavior for sections with web openings.
3. Previous research on the behavior of perforated plate elements and webs of flexural members.
4. Development of current AISI Specification provisions for web crippling and combined bending and web crippling.
5. AISI Specification provisions for web crippling, bending, and combined bending and web crippling.
6. Santaputra, Parks, and Yu web crippling equations.
7. Shear design provisions.
8. AISI Specification provisions for screw connections.
9. Resistance factor and factor of safety computations.

B. THEORETICAL ANALYSIS OF WEB CRIPPLING FOR COLD-FORMED STEEL FLEXURAL MEMBERS

The value of theoretical mechanics of deformable and ductile materials in predicting the web crippling behavior of cold-formed steel members is very complicated as summarized by Yu (1991):

> ... theoretical analysis of web crippling for cold-formed steel flexural members is rather complicated because it involves the following factors:
>
> 1. Nonuniform stress distribution under the applied load and adjacent portions of the web.
> 2. Elastic and inelastic stability of the web element.
> 3. Local yielding in the immediate region of load application.
> 4. Bending produced by eccentric load (or reaction) when it is applied on the bearing flange at a distance beyond the curved transition of the web.
> 5. Initial out-of-plane imperfection of plate elements.
> 6. Various edge restraints provided by beam flanges and interaction between flange and web elements.
> 7. Inclined webs for decks and panels.
>
> For these reasons, the present AISI design provisions for web crippling are based on the extensive experimental investigations conducted at Cornell University by Winter and Pian [1946], and by Zetlin [1955] in the 1940s and 1950s, and more recently at the University of Missouri-Rolla by Hetrakul and Yu [1978].

Yu's (1991) summary was made concerning the nature of web crippling phenomenon of solid web cold-formed steel sections. Furthermore, Yu and Davis (1973) in their review of web crippling behavior add, "For perforated beam webs, the analysis becomes even more complex."

A summary of previous theoretical research for the study of the web crippling behavior of solid web flexural members was presented by Hetrakul and Yu (1978) and Santaputra and Yu (1986). Both of these investigations provide equations which address web crippling behavior and combined bending and web crippling behavior; however, the equations provided were strictly empirical and were not based on the theoretical analysis reviewed therein. The equations were adopted for inclusion in AISI (1986) and AISI (1991b), respectively.

Santaputra and Yu (1986) provide an overview of numerical approximation method investigations which primarily used the finite element and finite strip methods applied to web crippling of solid web sections. As stated by Santaputra and Yu (1986), "Mathematical difficulties arising from the nature of complex stress field associated with this problem prohibit an exact solution." The investigations discussed in Santaputra and Yu (1986) are from Bagchi and Rockey (1968), Rockey and Bagchi (1970), Rockey and El-gaaly (1972), Graves Smith and Sridharan (1978), Gierlinski and Graves Smith (1984), and Lee, Harris, and Hsu (1984). Additionally Bakker, Pekőz, and Stark (1990) performed an investigation which used a yield line analysis of failure mechanisms for web crippling of solid web sections.

Santaputra and Yu (1986) provide results using the finite element program "Automatic Dynamic Incremental Nonlinear Analysis" (ADINA) to investigate the web crippling behavior of hat-shaped solid web sections. They provide information concerning their modeling of the section to include the discretizing of the domain, the loading and boundary conditions, the material properties, and the geometric non-linear characteristics of the deformation. The results were compared to those of experimental tests for determining the ultimate capacity, and the results were within 21 and 23 percent for the EOF and IOF loading conditions, respectively. The ADINA program consistently underestimated the web crippling capacity. As concluded by Santaputra and Yu (1986), "the desired design expressions [for predicting web crippling capacity] have to be developed experimentally."

C. <u>PREVIOUS RESEARCH ON WEB CRIPPLING BEHAVIOR FOR SECTIONS WITH WEB OPENINGS</u>

1. <u>General.</u> There is limited research on the web crippling behavior of sections with web openings. Yu and Davis (1973) and Sivakumaran and Zielonka (1989), performed experimental and empirical studies on the web crippling behavior of cold-formed steel flexural members with web openings. Both of these investigations were concerned strictly with the IOF loading condition with the web opening centered on the longitudinal location of the load plate and will be discussed herein.

2. <u>Yu and Davis.</u> Yu and Davis (1973) reported the results of 20 IOF web crippling tests conducted on cold-formed steel members. The tests were conducted on specimens composed of two channels with square or circular web openings. The web openings were located at mid-height of the web and were longitudinally centered on the IOF load plate. The channels were connected either back-to-back as I-beams or through the simple lip edge stiffeners. The

overall depth to thickness ratios ranged from 66.7 to 101, the hole opening to overall depth ratio ranged from zero to 0.641, and F_y values ranged from 57.9 to 70.7 ksi. All tests were performed with a constant bearing length of 3.5 inches. The ultimate loads were the only recorded results, and therefore were the primary measure of web crippling behavior. The research was preliminary in nature and was intended to provide design information to engineers.

Yu and Davis (1973) provided two reduction factor, RF, equations, which are distinguished from each other by whether or not the web opening is square or circular. For circular web openings with $0 \le d/h \le 0.5$:

$$RF = 1.0 - 0.6\frac{d}{h} \tag{4}$$

where d = the diameter of the circular web opening, and; h = the clear distance between flanges measured in the plane of the web. For square web openings with $0 \le h_s/h \le 0.642$:

$$RF = 1.0 - 0.77\frac{h_s}{h} \tag{5}$$

where h_s = the width of the square web opening, and; h = the clear distance between flanges measured in the plane of the web.

For both Equations 4 and 5, no restriction is placed on the value of the bearing length for applicability of the equations. As can be seen by both Equations 4 and 5, in the limiting case of a value of d or h_s is equal to zero, the reduction factor equations produce a value of unity, and hence, no capacity reduction is required.

The effects of a square web opening are more pronounced in reducing the web crippling buckling load, as can be seen by a comparison of the coefficients of the second terms of both reduction factor equations. The increased stress concentration and a greater removal of material for square openings resulted in a greater propensity for the square hole to cause buckling at a lower web crippling load.

3. Sivakumaran and Zielonka. Sivakumaran and Zielonka (1989) developed a reduction factor equation for sections with web openings subjected to IOF loading:

$$RF = \left(1-0.197\left(\frac{a}{h}\right)^2\right)\left(1-0.127\left(\frac{b}{n_1}\right)^2\right) \qquad \textbf{(6)}$$

where $n_1 = N + h - a$; N = bearing load length; h = flat height of web; a = height of web opening, and; b = longitudinal length of web opening. Limits are: $b/n_1 \leq 2.0$, and; $a/h \leq 0.75$.

Equation 6 is always less than unity for sections with web openings, i.e. when the parameters a and b are greater than zero. This reduction factor equation was developed based on the results of 103 tests with the web opening centered on the longitudinal location of the load plate. This experimental research was performed on C-shaped, edge-stiffened, channel sections subjected to the IOF loading condition, and having rectangular web openings at mid-height of the web. The value of N was equal to 51 mm (2.00 in.) for all tests.

Sivakumaran and Zielonka (1989) state, "The bending moments associated with the present tests were calculated and were compared to the corresponding moment capacity of the section and the effects were found negligible." The effect of bending moment interaction will occur when "bending moments higher than 30% of moment capacity of the section influence [degrade] the web crippling strength." Bending and web crippling did not interact because the simply supported test specimens used by Sivakumaran and Zielonka (1989) had short span lengths, hence insignificant bending moment was created in the specimen in the mid-span region of the web opening and web crippling failures. The reduction factor equation was based on the assumption that the dispersion of the load occurs at a 45 degree angle.

Sivakumaran and Zielonka (1989) subsequently evaluated the performance of Equation 6 by use of the ratio of the predicted capacity, using the reduction factor equation, to the tested capacity. Ninety-six percent of the ratio values ranged between 0.9 and 1.1. Or, in the terminology of the current investigation, 96 percent of the test results satisfied the following relationship:

$$0.90 \le \frac{RF \times (P_n)_{test,\ solid\ web}}{(P_n)_{test,\ web\ opening}} \le 1.1 \tag{7}$$

As stated in Section I.D, Terminology, the value of the expression is ideally equal to unity.

LaBoube (1990a) proposed using a modified form of the Sivakumaran and Zielonka reduction factor equation as an interim design recommendation to account for web openings:

$$RF = \left(1-0.197\left(\frac{a}{D}\right)^2\right)\left(1-0.127\left(\frac{b}{n_1}\right)^2\right) \tag{8}$$

where D = the total depth of the section, and the remaining parameters are the same as for Equation 6.

4. Summary. The following conclusions result from the investigations by Yu and Davis (1973) and Sivakumaran and Zielonka (1989):

i. No research has been performed on the EOF condition for flexural members with web openings.

ii. No research has been performed on either the EOF or IOF loading condition which does not have coincident locations of the centerline of the concentrated load and the web opening.

iii. The location of the web opening relative to the location of the load plate was not considered as a parameter in the reduction factor equations because the two positions invariably had coincident centerlines. Otherwise, this would influence the web crippling behavior, and the effect must be quantified as a parameter in the reduction factor equation.

iv. The experimental investigation can be accomplished at a single bearing length value, N.

v. Bending moment must be evaluated for its magnitude, and if greater than 30 percent of the ultimate moment capacity of the section, must be considered for its degrading effect on web crippling capacity.

vi. There is precedence for the development and use of reduction factor equations as defined in Section I.D, Terminology, as applicable to web crippling behavior of cold-formed steel sections with web openings. It is possible to develop reduction factor equations which relate the strength of a section with web openings to the strength of its solid web counterpart. The development and use of this reduction factor equation has the following characteristics:

(a) It is based strictly upon statistical analysis of experimental results, and therefore is empirical.

(b) It incorporates non-dimensional measures of the size of the web opening.

(c) It is not limited for use at the N value used in the testing, nor must the value of N be incorporated into the reduction factor equations as a parameter. The primary influence of the N value is maintained by its inclusion in the equation which provides the predicted capacity of the solid web cross section.

(d) It is based on the ultimate capacity of the test specimens, in the absence of significant bending moment.

(e) No stress level or serviceability requirements are imposed.

(f) It obtains a value of unity as the size of the web opening approaches zero.

(g) It has limits for applicability based on cross-section parameters used during the testing procedure and on engineering judgement. The limits include the maximum value of the ratio of the web opening height to height of the web, and a non-dimensional maximum limit on the web opening length.

(h) If the testing procedure has variable centerline locations of the web opening relative to the load plate, the reduction factor equation should contain a parameter which considers the relative locations of the load plate and the web opening. In keeping with the convention of other parameters in the reduction factor equation, the parameter should be non-dimensional.

(i) No consideration is given to the predicted capacity of the solid web section from provision equations.

D. PREVIOUS RESEARCH ON THE BEHAVIOR OF PERFORATED PLATE ELEMENTS AND WEBS OF FLEXURAL MEMBERS

1. General. Numerous investigations have been performed on the effect of openings or perforations in structural elements and members. This research incorporates

combinations of analytical and experimental investigations, and the research can be categorized into two general areas: research performed on perforated plate elements, and research performed on flexural members with web openings. These two areas are discussed herein as Paragraphs 2 and 3, respectively. It is concluded that the research does not specifically address web crippling behavior of flexural members with web openings.

In order to adequately investigate web crippling behavior of flexural members with web openings, the following two conditions must exist. First, the testing procedure must be performed on flexural members, instead of plate elements. Second, the load must be applied to the flanges of the flexural member in the vicinity of the web opening, else web crippling in the vicinity of the web opening is precluded. Otherwise, the results, though useful in providing generalities and trends, does not thoroughly incorporate the complexities of web crippling behavior.

2. <u>Perforated Plate Elements.</u> Although webs of flexural members are typically plate elements, the adoption of plate research to web crippling has limited value because of the complexity of the loading and boundary conditions which exist for the webs of flexural members.

The boundary conditions for plate research can be made ideal, i.e. the boundary conditions are often created such that they satisfy the discrete conditions of either free, fixed, or simply supported: a web of a flexural member typically does not satisfy any of these ideal conditions. The web of a flexural member is provided some degree of rotational support by the flanges, and the magnitude of the restraint is between that of the simply supported and fixed conditions. Furthermore, the support will vary depending upon the state of stiffness due to elastic or plastic behavior.

Likewise, the loading conditions for plate research can be made ideal, i.e. the loading conditions are often created such that they are either subjected to in-plane shear, flexure, or normal forces, and each of these can be made to act in the absence of each other. Conversely, it is difficult to discretely categorize the loading conditions for the web of a flexural member, which exists at the web and flange interface, into any of these ideal loading condition types. Furthermore, unlike the known location of the edge of a plate, the location of the boundary along the length of the web is unknown. Therefore, the loading provided at this fictitious boundary is difficult to quantify. Additionally, the large deflections typically exhibited during web crippling analysis change the equilibrium relationships and the resultant location of flange load application.

However, both the webs of flexural members and plate elements are susceptible to the same general categories of limit states of strength, stability, and serviceability, for both elastic and inelastic behavior.

a. <u>Stiemer and Prion.</u> Stiemer and Prion (1990) performed analytical and experimental research to determine the plastic buckling capacity of square shear plates with circular perforations. The analytical results show that the ultimate capacity can exhibit either material yielding or out-of-plane buckling. Hence, the failure can be of the strength or stability type. Stiemer and Prion performed studies for various sizes of circular perforations, and various locations of circular perforations. To verify the analytical results, four experimental tests were conducted on plates of 3.4 mm thickness and edge dimensions of 500 mm. The load was applied using a diagonal tension apparatus to create the boundary shear forces.

Stiemer and Prion report that the ultimate in-plane yield capacity is inversely proportional to the hole diameter, and that the relationship was linear. For yielding failures, the location of the perforation is not a critical factor, and the capacity of the plate did not vary with a perforation generally located in the interior region of the plate. They state, "For the case where the hole was too close to the plate edge, however, local material yielding between the hole and the plate edge dictated the failure mode."

For buckling failures, the ultimate capacity due to inelastic buckling,

> ... involved a combination of the yield capacity and the elastic buckling capacity. When the elastic buckling load became significantly higher

> than the in-plane yield resistance, the ultimate capacity was governed by the in-plane yield load, rather than the elastic-plastic buckling load.", (Stiemer and Prion, 1990).

For the inelastic buckling mode, a centrally located perforation resulted in lower capacity than a perforation closer to the edge of the plate. Stiemer and Prion (1990) contribute this to the significant influence of the perforation being located on the path of the compression diagonal.

b. <u>Narayanan and Chow.</u> Narayanan and Chow (1984) performed experimental research on the ultimate capacity and post-buckling behavior of perforated steel plates. They provide design curves for perforated square plates with either circular or square holes in the center of the plate subjected to uniform compression and with simply supported boundaries. These curves provide an approximate method of evaluating the ultimate capacity of the plates. As stated by Narayanan and Chow (1984):

> The method avoids tedious calculations which would become necessary when 'large deflection theory' or nonlinear finite element analysis is used.... By comparing with test results, the method has been shown to give reliable predictions for the ultimate capacity of perforated plates.

c. <u>Yu.</u> Article 3.6 of Yu (1991) discusses the structural behavior of perforated elements under uniform stress, and provides an overview of plate buckling research for perforated plates under an uniform state of stress at the plate boundaries. The research presented was performed on flat plate elements with openings subjected to idealized loading and boundary restraint conditions. For the research discussed, the loading conditions were limited to in-plane normal, shear, and moment loads. The boundary restraint conditions consisted of either fully free, simple support, or fully restrained.

Because the web is a component element of flexural members, the overall behavior of the flexural member is related to the behavior of the web element. As stated by Yu (1991):

> For perforated cold-formed steel structural members, the load-carrying capacity of the member is usually governed by the buckling behavior and the post-buckling strength of the component elements. The critical buckling loads for perforated plates and members have been studied by numerous investigators.

The research discussed by Yu (1991) covers two situations. The first situation is a square plate with a square or circular hole at the center of the plate subjected to full width in-plane uniform compressive forces and simple support boundary conditions. For this situation, the plate buckling coefficient ratio, k_c/k, is provided. The value of k_c is the plate buckling coefficient due to the perforation, and the value of k is the plate buckling coefficient of the plate in the absence of a perforation. The value of k_c/k is dependent on the diameter, $d_{opening}$, of a circular perforation or width, $h_{opening}$, of a square perforation divided by the width, w_{plate}, of the uniformly compressed plate in the direction of the load. The value of k_c/k is given graphically by Yu (1991) as a function of the value of either $d_{opening}/w_{plate}$ or $h_{opening}/w_{plate}$. Because the value of k has been determined for the idealized simply supported boundary conditions, the effect of the perforation can likewise be considered by use of the value of k_c/k.

The second situation discussed is a square plate with a circular hole at the center of the plate subjected to uniform shear along all edges, and with boundary conditions of simply supported or fixed against out-of-plane rotation and transverse displacement. For this situation, the plate buckling coefficient, k, is directly provided for the perforated plate.

For the above conditions, the value of k, adjusted for the effects of the perforation, may be used in the well-known plate buckling equation, which was derived for unperforated plates (Yu, 1991):

$$f_{cr} = \frac{k\pi^2\sqrt{EE_t}}{12\,(1-\mu^2)\,(w/t)^2} \tag{9}$$

where f_{cr} = critical plate buckling stress; k = plate buckling coefficient; E = modulus of elasticity; E_t = tangent modulus of elasticity; μ = Poisson's ratio, and; w/t = the width to thickness ratio of the plate.

The above equation results from an eigenvalue problem based on the solution of Bryan's differential equation and boundary value problem governing a simple supported square plate subjected to uniform compression using small deflection theory (Yu, 1991):

$$\frac{\partial^4 \omega}{\partial x^4} + 2\,\frac{\partial^4 \omega}{\partial x^2\,\partial y^2} + \frac{\partial^4 \omega}{\partial y^4} + \frac{f_x t}{D}\,\frac{\partial^2 \omega}{\partial x^2} = 0 \qquad (10)$$

where:

$$D = \frac{E t^3}{12\,(1-\mu^2)} \qquad (11)$$

ω = deflection of plate perpendicular to surface; E = modulus of elasticity; t = thickness of plate; μ = Poisson's ratio, and; f_x = compressive stress in x direction.

3. Perforated Web Elements of Flexural Members. Numerous investigators have performed analytical research and verification tests on the behavior of web elements with openings of flexural members. The previous research performed on perforated webs of flexural members avoided web opening influenced web crippling as a limit state. This was accomplished by ensuring that the concentrated load was not located in the region of the web opening and by providing few web openings in the member. Typically, only one web opening was used.

a. Thick Web Flexural Members with Web Openings. A majority of the work on the behavior of web elements of flexural members with web openings was performed on hot-rolled or composite sections. In these investigations, web crippling was not addressed. As stated by Yu (1991),

> The exact analysis and the design of steel sections having perforated elements are complex, in particular when the shapes and the arrangement of the elements are unusual. Even though limited information is available for relatively thick steel sections, on the basis of previous investigations, these design criteria may not be applicable completely to perforated cold-formed steel sections due to the fact that local buckling

> is usually a major concern for thin-walled structural members.

Also, as stated by Chan and Redwood (1974) for thick-walled sections, "Attention is restricted to stress analysis and it is assumed that buckling does not occur."

b. <u>AISC Guidelines.</u> Much of the research conducted on thick web flexural members with web openings was performed for the American Institute of Steel Construction (AISC) and incorporated therein. Therefore, the AISC Guidelines (1990) provide a recent and concise summary of the research performed on the effect of web openings on thick-walled sections and the practical implementation of the results. Fifty-seven investigations, guidelines, and specifications were used in the development of the AISC Guidelines (1990). An overview of the AISC Guidelines (1990) for steel sections with web openings are provided in the following discussion. Guidelines for composite sections are not provided herein.

The purposes of web openings in thick-walled hot-rolled sections are generally the same as those stated previously for cold-formed sections. However, due to the great differences in the manufacturing process, web openings in thick-walled hot-rolled sections are placed only at needed locations, instead of at constant 24 inch intervals along the longitudinal axis of the member, as is the industry standard for cold-formed steel sections.

Furthermore, for thick-walled, hot-rolled steel sections, the web openings can have the minimum necessary size required to accommodate the conduit dimensions. In contrast, for cold-formed steel construction, a design must use the next larger size of standard web opening.

The considerations included in the AISC guidelines most closely related to the concerns of the current investigation for thin-walled sections are provided in Section 3.7, Guidelines for Proportioning and Detailing Beams with Web Openings. Section 3.7 provides guidelines to ensure stability to preclude web buckling and buckling of the tee-shaped compression zone. Additional considerations in Section 3.7 are provided for by relationships which consider an equivalent circular opening for a rectangular opening, reinforcement of an opening, and spacing requirements between openings.

For stability concerns, web crippling, due to the effect of a concentrated load being transferred into the web in the vicinity of a web opening, is precluded by either requiring a conservative minimum distance between the concentrated load and the web opening, or by requiring web reinforcement if this minimum distance is not achieved. The guidelines for the placement of a concentrated load are given by AISC (1990) as follows:

> Concentrated loads are not allowed over the opening because the design expressions are based on a constant value of shear through the openings and do not account for the local bending and shear that would be caused by a load on top of the tee.... The requirements represent an extension of the criteria suggested by Redwood and Shrivastava (1980). These criteria are applied to composite and noncomposite members with and

without reinforcement, although only limited data exists except for unreinforced openings in steel sections (Cato 1964). The requirement that openings be placed no closer that a distance d to a support is to limit the horizontal shear stress that must be transferred by the web between the opening and the support.

Sections 3.4, Moment-Shear Interaction Equations, 3.5, Equations for Maximum Moment Capacity, and 3.6, Equations for Maximum Shear Capacity, provide requirements for adequate strength of the web opened thick-walled steel sections. For other considerations, Section 3.7 gives design guidelines which consider web stability and the parameter limitations used in the numerous basis investigations, and therefore is more closely related to web crippling than is the other sections. An overview of Section 3.7 is as follows:

i. <u>Section 3.7-a-2.</u> Section 3.7-a-2 addresses stability considerations for web buckling. To prevent buckling of the web, two criteria are provided:

1. the opening parameter, p_o, should be limited to a maximum value of 5.6 for steel sections. The Guideline Equation is:

$$p_o = \frac{a_o}{h_o} + \frac{6\,h_o}{d} \tag{12}$$

where a_o = length of web opening; h_o = depth of web opening, and; d = depth of steel section.

Using the convention of Figures 2, 3, and 4, this is rewritten as:

$$p_o = \frac{b}{a} + \frac{6a}{D} \tag{13}$$

Therefore, the AISC Guidelines provide a maximum limit of p_o on a linear summation of the aspect ratios of the web opening length to web opening height, and the web opening height to the total height of the section.

2. The web width-thickness ratio and the length of the web opening, a_o, to the depth of the web opening, h_o, ratio should be limited as follows. These guidelines limit the a_o/h_o ratio based on the slenderness ratio of the web, $(d-2t_f)/t_w$, as a function of the F_y value of the material. The Guideline Equation is:

$$\frac{d-2t_f}{t_w} = \frac{520}{\sqrt{F_y}} \tag{14}$$

where t_f = thickness of the flange, and; t_w = thickness of web.

If $(d-2t_f)/t_w \le 420/(F_y)^{1/2}$, the web qualifies as stocky. In this case, the upper limit on a_o/h_o is 3.0 and the upper limit on V_m, maximum nominal shear capacity, for non-composite sections is 2/3 $\bar{V}_p$, in which $\bar{V}_p = F_y t_w d/(3)^{1/2}$, the plastic shear capacity of the unperforated web. All standard rolled W-shape sections qualify as stocky.

If $420/(F_y)^{1/2} < (d-2t_f)/t_w \le 520/(F_y)^{1/2}$, the a_o/h_o should be limited to 2.2, and V_m should be limited to 0.45 $\bar{V}_p$ for both composite and non-composite members.

ii. <u>Section 3.7-a-3.</u> Section 3.7-a-3 addresses stability considerations for buckling of the tee-shaped compression zone:

> For steel beams only: The tee which is in compression should be investigated as an axially loaded column following the procedures of [AISC (1989)]. For unreinforced members this is not required when the aspect ratio of the tee ($v = a_o/s$) is less than or equal to 4. For reinforced openings, this check is only required for large openings in regions of high moment.

where a_o = length of the opening, and; s = the depth of the tee.

iii. <u>Section 3.7-b-1.</u> Section 3.7-b-1 addresses the opening and tee dimensions and provides additional criteria to that given in Section 3.7-a-3. The web opening depth, h_o, cannot exceed 70 percent of the section depth. For steel sections, the depth of the top tee, s_t, and depth of the bottom tee, s_b, should not be less than 15 percent of the depth of the steel section. The aspect ratios of the tees ($v = a_o/s$) should not be greater than 12.

iv. <u>Section 3.7-b-3.</u> Section 3.7-b-3 addresses other considerations for concentrated loads. The following guideline equations show that in the absence of web stiffeners, the clear distance between a web opening and the closest edge of a concentrated load is dictated by the slenderness of the web element, $(d-2t_f)/t_w$, and the slenderness of the flange, b/t, in relation to the yield stress. Furthermore, for the situation where local buckling of the elements is determined not to govern, the web opening cannot be a distance less than d/2 or d, as applicable, from a concentrated load or distance d from a support. Conversely, if local buckling has been determined to govern, or if the load is close to a concentrated load, the web stiffeners must be used to prevent web crippling. An additional observation is that the slenderness of the flange is a critical parameter, because the flange must have adequate stiffness in order to provide the rotational restraint for the web element. The guidelines which quantify these concepts are summarized in the following paragraphs.

First, no concentrated loads should be placed above an opening. Secondly, unless needed otherwise, bearing stiffeners are not required to prevent web crippling in the vicinity of an opening due to a concentrated load if:

1. the slenderness of the web:

$$\frac{d-2t_f}{t_w} \leq \frac{420}{\sqrt{F_y}} \tag{15}$$

2. the slenderness of the flange:

$$\frac{b}{t} \leq \frac{54}{\sqrt{F_y}} \tag{16}$$

and, 3. the load is placed at least d/2 from the edge of the opening,

or, if: 1. The slenderness of the web:

$$\frac{d-2t_f}{t_w} \le \frac{520}{\sqrt{F_y}} \tag{17}$$

2. the slenderness of the flange:

$$\frac{b}{t} \le \frac{65}{\sqrt{F_y}} \tag{18}$$

and, 3. the load is placed at least d from the edge of the opening. Finally, in any case, the edge of an opening should not be closer than a distance d to a support. Where the value of b is the projecting width of the flange, and the value of d is the depth of the section.

v. Section 3.7-b-4. Section 3.7-b-4 addresses other considerations for circular openings, and gives an equivalent relationship between circular and rectangular web openings. Circular openings may be designed using the following substitutions for h_o and a_o.

Unreinforced web openings:

$h_o = D_o$ for bending
$h_o = 0.9\ D_o$ for shear
$a_o = 0.45\ D_o$

in which D_o = diameter of circular opening.

Reinforced web openings:

$h_o = D_o$ for bending and shear
$a_o = 0.45\ D_o$

vi. Section 3.7-b-6. Section 3.7-b-6 addresses other considerations for the spacing of openings, and gives limitations on the closeness of adjacent web openings.

For steel beams, openings should be spaced in accordance with the following criteria to avoid interaction between openings.

For rectangular openings: $S \geq h_o$

$$S \geq a_o\left(\frac{V_u/\phi\overline{V_p}}{1 - V_u/\phi\overline{V_p}}\right) \tag{19}$$

For circular openings: $S \geq 1.5\ D_o$

$$S \geq D_o\left(\frac{V_u/\phi\overline{V_p}}{1 - V_u/\phi\overline{V_p}}\right) \tag{20}$$

where S = clear distance between openings; ϕ = 0.90 for steel beams; V_u = factored shear force, and; $\overline{V}_p$ = plastic shear capacity for unperforated beams.

c. <u>Thin-Walled Flexural Members with Web Openings.</u> Investigations have also been performed using analytical and experimental research techniques on the flexural behavior of thin-walled rolled or welded plate elements with openings. This includes studies by Redwood, Baranda, and Daly (1978), and Redwood and Uenoya (1979). These investigations on thin-walled elements were concerned with consideration of the open web section as a flexural member subjected to concentrated loads, and the investigation of the effect of the resulting shear and bending moment forces on the web elements in the vicinity of the web opening. The emphasis was placed on the shear, moment, and shear-moment interaction behaviors due to flexure. Although the web elements may buckle due to the compressive stresses caused by the shear and flexural stresses, these investigations did not specifically address web crippling behavior.

Typically, the location of the concentrated load(s) was far from the web opening and therefore precluded web crippling in the vicinity of the web opening. The loads, though not in the vicinity of the web opening, were used to generate desired shear or moment regions in the member in the vicinity of the web opening.

In the portion of the member located in the vicinity of the web opening, the compression region of the cross section behaved like a tee or angle section under compression because of the free edge along the web opening. Therefore, the compression region of the web near the web opening was highly susceptible to buckling. Due to the free edge along the web opening, the section did not receive the restraint provided by the web material of the section nearer the neutral axis or in the tension region of the web, as exists in unperforated web sections. The buckling situation is different from web crippling which is caused by a concentrated load applied to the section in the region of the web opening.

Redwood, Baranda, and Daly, (1978) state that the most critical factors influencing the behavior of the sections with web openings are:

1. The shear force at the hole,
2. The moment at the hole centerline,
3. The web slenderness,

4. The slenderness of the web of the tee section formed by the part of the beam above or below the hole,
5. The length of the hole,
6. The shape of the hole, and
7. The presence of transverse stiffeners near the hole.

General observations were provided for the situation when the web buckling did not exist. These observations are: the presence of the hole reduces the maximum values of bending moment and shear force that can be applied to the beam in the region of the hole. In the absence of shear, the plastic bending moment is reduced by two to five percent. In contrast, the ultimate shear capacity is significantly reduced.

E. DEVELOPMENT OF CURRENT AISI SPECIFICATION PROVISIONS FOR WEB CRIPPLING AND COMBINED BENDING AND WEB CRIPPLING

1. General. The current provisions for web crippling and combined bending and web crippling (Table VI) were adopted from an investigation by Hetrakul and Yu (1978), based on the results of 224 web crippling tests conducted at Cornell University and the University of Missouri-Rolla. All tests were performed on solid web specimens, and the resulting equations were intended for use on solid web sections only.

The form of the equations, including all terms and parameters, of Hetrakul and Yu (1978) were fully adopted for the AISI Specification with only minor changes as reviewed

Table VI: ASD and LRFD Specification Web Crippling Design Situations and Equations Numbers

		Shapes Having Single Webs		Shapes Having Multiple Webs
		Partially-Stiffened or Stiffened Flanges	Unstiffened Flanges	
Opposing Loads Spaced > 1.5h (One-flange Loading)	End Reaction	Eqs. 30 & 31 AISI Eq. C3.4-1	Eqs. 32 & 33 AISI Eq. C3.4-2	AISI Eq. C3.4-3
	Interior Reaction	Eqs. 34 & 35 AISI Eq. C3.4-4	Eqs. 34 & 35 AISI Eq. C3.4-4	AISI Eq. C3.4-5
Opposing Loads Spaced ≤ 1.5h (Two-flange Loading)	End Reaction	AISI Eq. C3.4-6	AISI Eq. C3.4-6	AISI Eq. C3.4-7
	Interior Reaction	AISI Eq. C3.4-8	AISI Eq. C3.4-8	AISI Eq. C3.4-9

in Section II.F. The provisions reviewed in this section first appeared in the 1980 edition of the AISI Specification. The resulting equations from the investigation by Hetrakul and Yu (1978) are based strictly on statistical analysis of test results and therefore are empirical.

Hetrakul and Yu (1978) provided an extensive review of investigations on web crippling and combined bending and web crippling behavior from 34 sources. This included a review of provisions and recommendations from the AISI Specification (AISI, 1968), Canadian Specification (CSA, 1974), French Specification (Moreau and Tebedge, 1974), British Specification (BSI, 1969), and the European Recommendations and Swedish Specification (1975).

2. Web Crippling Capacity. Hetrakul and Yu (1978) provide equations for the allowable web crippling capacity of cold-formed steel members subjected to the EOF, IOF, ETF, and ITF loading conditions (Fig. 1) for single web or multiple web sections with or without edge-stiffened flanges. The equations provide the maximum allowable web crippling capacity and therefore incorporate a factor of safety. The equations which are applicable to the conditions of the current investigation, i.e. for single web sections subjected to the EOF or IOF loading conditions, are provided as follows. The equations are given in pairs for each design situation addressed in this investigation. The first equation in each pair is from Section III.1.D.2 of Hetrakul and Yu (1978) and applies to the situation where the value of N/t is less than or equal to 60. The second equation in each pair is from Section V.2.D of Hetrakul and Yu (1978) and applies to the situation where the value of N/t is greater than 60.

a. EOF Loading of Single Unreinforced Webs.

i. Sections with Edge-Stiffened Flanges.

For $N/t \leq 60$:

$$(P_a)_{comp}=t^2\frac{F_y}{33}C_3C_4\left(178.70-0.33\frac{h}{t}\right)\left(1+0.0102\frac{N}{t}\right),kips \tag{21}$$

For $N/t > 60$:

$$(P_a)_{comp}=t^2\frac{F_y}{33}C_3C_4\left(178.70-0.33\frac{h}{t}\right)\left(0.922+0.0115\frac{N}{t}\right),kips \tag{22}$$

ii. Sections without Edge-Stiffened Flanges.

For $N/t \leq 60$:

$$(P_a)_{comp}=t^2\frac{F_y}{33}C_3C_4\left(117.19-0.15\frac{h}{t}\right)\left(1+0.0099\frac{N}{t}\right),kips \tag{23}$$

For $N/t > 60$:

$$(P_a)_{comp}=t^2\frac{F_y}{33}C_3C_4\left(117.19-0.15\frac{h}{t}\right)\left(0.706+0.0148\frac{N}{t}\right),kips \tag{24}$$

The above two pairs of single web EOF equations are distinguished solely based on whether the flange is unstiffened or edge-stiffened. As stated by Hetrakul and Yu (1978):

> For this particular case [single web sections subjected to EOF loading], a study of a Cornell report reveals that specimens with stiffened and unstiffened flanges have considerable difference in load-carrying capacities against web crippling.

However, for the single web IOF condition, "the type of flange will not significantly affect the web crippling loads." (Hetrakul and Yu, 1978), hence, the same equation applies to both stiffened and unstiffened flanges as follows:

b. <u>IOF Loading of Single Unreinforced Sections with Stiffened or Unstiffened Flanges.</u>

For $N/t \leq 60$:

$$(P_a)_{comp} = t^2 \frac{F_y}{33} C_1 C_2 \left(291.06 - 0.40 \frac{h}{t}\right)\left(1 + 0.0069 \frac{N}{t}\right), kips \tag{25}$$

For $N/t > 60$:

$$(P_a)_{comp} = t^2 \frac{F_y}{33} C_1 C_2 \left(291.06 - 0.40 \frac{h}{t}\right)\left(0.748 + 0.0111 \frac{N}{t}\right), kips \tag{26}$$

Where, for Equations 21 thru 26:

$C_1 = (1.22 - 0.22\ F_y/33)$
$C_2 = (1.06 - 0.06\ R/t) \leq 1.00$
$C_3 = (1.33 - 0.33\ F_y/33)$
$C_4 = (1.15 - 0.15\ R/t) \leq 1.0$
F_y = Design yield stress of the web
h = Depth of the flat portion of the web
t = Web thickness, inches
R = Inside bend radius
N = Bearing length of load or reaction

For each of the previous three pairs of equations, the allowable increase for the equations when N/t is greater than 60 is explained by Hetrakul and Yu (1978).

Equations 21 thru 26 incorporate a factor of safety of 1.85. This factor of safety for web crippling is primarily attributed to the typically high variance found in web crippling analysis. As stated by Hetrakul and Yu (1978),

> According to the scatters likely to be found for the web crippling tests of beam specimens having single, unreinforced webs, a safety factor of 1.85 against the ultimate web crippling load is recommended for the development of design criteria. This factor has been used in the current AISI Specification and found to be

> satisfactory for practical design. It is slightly larger than the normal value of 1.67 because it is used to determine the allowable load on the basis of the ultimate load.

The origins of the transition between one-flange and two-flange loading of a clear distance between oppositely directed load plates of 1.5h (Fig. 1) is based on engineering judgement which precedes the research performed by Hetrakul and Yu (1978). As stated by Hetrakul and Yu (1978),

> ...the use of 1.5h as the minimum distance between bearing plates is to eliminate the effect of the two-flange loading. It is based on the current limitation included in Section 3.5 of the 1968 AISI Specification. The same criteria were previously used for the Cornell tests.

Similarly, the use of the clear distance of the load plate from the end of the section of 1.5h as the transition between the end and interior loading condition is presumably also based on analogous reasoning. This was not stated specifically by Hetrakul and Yu (1978).

3. <u>Bending and Web Crippling Interaction Equations.</u> In Section IV.1 of Hetrakul and Yu (1978) separate bending and web crippling interaction equations are provided for the two cases of either single unreinforced webs or multiple unreinforced webs. Applicable to the current study is the following equation for single unreinforced webs:

$$1.22(P/P_{max}) + (M/M_{max}) \leq 1.53 \tag{27}$$

where P = concentrated load or reaction in the presence of bending moment; P_{max} = allowable concentrated load or reaction in the absence of bending moment; M = applied bending moment at, or immediately adjacent to, the point of application of the concentrated load or reaction, and; M_{max} = allowable bending moment permitted if bending stress only exists.

Equation 27 is based on the allowable bending moment capacity, M_{max}, and the allowable web crippling capacity, P_{max}, in the absence of each other. Therefore, since these values are allowable capacities, Equation 27 incorporates the factors of safety of 1.67 for bending moment and 1.85 for web crippling. According to Equation 27, bending moment causes degradation in web crippling capacity when M/M_{max} exceeds 0.31.

Equation 27 was developed from a regression analysis of the test results shown in Figure 7 and recognizes the appropriate factors of safety for bending and web crippling. Figure 7 is a reproduction of Figure 94 from Hetrakul and Yu (1978). The interaction relationship shown in Figure 7 is:

$$1.07\frac{(P_n)_{test}}{(P_n)_{comp}} + \frac{(M_n)_{test}}{(M_n)_{comp}} = 1.42 \qquad (28)$$

Equation 28 was developed from a regression analysis of the test results shown in Figure 7.

The data points in Figure 7 shows the tremendous scatted associated with the phenomenon of the interaction behavior. Essentially, this scatter superposes the variations associated with the separate web crippling and

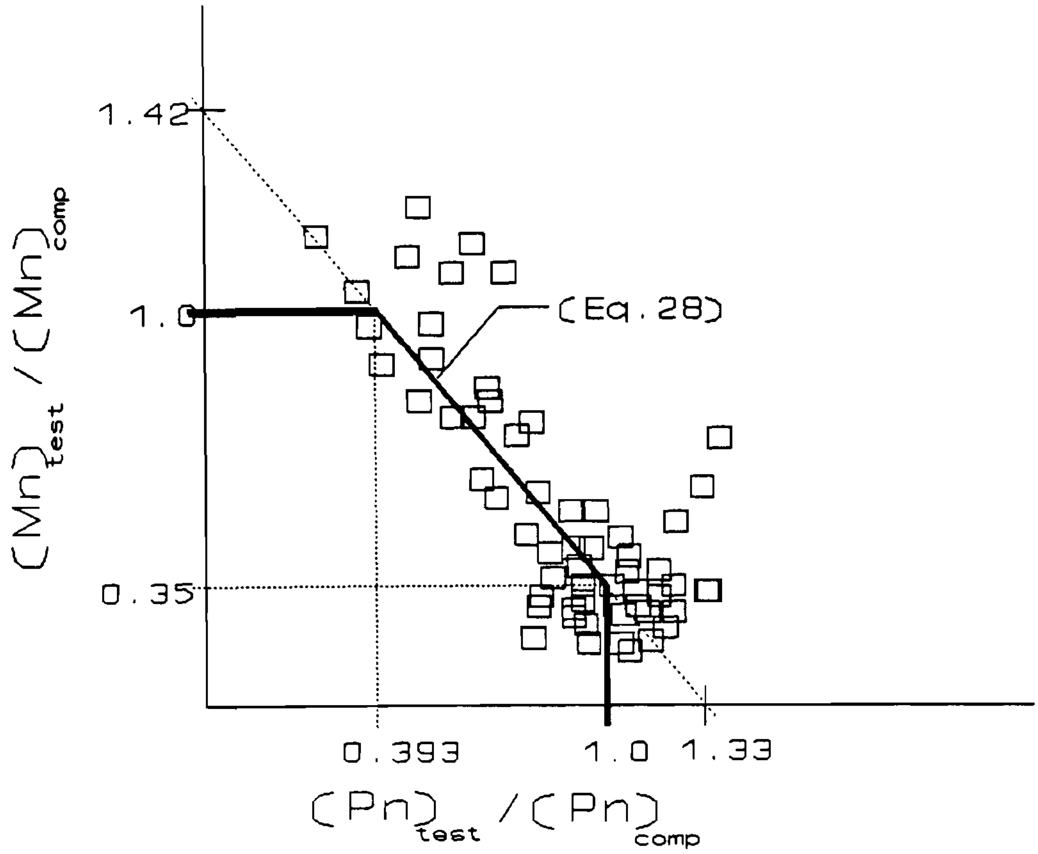


Figure 7: AISI LRFD Specification Nominal Bending and Web Crippling Interaction

bending moment phenomenons. The high magnitude of this scatter is closely related to the complexity of web crippling and combined bending and web crippling. Concerning the complexity of combined bending and web crippling, Hetrakul and Yu (1978) state,

> Because of the large number of significant parameters involved and the complex nature of the interaction behavior between the flange and web element, an analytical solution of this type of problem seems to be extremely difficult. For these reasons, an experimental study was conducted to develop the interaction formulas for the design of beam webs.

According to Equation 28, bending moment causes degradation in web crippling capacity when $(M_n)_{test}/(M_n)_{comp}$ exceeds 0.35.

The high variance in web crippling data, even in the absence of bending moment, can be observed from the scatter of the $(P_n)_{test}/(P_n)_{comp}$ values from Figure 7 for $(M)_{test}/(M_n)_{comp}$ less than 0.35.

4. Shear and Web Crippling Interaction. Shear interaction does not significantly degrade web crippling capacity. Accordingly, there are no AISI Specification provisions governing this interaction. As stated by Hetrakul and Yu (1978),

> For beams having $V/V_u \leq 0.40$ used in the tests, the presence of shear force does not significantly reduce the web crippling load. It is expected that even for beams having high shear stress, the web crippling capacity will not be significantly reduced.

Where V_u is the nominal shear capacity of the section.

F. AISI SPECIFICATION PROVISIONS FOR WEB CRIPPLING, BENDING, AND COMBINED BENDING AND WEB CRIPPLING

1. General. The provisions of the AISI Allowable Stress Design (ASD) Specification and the AISI Load and Resistance Factor Design (LRFD) Specification are reviewed herein. The areas of the provisions reviewed in this paragraph pertain to the failure modes of web crippling, bending, and combined bending and web crippling. The AISI Specification provisions for the design for shear and for

screw connections are provided in Paragraphs II.H and II.I, respectively.

The current ASD Specification (AISI, 1986) for web crippling and combined bending and web crippling were adopted from Hetrakul and Yu (1978), as was reviewed in Section II.E. As discussed herein, some minor differences exist between the equations for these two limit states as given by Hetrakul and Yu (1978) and as adopted in the current ASD Specification provisions (AISI, 1986). Also, as discussed herein, the LRFD Specification (AISI, 1991a) web crippling and combined bending and web crippling provision equations were adopted from the AISI ASD Specification provisions.

Only relevant provisions for the three failure modes of web crippling, bending, and combined bending and web crippling are reviewed herein. The primary intent of the review of AISI Specification provisions is to define the applicability of the provisions to the test specimens and the resulting analysis of test data. The cross-section shape of the test specimens used in the study, specifically edge-stiffened C-shaped sections, is a subset of the total types of cross-section shapes for which the recommended design provisions are valid.

In the context of an ASD format, the web crippling equations (AISI, 1986) are based on allowable load capacity, and are not based on allowable stress. Specifically, stress is not directly computed in any manner for the failure mode of web crippling. The web crippling and combined bending and web crippling provisions are based strictly on analysis of test results of the demonstrated load carrying capacity of tested sections. The LRFD Specification (AISI, 1991a) equations were adapted from the ASD Specification (AISI, 1986) equations by removal of the ASD factor of safety and by performing a statistical analysis to determine the LRFD resistance factor.

2. Web Crippling Capacity.

a. General. The current ASD (AISI, 1986), and LRFD (AISI, 1991a) Specification web crippling provisions are given in Section C3.4, Web Crippling Strength. The provisions apply to unreinforced flat webs of flexural members without web openings for single web sections and multiple web sections.

An overview of the application of the provisions is given by Specifications (AISI, 1986, and AISI, 1991a):

> [The] provisions are applicable to webs of flexural members subject to concentrated loads or reactions, or the components thereof, acting perpendicular to the longitudinal axis of the member, acting in the plane of the web under consideration, and causing compressive stresses in the web.

The maximum limits on the ASD and LRFD web crippling equations for application to beams are: h/t, R/t, N/t, and N/h values of 200, 6, 210, and 3.5, respectively.

The h/t limit of 200 is a general requirement for flexural members. As given in Section C3.4 of the Specification (AISI, 1986, and AISI, 1991a), "Webs of flexural members for which h/t is greater than 200 shall be provided with adequate means of transmitting concentrated loads and/or reactions directly into the webs." The h/t limit is in accordance with Section B1.2, Maximum Web Depth-to-Thickness Ratio, and this limit can be increased to 260 when transverse bearing stiffeners are used, and to 300 when transverse bearing and intermediate stiffeners are used. The transverse stiffeners must meet the requirements of Section B6.1, Transverse Stiffeners, which provides provisions to prevent crushing of the stiffeners and to ensure overall column stability of the stiffeners.

The R/t, N/t, and N/h limitations generally result from the range of parameters of the test specimens studied during the development of the web crippling equations (Hetrakul and Yu, 1978), though Hetrakul and Yu did not state specific limitations for these three parameters.

The web crippling equations of the AISI ASD Specification provide the maximum allowable load per web, P_a or $(P_a)_{comp,\ solid\ web}$, in kips to prevent web crippling failure. The web crippling equations of the LRFD Specification provide the maximum nominal load per web, P_n or $(P_n)_{comp,\ solid\ web}$, in kips and the associated resistance factor to prevent web crippling failure.

b. <u>Web Crippling Equations.</u> Based on the design situation, the nine applicable web crippling equations are given in Table VI. The AISI ASD Specification (AISI, 1986) and AISI LRFD Specification (AISI, 1991a) equation numbers are the same for each design situation.

The ASD Specification equations incorporate a factor of safety of 1.85 for single web sections. Therefore, the ASD equations provide the allowable web crippling load, $(P_a)_{comp, solid web}$. The LRFD equations provide the nominal web crippling load $(P_n)_{comp, solid web}$. The nominal web crippling load, $(P_n)_{comp, solid web}$, can be obtained from the applicable ASD web crippling equation by multiplying the result from the ASD equation, $(P_a)_{comp, solid web}$, by 1.85. Therefore, the ASD web crippling provisions can be used to provide $(P_n)_{comp, solid web}$, and this value is equal to the results from the counterpart LRFD web crippling equation.

The AISI LRFD Specification equation for single web sections are to be used with a web crippling resistance factor, Φ_w, of 0.75. The LRFD design strength is therefore Φ_w $(P_n)_{comp, solid web}$, which is the right hand side of the equation:

$$\sum \gamma R_p \leq \Phi_w R_n \tag{29}$$

where γ = load factor; R_p = service load; Φ_w = web crippling resistance factor = 0.75 for single web sections, and; R_n = nominal capacity or resistance, $(P_n)_{comp, solid web}$.

The reason for the relatively low value of Φ_w for the LRFD Specification provisions is the same as the high ASD Specification factor of safety as discussed in the review of Hetrakul and Yu (1978).

The three web crippling design situations pertinent to this investigation are:

i. <u>EOF Loading of Single Unreinforced Webs.</u> Separate equations are provided for partially stiffened or stiffened flanges and for unstiffened flanges:

For sections with partially stiffened or stiffened flanges, AISI Equation C3.4-1:

$$(P_a)_{comp}=t^2kC_3C_4C_\theta\left(179-0.33\frac{h}{t}\right)\left(1+0.01\frac{N}{t}\right), kips \tag{30}$$

$$(P_n)_{comp}=t^2kC_3C_4C_\theta\left(331-0.61\frac{h}{t}\right)\left(1+0.01\frac{N}{t}\right), kips \tag{31}$$

For sections with unstiffened flanges, AISI Equation C3.4-2:

$$(P_a)_{comp}=t^2kC_3C_4C_\theta\left(117-0.15\frac{h}{t}\right)\left(1+0.01\frac{N}{t}\right), kips \tag{32}$$

$$(P_n)_{comp}=t^2kC_3C_4C_\theta\left(217-0.28\frac{h}{t}\right)\left(1+0.01\frac{N}{t}\right), kips \tag{33}$$

For Equations 32 and 33, when N/t>60, the factor [1+0.01(N/t)] may be increased to [0.71+0.015(N/t)].

As can be seen by a comparison between Equations 30 and 31, which apply to sections with partially edge-stiffened or stiffened flanges, and Equations 32 and 33 which apply to sections with unstiffened flanges, the EOF loading condition for single web sections is the only situation that provides different equations based on the stiffening, or edge-restraint, provided for the flange (Table VI). The explanation for this was provided in the review of the

Hetrakul and Yu (1978) investigation (Section II.E). The definitions of the various categories of flange stiffening are provided in this paragraph.

ii. IOF Loading of Single Unreinforced Webs. The following applies to both sections with stiffened or unstiffened flanges, AISI Equation C3.4-4:

$$(P_a)_{comp}=t^2kC_1C_2C_\theta\left(291-0.40\frac{h}{t}\right)\left(1+0.007\frac{N}{t}\right), kips \tag{34}$$

$$(P_n)_{comp}=t^2kC_1C_2C_\theta\left(538-0.74\frac{h}{t}\right)\left(1+0.007\frac{N}{t}\right), kips \tag{35}$$

For Equation 34 and 35, when N/t>60, the factor [1+0.007(N/t)] may be increased to [0.75+0.011(N/t)].

Where, for Equations 30 thru 35:

$k = F_y/33$
$C_1 = (1.22-0.22k)$
$C_2 = (1.06-0.06\ R/t) \leq 1.00$
$C_3 = (1.33-0.33k)$
$C_4 = 0.50 < (1.15-0.15\ R/t) \leq 1.0$
$C_\theta = 0.7 + 0.30\ (\theta/90)^2$
F_y = Design yield stress of the web
h = Depth of the flat portion of the web
t = Web thickness, inches
R = Inside bend radius
θ = Angle between the plane of the web and the plane of the bearing surface ≥ 45°, but not more than 90°
N = Bearing length of load or reaction.

c. Equation Condition Factors. Nine web crippling equations are provided, and the selection of the applicable equation is based on four factors which are defined separately herein: i. one-versus two-flange loading, ii. end versus interior loading, iii. flange edge-stiffening, and, iv. single versus or multiple web.

Determination of the applicable loading condition of either EOF, IOF, ETF, and ITF (Fig. 1) is accomplished by defining the transition criteria between the one or two-flange loading conditions as defined in Paragraph i, and the transition criteria between the end or interior loading conditions as defined in Paragraph ii.

i. <u>One-versus Two-Flange Loading.</u> If the web in the region of a concentrated load is not simultaneously influenced by the close proximity of an oppositely directed concentrated load, or force component thereof, then the loading condition is considered to be one-flange loading. Conversely, if the web in the region of a concentrated load is simultaneously influenced by the close proximity of an oppositely directed concentrated load, or force component thereof, then the loading condition is considered to be two-flange loading. For the two-flange loading condition, the loads may have different magnitude. Therefore, for simplicity, the magnitude of the greater concentrated force component in the plane of the web is conservatively considered as the applied concentrated web crippling load.

For the one-flange loading condition, the effect of distributed loads is not considered. For example, as commonly exists in practice, an upward concentrated reaction produced by a distributed gravity load on the top-most flange of a section results in an one-flange loading condition for the web in the region of the concentrated reaction. This is true even if the distributed load is applied in the region of the reaction load.

The Specification specifies that close proximity, two-flange condition, is considered to be a clear distance between the oppositely directed load plates of less than or equal to 1.5h. This is shown as parameter d_2 of Figure 1. The two-flange loading condition equations allow significantly less capacity than their one-flange counterparts. Therefore, as a consequence, if a situation exists where the clear distance between the oppositely directed load plates is somewhat less than 1.5h, a considerable increase in capacity can be achieved by increasing the clear distance to a value anywhere equal to or greater than 1.5h. No provision exists for an incremental increase in web crippling capacity for the one-flange condition as the clear distance between the oppositely directed load plates increases from the 1.5h value. Likewise, no provision exists for an incremental increase in web crippling capacity for the two-flange condition as the clear distance between the oppositely directed load plates increases from that which exists when the two loading plates have coincident centerlines.

ii. End versus Interior Loading. End loading exists when any portion of the load plate of the concentrated load under consideration is at a distance less than 1.5h from an end of the member. This is shown as parameter d_1 of Figure 1. Conversely, the loading condition is considered interior loading if the clear distance between the end of the member and the load plate, for the concentrated load under consideration, is greater than or equal to 1.5h. For the end loading condition, the AISI Specification disregards the certain incremental increase in strength as d_1 (Fig. 1) increases towards 1.5h. This increase in strength will exist due to the greater web area available for the dissipation of the load. The neglect of increased capacity is rectified instantly when the interior loading condition is achieved. The interior loading web crippling equations correspondingly provide higher allowable capacities than their counterpart end loading equations. The end loading condition equations of the provisions were conservatively developed under the worst case scenario, i.e. when the edge of the load plate and the end of the section were coincident. The Commentary to the Specification recognizes the discrete nature of the conditions defining the design situation by stating, "These discrete conditions represent the experimental basis on which the design provisions were founded [Hetrakul, and Yu, 1978]".

iii. Flange Edge-Stiffening. The web crippling equations applicable to the condition of EOF loading for single web sections are Equations 30 thru 33 as shown in Table VI. As can be seen in Table VI, the single web EOF situation is the only situation which has separate equations based on the condition of flange stiffening, and therefore, the designer must understand the classification of flange stiffening in order to select the applicable equation for the single web EOF situation. According to the ASD Specification provision (AISI, 1986), single web EOF Equation 30 applies to the case of stiffened flanges, and single web EOF Equation 32 applies to unstiffened flanges. However, the ASD Specification (AISI, 1986) overlooked revisions in Section B4 of the Specification which impact on the applicability of the web crippling equations of Section C3.4. Specifically, this pertains to the added category of partially-stiffened flanges, which was incorporated into Section B4 of the ASD Specification (AISI, 1986), and therefore affects many failure modes in addition to web crippling. However, the change was not reflected in the web crippling equations of Section C3.4 of the ASD Specification (AISI, 1986). The definition of the ASD equations provided herein do include the added category of partially-stiffened flanges, and therefore, the definitions agreed with those of the LRFD Specification (AISI, 1991a), which were correctly furnished.

The selection of the applicable equation is based on the extent of rotational support provided for the flange. The flange is restrained on one edge by the web. The opposite edge of the flange can be free, or it can be rotationally restrained by an edge-stiffener or additional web. Note that rotational restraint does not imply rotational fixity. Edge-stiffeners can have many general shapes such as a curl or straight edge that may or may not be perpendicular to the flange. Edge-stiffeners that consist of straight sections are called simple lips.

Noting that a stiffened flange is a more restrictive case of a partially-stiffened flange, the selection of the correct web crippling equation is dependent on distinguishing between the two categories of partially-stiffened flanges and unstiffened flanges. Numerically, this is based on the plate buckling coefficient, k, of the flange. The k value for an unstiffened flange is 0.43, such as exists when the opposite edge of the flange is free. Therefore, if the computations for k in accordance with Section B4 of the Specification, produces a k value greater than 0.43, then the flange is considered partially-stiffened and Equations 30 and 31 govern. If k is equal to 0.43, the flange is considered unstiffened and Equations 32 and 33 govern.

Section B4 of the Specification provides equations for computing k. The value of k is computed from several equations in either Section B4.1, Uniformly Compressed Elements with an Intermediate Stiffener, or Section B4.2, Uniformly Compressed Elements with an Edge Stiffener, which are not reviewed herein. In general, k is based on many factors which influence the rotational restraint provided for the flange by the stiffener, to include the dimensions of the stiffener and flange, and F_y. The existence of a flange edge stiffener will ensure a k value greater than

0.43, and therefore the flange will be considered partially-stiffened.

iv. Single versus Multiple Web. The general shapes of single web sections are C-shaped, Z-shaped, hat, tubular, and deck sections. Therefore, the term single web denotes a web which is not adequately connected to another web, and single web sections can have several such webs. Multiple web sections have adequately connected webs, such as back-to-back channels, which provide a higher degree of restraint against rotation of the web. For sections with more than one single web, the total capacity is the sum of the P_a (AISI, 1986) or P_n (AISI, 1991a) values from the individual webs.

d. Development of the AISI ASD Specifications. Each of the above AISI ASD Specification web crippling equations was adopted from the investigation by Hetrakul and Yu (1978). Comparison of the equations given by Hetrakul and Yu (1978) and those adopted by the AISI ASD Specification (1986) shows that the equations given by Hetrakul and Yu (1978) and those of the current Specification are the same except for a reduction in significant digits for the Specification adopted equations and as follows.

The equation of Hetrakul and Yu (1978), Equation 22 for the situation with N/t is greater than 60 was not adopted by the Specification. The reason for this is the closeness of the capacity provided by Equations 21 and 22. This can readily be seen by the coefficients of the two equations.

The Specification adopted form of Hetrakul and Yu's equation for the parameter C_4, includes a lower limit of 0.50. The modification to the C_4 factor of the EOF equations was adopted by the Specification based on statistical analysis performed by Yu (1980), and Albrecht (1980). Additionally, AISI incorporates the parameter C_θ in order to generalize the results for the situation where the concentrated load is not applied in the plane of the web. Finally, for brevity, the Specification incorporates the parameter $k = F_y/33$ into each of the web crippling equations. With respect to the inclusion of the parameter k, the equations by Hetrakul and Yu (1978) and the current AISI web crippling provisions are equivalent.

e. Development of the AISI LRFD Specifications. It is evident from a comparison of the LRFD equations (Eqs. 31, 33, and 35) and their ASD counterparts (Eqs. 30, 32, and 34, respectively) that the LRFD equations were developed by factoring the ASD single web factor of safety of 1.85 into the bracket expression containing h/t. Specifically, the two ASD coefficients of the h/t term were multiplied by 1.85. This is equivalent to:

$$(P_n)_{comp,LRFD} = 1.85\ (P_a)_{comp,ASD} \tag{36}$$

f. Influence of High F_y Values. With some frequency, the yield stress, F_y, values of steels used to form cross sections used in practice exceeds those used in the development of the equations developed by Hetrakul and Yu

(1978). The highest F_y value used in the development of the current AISI provisions is 54.0 ksi (Hetrakul and Yu, 1978, and Yu, 1991). However, the current web crippling provisions are still applicable for any F_y value of sections that otherwise meet the requirements of Section A of the Specification (AISI, 1986, and AISI, 1991a). The current equations result in maximum P_a (AISI, 1986) or P_n (AISI, 1991a) values at F_y values of 66.5 ksi when using Equations 30 thru 33, and 91.5 ksi when using Equations 34 and 35.

At higher F_y values than these stated, direct use of the AISI Specification provision equations implies that the allowable web crippling capacity decreases as F_y increases. This is due to the parabolic relation of the equations with respect to F_y. The equations have a negative second derivative with respect to F_y and reach their maximum value at 66.5 or 91.5 ksi. This can be seen from the following zero slope relationships which contain all of the F_y terms of the equations:

Single Web-End equations:

$$\frac{\partial(Eqns.)}{\partial F_y} = \mathrm{K}\,\partial\frac{k\,C_3}{\partial F_y} = \mathrm{K}\,\partial\frac{(\frac{F_y}{33})(1.33-0.33(\frac{F_y}{33}))}{\partial F_y} = 0 \quad (37)$$

solution: $F_y = 66.5$

Single Web-Interior equations:

$$\frac{\partial(Eqns.)}{\partial F_y} = K\,\partial\frac{k\,C_1}{\partial F_y} = K\,\partial\frac{(\frac{F_y}{33})(1.22-0.22(\frac{F_y}{33}))}{\partial F_y} = 0 \tag{38}$$

solution: $F_y = 91.5$

where K collectively represents the constants with respect to the differentiation with respect to F_y.

After differentiating the quadratic equations, the resulting equations of the lines yield the aforementioned F_y values as their root or solution. Therefore, direct use of the equations will incorrectly produce an apparent decrease in P_a values for F_y values which are higher than those stated. No provision is currently allowed for increasing the web crippling strength for higher F_y values. Therefore, the stated F_y values of 66.5 or 91.5 ksi, as applicable, should be used if the cross section has a yield strength which exceeds these values.

The equations by Santaputra, Parks, and Yu (1991) were developed primarily to account for higher F_y values, up to 190 ksi. These equations are reviewed in Section II.G.

3. Bending Capacity.

a. General. To compute the bending interaction degradation on the web crippling strength or to use the combined bending and web crippling interaction provisions, the bending moment capacity of the section must be determined. The ASD allowable moment capacity and the LRFD nominal moment capacity are required entries for the subsequently reviewed combined bending and web crippling interaction equations.

b. Computation of Bending Capacity. For both the ASD Specification (AISI, 1986) and LRFD Specification (AISI, 1991a), Section C3, Flexural Members, C3.1.1, Strength for Bending Only, provides the bending moment capacity in the absence of interaction. The maximum allowable applied bending moment, M_a, which can be determined from the ASD Specification (1986), Equation C3.1-1:

$$M_a = M_n / \Omega_f \tag{39}$$

where Ω_f is the factor of safety for bending, which is equal to 1.67.

For both the ASD Specification (1986) and the LRFD Specification (1991a), the nominal bending moment strength, M_n is obtained in the same procedure. The value of M_n is the smallest value from Sections C3.1.1, Nominal Section Strength, C3.1.2, Lateral Buckling Strength, and C3.1.3, Beams Having one flange Through-Fastened to Deck or Sheathing.

The LRFD Specification resistance factor for bending, Φ_b, is equal to 0.90 for unstiffened flanges and 0.95 for partially-stiffened or stiffened flanges. The LRFD design strength for flexure is therefore Φ_b multiplied by $(M_n)_{comp}$, which is required for the equation:

$$\sum \gamma M \leq \Phi_b M_n \tag{40}$$

where γ = load factor; M = applied service moment; Φ_b = bending moment resistance factor, and; M_n = nominal moment capacity or resistance.

For the design situation of beams which have adequate lateral bracing of the compression flange, M_n is based strictly on the value determined from Section C3.1.1. Section C3.1.1, Nominal Section Strength, provides the nominal section strength based on either Section C3.1.1(a), Procedure I - Based on Initiation of Yielding, or Section C3.1.1(b), Procedure II - Based on Inelastic Reserve Capacity. Procedure II can only be used if overall stability of the member and local stability of the compression elements is ensured during partial plastification of the cross section.

According to Yu (1991), "Prior to 1980, the inelastic reserve capacity of beams was not included in the AISI Specification". Therefore, the combined bending and web crippling equations of the current AISI Specification provisions were based on tests which did not consider inelastic reserve capacity. Also, C-shaped sections, including those with edge-stiffened flanges, typically receive very little or no additional capacity from Procedure II. Therefore, only the provisions of Procedure I-Based on Initiation of Yielding are reviewed herein.

In accordance with Procedure I, M_n is computed by Equation 41 from the ASD Specification (1986) and LRFD Specification (1991a), Equation C3.1.1-1:

$$M_n = S_e F_y \tag{41}$$

where S_e = elastic section modulus of the effective section calculated with the extreme compression or tension fiber at F_y.

The value of S_e is determined from established procedures of the Specification (AISI, 1986, or AISI, 1991a) Section B, Elements. The procedures consider the possible reduction of effective width of the compression flange and compression region of the web.

In lieu of a review herein of the lengthy provision requirements for computing S_e, detailed information can be found in the Commentary and Illustrated Examples of the Manual (AISI, 1986, and AISI, 1991a), Yu (1991), and LaBoube (1990b).

4. Bending and Web Crippling Interaction.

a. General. The provisions for combined bending and web crippling are given in Section C3.5 of the ASD Specification (AISI, 1986) and LRFD Specification (AISI, 1991a). Two interaction equations are provided, and selection of the appropriate equation is based on whether or not the section has a single unreinforced web or multiple unreinforced web. Only the single web unreinforced situation is reviewed herein.

b. Interaction Equation for Single Web Sections. The interaction equation for sections having flat-single unreinforced webs subjected to a combination of bending and concentrated load or reaction, is given by AISI Equation C3.5-1 for both the ASD and LRFD formats. For the ASD Specification:

$$1.2(P/P_a)+(M/M_{axo})<1.5 \tag{42}$$

where P = concentrated load or reaction in the presence of bending moment; P_a = allowable concentrated load or reaction in the absence of bending moment determined in accordance with Section C3.4; M = applied bending moment at, or immediately adjacent to, the point of application of the concentrated load or reaction, and; M_{axo} = the allowable moment about the centroidal axes determined in accordance with Section C3.1, excluding the provisions of Section C3.1.2.

For the LRFD Specification:

$$1.07\left(\frac{P_u}{\Phi_w P_n}\right)+\left(\frac{M_u}{\Phi_b\, M_{nxo}}\right)\leq 1.42 \tag{43}$$

where Φ_b = resistance for bending (AISI LRFD Specification Section C3.1); Φ_w = resistance factor for web crippling (AISI LRFD Specification Section C3.4); P_u = required strength for the concentrated load or reaction in the presence of bending moment; P_n = nominal strength for concentrated load or reaction in the absence of bending moment determined in accordance with Section C3.4; M_u =

required flexural strength at, or immediately adjacent to, the point of application of the concentrated load or reaction P_u, and; M_{nxo} = nominal flexural strength about the centroidal x-axis determined in accordance with Section C3.1, excluding the provision of Section C3.1.2.

The above definitions of M_{axo} and M_{nxo} result from bending and web crippling interaction being influenced by the stress condition in the cross section, and not by the lateral stability of the member.

Equation 42 was adapted from Equation 27 with a reduction in the number of significant digits. Equation 42 is shown graphically as Figure 8. Equation 43 was adopted directly from Equation 28. Equation 43 is based on the results the test data reported by Hetrakul and Yu (1978) as shown on Figure 7.

The bending and web crippling interaction equations apply only to unreinforced webs. For a section to be considered web reinforced, and hence exempt from the interaction equations, the design must meet the provisions of the ASD Specification (1986) and LRFD Specification (1991a) Section B6, Stiffeners. The provisions ensure adequate strength and stability of transverse stiffeners.

c. <u>Influence of Interaction.</u> Except in the immediate vicinity of points of zero moment, i.e. at the end reactions of a simply supported member, or at points of inflection for continuous span members, the effects of the interaction of web crippling and bending must be considered. As stated by

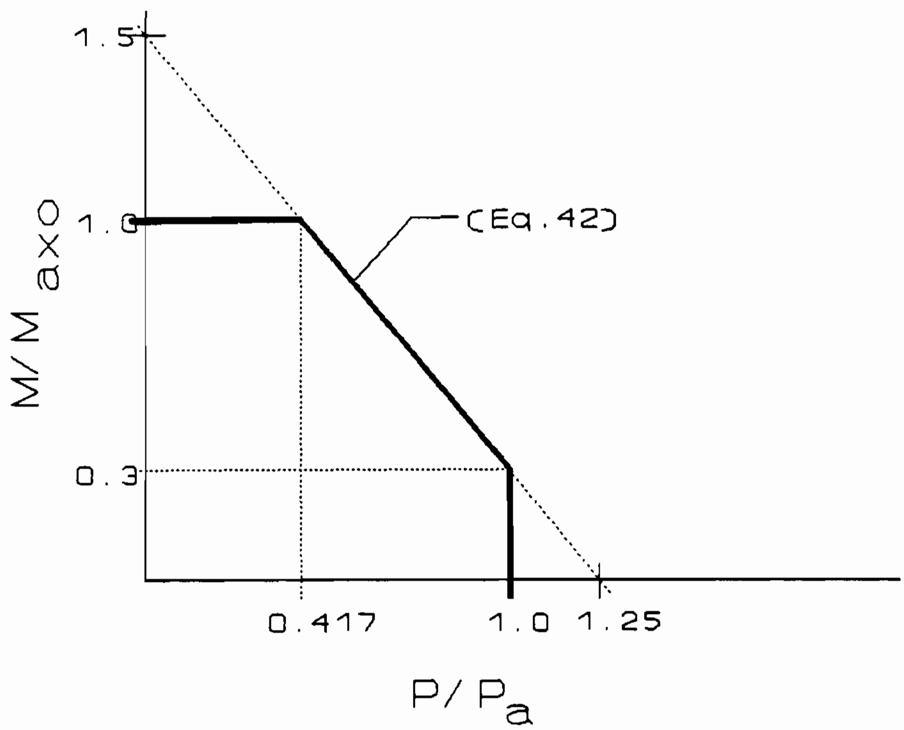


Figure 8: AISI ASD Specification Allowable Bending and Web Crippling Interaction

Yu (1991):

> The AISI [web crippling] design formulas were used to prevent any localized failure of webs resulting from the bearing pressure due to reactions or concentrated loads without consideration of the effect of other stresses. In practical applications a high bending moment may occur at the location of the applied concentrated load in simple span beams. For continuous beams, the reactions at supports may be combined with high bending moments and/or high shear. Under these conditions, the web crippling strength as determined by (AISI, 1986, Section 3.4 Web Crippling Strength) may be reduced significantly due to the effect of bending moments. The interaction relationship for the combination of bearing pressure and bending stress has been studied by numerous researchers. ... Based on the results of beam tests with combined web crippling and bending, interaction formulas have been developed for use in several design specifications.

Figure 8 graphically shows the maximum limits of Equation 42. The figure also shows the limits of 1.00 for M/M_{axo} and P/P_a. Therefore, any interaction value which falls within the region bounded by the three lines defined by: 1. M/M_{axo} is less than or equal to unity, 2. P/P_a is less than or equal to unity, and 3. satisfaction of the equality of Equation 42, is an acceptable design result. For the ASD Specification, at M/M_{axo} values greater than 0.30, bending moment is considered to degrade the web crippling capacity of the section. For the LRFD approach, essentially the same magnitude of bending moment is considered to cause degradation in web crippling strength. However, the minimum value of bending for which bending moment is considered not to degrade web crippling strength is provided in terms of $M/\Phi_b M_{nxo}$. For $M/\Phi_b M_{nxo}$ values greater than 0.35, bending moment is considered to degrade the web crippling capacity of the section (Eq. 43 and Fig. 7).

5. Web Crippling and Shear Interaction. As determined by Hetrakül and Yu (1978) and reviewed in Section II.E, web crippling and shear have no significant interaction. Hence, the AISI Specification has no provisions.

This finding has significant impact for sections where the shear and web crippling capacity are degraded by a mechanical alteration to the section, i.e. because of a web opening. If the values of the nominal shear capacity, V_n and web crippling capacity, P_n are reduced to $(V_n)_{comp,\ web\ opening}$ and $(P_n)_{comp,\ web\ opening}$, because of the mechanical alteration, then the values of $V/(V_n)_{comp,\ web\ opening}$ and $P/(P_n)_{comp,\ web\ opening}$ are both increased. In the typical form of an interaction equation, a linear sum of these two quantities must be less than a prescribed constant. Hence, if shear and web crippling interaction was significant, then the effect of a mechanical alteration to a section would cause the maximum interaction value to be exceeded more readily, i.e. at lower applied loads. Furthermore, due to the interaction, the applied web crippling concentrated load may not be allowed to reach the value of $(P_n)_{comp,\ web\ opening}$, and this value is already assumed to be less than $(P_n)_{comp,\ solid\ web}$.

G. <u>SANTAPUTRA, PARKS, AND YU WEB CRIPPLING EQUATIONS</u>

1. <u>General.</u> Santaputra, Parks, and Yu (1989) provide web crippling capacity equations for flexural members. The equations provide the ultimate web crippling capacity for unreinforced beams, and have maximum limits of F_y, h/t, N/t, N/h, and R/t of 190, 200, 100, 2.5, and 10, respectively. Although these equations were not adopted for inclusion into the Specification (AISI, 1986, or AISI, 1991a), they were adopted for inclusion into the Automotive Steel Design Manual (AISI, 1991b). As stated previously in Section II.F, the current Specification provisions do not consider any contribution in yield strength above 66.5 ksi for the end loading web crippling equations (Eqs. 30 thru 33), and 91.5 ksi for the interior loading web crippling equations (Eqs. 34 and 35). However, the Specification equations are still

applicable to higher F_y values although no increase in capacity can be realized. Santaputra, Parks, and Yu (1989) stated the primary purpose of their study as:

> Because high-strength steels with high yield strengths from 80 to 190 ksi (552 to 1,310 MPa) are now used for automotive structural components ... and because many of the existing design expressions have not been verified for very high yield strength materials, a comprehensive design guide is highly desirable.... The main purpose of the project had been to develop additional design criteria for the use of a broader range of high-strength sheet steels.

2. <u>Relationship to Current Specification Provisions.</u> The existing Specification (AISI, 1986, and AISI, 1991a) web crippling provisions have discrete transitions between the one-and two-flange conditions and between the end and interior conditions. The equations of Santaputra, Parks, and Yu (1989) are more versatile by allowing transitions between the one and two-flange conditions and the end loading and interior loading conditions. This is accomplished by linearly combining equations, and using pertinent geometric longitudinal parameters as the slope of the linear equation for these interpolations. Specifically, the geometric parameter e (Fig. 9) is a variable in the equations.

The equations developed by Santaputra, Parks, and Yu (1989) can be related to those for the EOF, IOF, ETF, and ITF loading condition conventions of the existing Specification provisions (AISI, 1986, and AISI, 1991a).

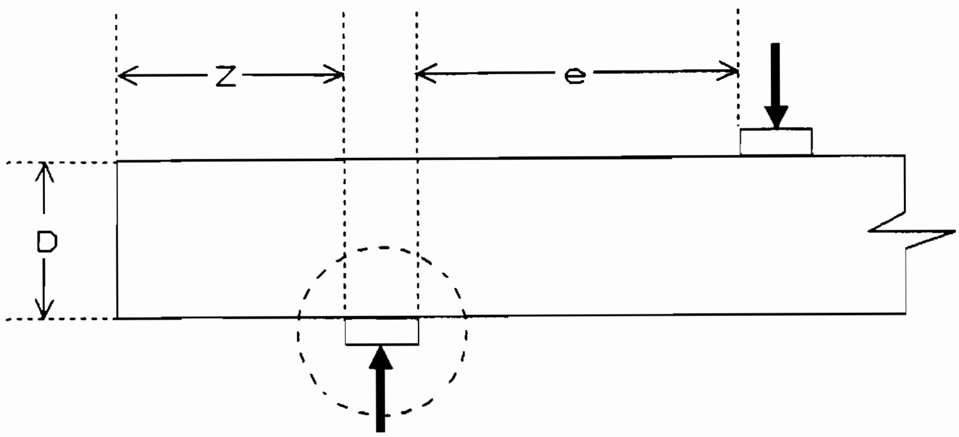


Figure 9: Santaputra, Parks, and Yu Web Crippling Equation Parameter Definitions

This can be accomplished by determining the values of the parameters Z and e as shown in Figure 9.

Figure 9 applies to the end loading conditions, EOF and ETF when Z is less than 1.5h. An e value greater than 1.5h is considered as an EOF loading condition, and less than or equal to 1.5h is considered as an ETF loading condition. Figure 9 applies to the interior loading conditions, IOF and ITF when Z is greater than or equal to 1.5h. An e value greater than 1.5h is considered as an IOF loading condition, and an e value less than or equal to 1.5h is considered as an ITF loading condition.

3. Strength Equations. Equations for single web sections which are applicable to the current investigation are provided as follows. When the end of the load plate and the end of the section coincide, the value of Z (Fig. 9) is

equal to zero. For Z equal to zero, the nominal or ultimate web crippling capacity, $(P_n)_{comp}$, is the lesser of:

$$P_{cy} = 9.9\, t^2 F_y C_{11} C_{21} (SIN\theta) \tag{44}$$

and,

$$P_{cb} = 0.047\, E t^2 C_{41} C_{51} (SIN\theta) \tag{45}$$

For the IOF loading condition, a necessary but not sufficient condition is that Z (Fig. 9) is greater than or equal to 0.5h. For $Z \geq 0.5h$, the nominal or ultimate web crippling capacity, $(P_n)_{comp}$, is the lesser of:

$$P_{cy} = 7.80\, t^2 F_y C_{12} C_{22} (SIN\theta) \tag{46}$$

and,

$$P_{cb} = 0.028\, E t^2 C_{32} C_{42} C_{52} (SIN\theta) \tag{47}$$

where, for each of the above equations:

P_{cy} = the ultimate web crippling capacity, per web, caused by bearing, kips
P_{cb} = the ultimate web crippling capacity, per web, caused by buckling, kips
$C_{11} = 1 + 0.0122(N/t) \leq 2.22$
$C_{12} = 1 + 0.0122(N/t) \leq 3.17$
$C_{21} = 1 - 0.247\ (R/t) \geq 0.32$
$C_{22} = 1 - 0.0814\ (R/t) \geq 0.43$
$C_{32} = 1 + 2.4\ (N/h) \leq 1.96$
$C_{41} = 1 - 0.00348\ (h/t) \geq 0.32$
$C_{42} = 1 - 0.00170\ (h/t) < 0.81$
$C_{51} = 1 - 0.298\ (e/h) \geq 0.52$
$C_{52} = 1 - 0.120\ (e/h) \geq 0.40$
t = web thickness, in.
E = modulus elasticity of steel, 29500 ksi
F_y = yield strength of web, ksi
θ = angle between the plane of the web and the plane of the bearing surface ≥ 45°, but not more than 90°.
h = depth of the flat portion of the web
N = length of bearing, in.
R = inside bend radius, in.
e = defined in Figure 9

Each of the above equations pertain to an e value greater than or equal to 0.5h, for which the EOF and IOF loading condition meet by the definition of the one-flange loading condition (Fig. 1).

H. SHEAR DESIGN PROVISIONS

1. General. Although web crippling is the major focus of this investigation, and Hetrakul and Yu (1978) observed that web crippling and shear do not significantly interact, under certain conditions, shear may be the governing failure mode. Because the AISI LRFD Specification (1991a) shear provisions are essentially the same as the ASD Specification shear provisions, the LRFD Specification provisions are not reviewed herein.

2. Provision Equations. Allowable shear capacity, for solid web sections, is computed in accordance with Specification (AISI, 1986) Section C3.2, Strength for Shear Only. The allowable shear force, V_a, is the lesser of:

For,

$$h/t \leq 1.38 \sqrt{E k_v / F_y} \tag{48}$$

$$V_a = 0.38\ t^2 \sqrt{k_v F_y E} \tag{49}$$

and,

$$V_a = 0.4\ F_y\ h\ t \tag{50}$$

and for,

$$h/t > 1.38 \sqrt{E k_v / F_y} \tag{51}$$

$$V_a = 0.53 E k_v t^3 / h \tag{52}$$

where: t = web thickness
h = height of the flat portion of the web
k_v = shear buckling coefficient determined as follows:
1. For unreinforced webs, $k_v = 5.34$
2. For beam webs with transverse stiffeners satisfying the requirements of Section B6.

when $a/h \leq 1.0$:

$$k_v = 4.00 + \frac{5.34}{(a/h)^2} \tag{53}$$

when $a/h > 1.0$:

$$k_v = 5.34 + \frac{4.00}{(a/h)^2} \tag{54}$$

where a = the shear panel length for unreinforced web elements, or the distance between transverse stiffeners for web elements.

Equations 49, 50, and 52 consider inelastic shear buckling, shear yielding, and elastic shear buckling, respectively, and incorporate factors of safety of 1.67, 1.44, and 1.71, respectively, (AISI, 1986).

I. AISI SPECIFICATION PROVISIONS FOR SCREW CONNECTIONS

This section is included for design and analysis of the attachment of web reinforcement. The equations reviewed herein for the capacity of screw connections apply to the web reinforcement study contained in Section V of this document. For screw connections, the Specification provisions published by the Center for Cold-Formed Steel Structures, CCFSS, (1993), apply. These provisions and their commentary were approved for inclusion in future editions of the Specification, as Section E4, Screw Connections. Other types of connections such as welds and bolts must be designed in accordance with the Specification (AISI, 1986, and AISI, 1991a) Section E, Connections and Joints.

An essential portion of the overall adequacy of the connection attachments joining two elements is the adequacy of each of the individual screw connections. This is provided for by CCFSS (1993), which ensures adequate strength of each component of the connection, which includes both the screw connectors and the connected parts. The provision equations are provided in Appendix B.

J. RESISTANCE FACTOR AND FACTOR OF SAFETY COMPUTATIONS

A valuable tool in evaluating the results of tests and developed design equations, such as capacity predicting equations and reduction factor equations, is the resistance factor, Φ, which aids to ensure an acceptable level of safety. Commonly, design equations are developed from a regression analysis of the test results, and correspondingly provide the nominal capacity for the applicable failure mode. The plot of the design equation versus the test results generally pass through the center of the scatter of the data, unless the data was specifically modified or shifted.

As the scatter of the tests results increases, confidence in the design equation is reduced. Therefore, the determination of the value of Φ, and its comparison to unity is an indicator of the scatter of the tests results. Furthermore, the inclusion of an additional factor which produces more uncertainty in the design model, such as a significant mechanical alteration to a section, will likely result in a decrease in the Φ value. An example of a mechanical alteration is the creation of a web opening in a flexural member. Additionally, the comparison of the Φ values with and without a mechanical alteration is useful. For example, an useful comparison could be between the values of $\Phi_{\text{web crippling, solid web}}$ and $\Phi_{\text{web crippling, web opening}}$.

Inherent to the concept of the LRFD approach is the knowledge of the resistance factor, Φ, associated with the provision equations governing the particular failure mode or limit state. The resistance factor "accounts for the uncertainties and variabilities inherent in the R_n, and it is usually less than unity." (AISI, 1991a).

The Φ factor can be computed in accordance Equation F1-2 of AISI (1991a):

$$\Phi = 1.5(M_m F_m P_m)\exp\left(-\beta_0\sqrt{V_M^2 + V_F^2 + C_P V_P^2 + V_Q^2}\right) \tag{55}$$

Where, in general:

M_m = Mean value of the material factor for the type of component involved.

F_m = Mean value of the fabrication factor for the type of component involved.

P_m = Mean value of the tested-to-predicted load ratios.

β_o = Target reliability index = 2.5 for structural members and 3.5 for connections.
V_M = Coefficient of variation of the material factor for the type of component involved.
V_F = Coefficient of variation of the fabrication factor for the type of component involved.
C_P = Correction factor = (n-1)/(n-3)
V_P = Coefficient of variation of the tested to-predicted load ratios.
n = number of tests values.
V_Q = Coefficient of variation of the load effect = 0.21

Specific values for web crippling for the parameters M_m, V_M, F_m, and V_F are from F1 of (AISI, 1991a). These values are: M_m = 1.10, V_M = 0.10, F_m =1.00, and V_F =0.05; P_m and V_P are determined from statistical analysis of all test results used to compute $(P_n)_{comp}$, and; β_o = 2.5.

As the scatter of the test results increases, V_p, increases, and therefore as can be seen by Equation 55, the value of Φ is reduced. Specifically, a given limit state fixes the M_m, V_m, F_m, V_F, and β_o values. Therefore, for given number of tests, n, each of the parameters of Equation 55 are constant except for P_m and V_m.

Conversely, the comparable LRFD factor of safety, $(F.S.)_{LRFD}$, based on the value of Φ and a prescribed ratio of dead to live load, is computed using Equation 56, which was taken from Equation II.7 from Hsiao, Yu, and Galambos, (1988):

$$(F.S.)_{LRFD}=(1.2D_n/L_n+1.6)/[(\Phi(D_n/L_n+1)] \qquad \textbf{(56)}$$

where D_n/L_n = the dead load to live load ratio is = 1/5.

As can be seen by Equation 56, $(F.S.)_{LRFD}$ is inversely proportional to Φ.

For a given D_n/L_n value, the magnitude of the $(F.S.)_{LRFD}$ value is also useful in evaluating the variance of the test results. Specifically, a mechanical alteration to a section will likely provide an increase in the factor of safety required to obtain a target reliability index or safety index because of the reduced Φ value.

III. END-ONE-FLANGE UNREINFORCED WEB OPENING STUDY

A. INTRODUCTION

This section comprises the complete findings of the UMR study on the web crippling behavior of single unreinforced webs for cold-formed steel flexural members with web openings subjected to the End-One-Flange, EOF, loading condition (Fig. 1). This is the first known study of the effect of web openings on the web crippling behavior of flexural members with web openings subjected to the EOF loading condition. The experimental investigation, test results, evaluation of test results, and design recommendations provided in this section are independent of those of Section IV, Interior-One-Flange Unreinforced Web Opening Study, and Section V, End-One-Flange and Interior-One-Flange Reinforced Web Opening Study.

The primary results of the study are design recommendations which quantify the web crippling behavior in a manner suitable for implementation in practice. The design recommendations provided in this section are in the form of a reduction factor, RF, equation, as defined in Section I.D, Terminology. Limits of the applicability of the reduction factor equation based on the parameters of the design situation are also specified. The design recommendations are also summarized in Section VI.

The numerical value from the reduction factor equation can be used in Equations 2 or 3 to provide the reduced EOF web crippling capacity for a section with single unreinforced webs with web openings. Furthermore, for sections with web openings, these capacities are required entries for the ASD Specification (1986) and the LRFD (1991a) Specification equations for combined bending and web crippling for single unreinforced web sections, Equations 42 and 43, respectively.

B. PURPOSE

The purpose of the overall investigation for the EOF loading condition for unreinforced single web sections are, respectively:

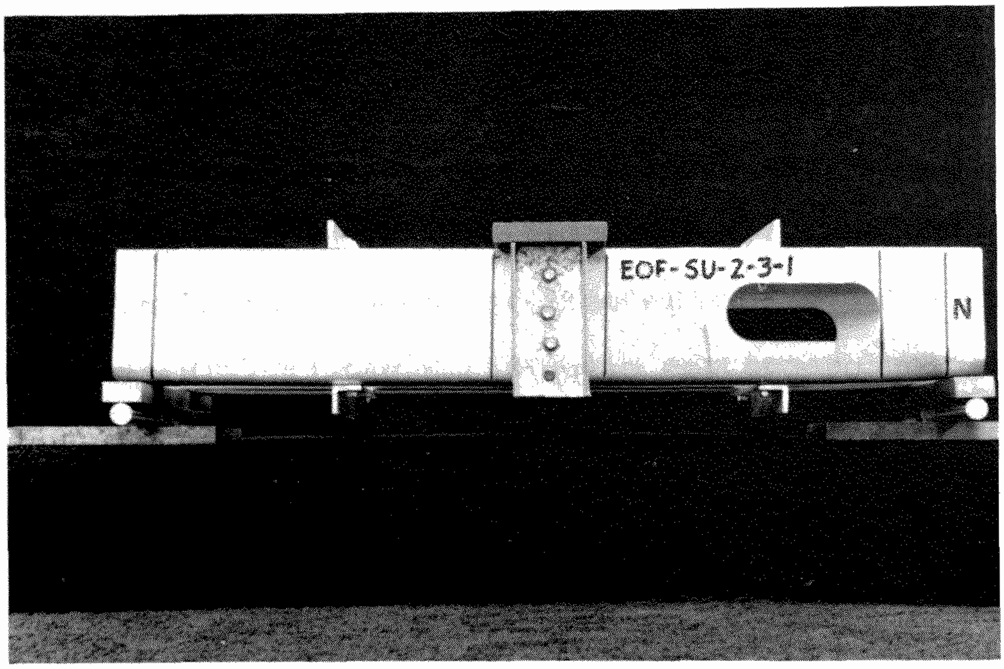
1. To study the web crippling behavior of single unreinforced webs of cold-formed steel flexural members with web openings subjected to the EOF loading condition, and, if necessary, to develop appropriate design recommendations based on the web crippling behavior of the test specimens.

2. To evaluate the existing AISI EOF web crippling design provisions for single web unreinforced sections by comparing the following two sets of test results with the AISI Specification EOF web crippling provisions (Eqs. 30 thru 33). The first test of test results are those of the unreinforced solid web EOF tests, and the second set of test results are those of the unreinforced EOF tests performed on test specimens with web openings.

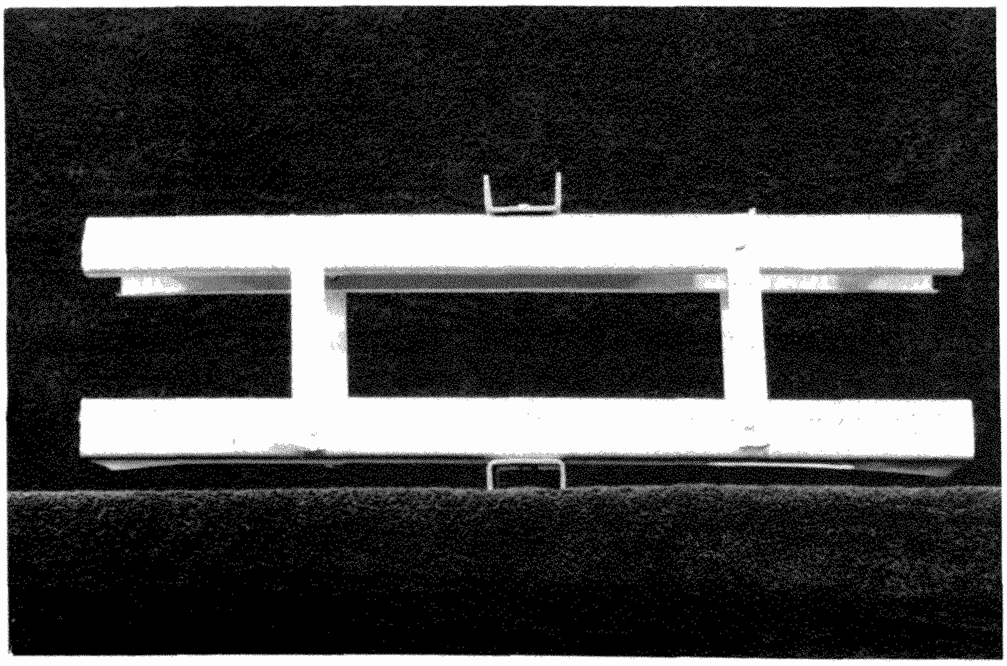
The existing Specification web crippling provisions provide the capacities of solid web sections in the absence of bending moment. Therefore, a necessary condition for an useful comparison is that the results be considered only for tests which were performed in the absence of significant bending moment. As discussed herein, all EOF tests performed during the investigation had no bending moment degradation of the web crippling capacity. This was accomplished because of the configuration of test specimens used in the investigation, and is not generally true for all EOF loading situations.

C. EXPERIMENTAL INVESTIGATION

1. Test Specimens. The test specimens were fabricated from industry standard C-sections with edge-stiffened flanges. Therefore, the flanges are classified as partially-stiffened in accordance with the AISI Specifications (1986, and 1991a). The web openings were rectangular with fillet corners and were located at mid-height of the web. See Figures 2 and 3 for the cross-section and longitudinal geometry of the test specimens, respectively. Figure 10 shows a typical test specimen. Thirteen sections were tested with cross-section properties as listed in Table I. The tested range of cross-section parameters are given in Table IV. Two sizes of web openings were used in this test program, 0.75 x 2 inches and 1.50 x 4 inches, and are designated by dimensions a and b as shown on Figure 3.



(a) Side View



(b) Top View

Figure 10: Typical Unreinforced EOF Specimen

The sections were fabricated to ensure that the web opening in each test specimen was at the desired distance x (Fig. 3) from the EOF load bearing plate. The value of x was the major parameter varied within each common cross section. The value of x was converted to a non-dimensional parameter α, where α is equal to x/h. Tests were conducted for α values in increments of 0, 0.5, 0.7, 1.0, and 1.5.

The length of the EOF bearing reaction plate, N, (Fig. 3) affected the test specimen configuration. In conjunction with the value of x, the value of N determined the longitudinal distance between the end of the section and the web opening. As can be seen from Figure 3, the end of the test specimen was cut at a distance from the web opening equal to the sum of N and x. Tests were performed at N values of 1.0, 3.0, 4.0, 5.0, and 6.0 inches.

The AISI Specification web crippling provisions state that for the loading situation to be considered as an one-flange condition, the value of d_2 (Fig. 1) must be greater than 1.5h. As can be seen by Figure 3, the length of each test specimen is dependent upon the clear distance between the EOF load plates and the mid-span load plate. The L value of the test specimens often exceeded the L value necessary to satisfy the one-flange loading condition requirement. This is because of the imposition of the additional requirement that the value of x′ (Fig. 3) be greater than or equal to zero. This requirement was imposed in order to prevent reinforcement of the web opening by the load point stiffener (Fig. 3). Therefore, this requirement ensured that the entire length of the web opening, b, (Fig. 3) was located in the clear distance between the EOF reaction bearing plate and the mid-span load application plate.

The minimum length, L_{min}, of each test specimen needed to meet the requirement that d_2 was greater than 1.5h is given by the equation:

$$L_{min} = (2 \times 1.5h) + 2N + 3,\ inches \tag{57}$$

The L_{min} value needed to meet the requirement that x′ is greater than or equal to zero is given by the equation:

$$L_{min} = (2(x+b)) + 2N + 3,\ inches \tag{58}$$

Therefore, the L value of each test specimen was equal to the greater of:

$$L = 2(1.5h+N) + 3,\ inches \tag{59}$$

and,

$$L = 2(x+b+x') + 3,\ inches \tag{60}$$

For Equations 57 thru 60, the coefficient of two results from the symmetry of the application of the load at mid-span. The value of three inches in each of the equations is equal to the bearing length of the mid-span loading plate (Fig. 3).

The value of b is a cross-section parameter and invariant for a given cross section as defined in Section I.D, Terminology. Therefore, for a given cross section, and hence a given b value, Equation 58 controls the value of L_{min} at high α values. Tables VII, VIII and IX contain a summary of the overall specimen length, L, bearing length, N, and α of each specimen.

Equations 58 and 60 do not apply to solid web test specimens. The previous EOF research performed by Hetrakul and Yu (1978) did not have the additional requirement that the value of x' was greater than or equal to zero, because their investigation was limited to solid web sections. The current investigation is the first EOF web crippling research where the L_{min} value was governed by a factor other than the requirement for one-flange loading (Eq. 57), and hence often resulted in test specimens with significant bending in the interior region of the simply supported test specimen (Fig. 3).

The highest α value used in the test procedure was limited to 1.5. This limit was imposed because high α, or x/h, values will increase the length of the specimen (Eq. 60), and will therefore increase the bending moment. Therefore, mid-span flexural failures become significantly more likely as α is increased.

As part of the evaluation of the test specimen configuration, the related parameters L and x' were studied for their effect on the web crippling behavior in the absence of significant bending moment. The values of L and x' are extraneous parameters to EOF web crippling behavior. Specifically, they are required parameters for the test

Table VII: Unreinforced EOF Diagnostic Test Results

Specimen Number	L (in.)	N (in.)	α	$(P_n)_{test}$ (lbs.)				Comments
				test 1	test 2	test 3	Avg.	
L and x' Study								
EOF-SU-9-12a	16.28	1.0	0.50	669	656	---	663	x' = 0.00 in.
EOF-SU-9-12b	19.54	1.0	0.50	675	---	---	675	x' = 1.67 in. = 0.50h
EOF-SU-9-12c	22.81	1.0	0.50	663	644	---	654	x' = 3.27 in. = 1.00h
Load Application Rate Study								
EOF-SU-11-1a	18.00	1.0	Solid	750	738	725	738	constant and gradual rate
EOF-SU-11-1b	18.00	1.0	Solid	806	738	825	790	incremental method: 5 minute maintenance of load at 15 percent increments of the expected failure load.

Notes: 1. The expected failure load (100 percent) for the incremental loaded specimens was equal to 738 lbs., based on the average of the constant and gradually loaded test specimens.
2. Cross-section designations:
EOF: End-One-Flange loading condition, SU: Single Unreinforced web
EOF-SU-cross section number-specimen designation
3. The mid-span bearing length for all specimens was 3.00 inches.

Table VIII: Unreinforced EOF Test Results

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	PSW_{adj}	Limit State	Reduction Factor	
							Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-1-1-1	39.64	1.0	SOLID	994	97.3	WEB CRIPPLING	1.000	1.000
EOF-SU-1-1-2	39.64	1.0	SOLID	1050	102.7	WEB CRIPPLING	1.000	1.000
EOF-SU-1-2-1	39.64	1.0	0.00	1175	115.0	WEB CRIPPLING	0.980	0.997
EOF-SU-1-2-2	39.64	1.0	0.00	1100	107.6	WEB CRIPPLING	0.980	0.997
EOF-SU-2-1-1	20.00	1.0	SOLID	706	100.9	WEB CRIPPLING	1.000	1.000
EOF-SU-2-1-2	20.00	1.0	SOLID	694	99.1	WEB CRIPPLING	1.000	1.000
EOF-SU-2-2-1	22.66	1.0	0.00	488	69.7	WEB CRIPPLING	0.695	0.786
EOF-SU-2-2-2	22.66	1.0	0.00	506	72.3	WEB CRIPPLING	0.695	0.786
EOF-SU-2-3-1	22.66	1.0	0.50	581	83.0	WEB CRIPPLING	0.695	0.846
EOF-SU-2-3-2	22.66	1.0	0.50	588	84.0	WEB CRIPPLING	0.695	0.846
EOF-SU-2-4-1	22.66	1.0	0.70	600	85.7	WEB CRIPPLING	0.695	0.870
EOF-SU-2-4-2	22.66	1.0	0.70	613	87.6	WEB CRIPPLING	0.695	0.870
EOF-SU-2-5-1	22.66	1.0	1.00	663	94.7	WEB CRIPPLING	0.695	0.907
EOF-SU-2-5-2	22.66	1.0	1.00	650	92.9	WEB CRIPPLING	0.695	0.907

Table VIII: Unreinforced EOF Test Results (cont.)

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	PSW_{adj}	Limit State	Reduction Factor	
							Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-2-6-1	22.66	1.0	1.50	688	98.3	WEB CRIPPLING	0.695	0.967
EOF-SU-2-6-2	22.66	1.0	1.50	681	97.3	WEB CRIPPLING	0.695	0.967
EOF-SU-2-7-1	22.66	3.0	0.50	831	---	WEB CRIPPLING	0.870	0.846
EOF-SU-2-7-2	22.66	3.0	0.50	775	---	WEB CRIPPLING	0.870	0.846
EOF-SU-3-1-1	20.00	1.0	SOLID	463	100.7	WEB CRIPPLING	1.000	1.000
EOF-SU-3-1-2	20.00	1.0	SOLID	456	99.1	WEB CRIPPLING	1.000	1.000
EOF-SU-3-2-1	22.66	1.0	0.00	363	78.9	WEB CRIPPLING	0.695	0.786
EOF-SU-3-2-2	22.66	1.0	0.00	338	73.5	WEB CRIPPLING	0.695	0.786
EOF-SU-3-3-1	22.66	1.0	0.50	431	93.7	WEB CRIPPLING	0.695	0.846
EOF-SU-3-3-2	22.66	1.0	0.50	406	88.3	WEB CRIPPLING	0.695	0.846
EOF-SU-3-4-1	22.66	1.0	1.00	444	96.5	WEB CRIPPLING	0.695	0.907
EOF-SU-3-4-2	22.66	1.0	1.00	444	96.5	WEB CRIPPLING	0.695	0.907
EOF-SU-4-1-1	19.75	1.0	SOLID	2413	100.4	WEB CRIPPLING	1.000	1.000

Table VIII: Unreinforced EOF Test Results (cont.)

Specimen Number[2]	L[1] (in.)	N[1] (in.)	α[1]	$(P_n)_{test}$ (lbs.)	PSW_{adj}	Limit State	Reduction Factor	
							Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-4-1-2	19.75	1.0	SOLID	2394	99.6	WEB CRIPPLING	1.000	1.000
EOF-SU-4-2-1	22.54	1.0	0.00	1763	73.3	WEB CRIPPLING	0.685	0.782
EOF-SU-4-2-2	22.54	1.0	0.00	1775	73.8	WEB CRIPPLING	0.685	0.782
EOF-SU-4-3-1	22.54	1.0	0.50	2038	84.8	WEB CRIPPLING	0.685	0.842
EOF-SU-4-3-2	22.54	1.0	0.50	2019	84.0	WEB CRIPPLING	0.685	0.842
EOF-SU-4-4-1	22.54	1.0	0.70	2100	87.4	WEB CRIPPLING	0.685	0.866
EOF-SU-4-4-2	22.54	1.0	0.70	2062	85.8	WEB CRIPPLING	0.685	0.866
EOF-SU-4-5-1	22.54	1.0	1.00	2219	92.3	WEB CRIPPLING	0.685	0.903
EOF-SU-4-5-2	22.54	1.0	1.00	2256	93.8	WEB CRIPPLING	0.685	0.903
EOF-SU-4-6-1	22.54	1.0	1.50	2269	94.4	WEB CRIPPLING	0.685	0.963
EOF-SU-4-6-2	22.54	1.0	1.50	2350	97.8	WEB CRIPPLING	0.685	0.963
EOF-SU-4-7-1	26.54	3.0	0.50	2738	---	SHEAR	---	---
EOF-SU-4-7-2	26.54	3.0	0.50	2781	---	SHEAR	---	---
EOF-SU-5-1-1	19.10	1.0	SOLID	1331	102.9	WEB CRIPPLING	1.000	1.000

Table VIII: Unreinforced EOF Test Results (cont.)

Specimen Number(2)	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	PSW_{adj}	Limit State	Reduction Factor	
							Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-5-1-2	19.10	1.0	SOLID	1256	97.1	WEB CRIPPLING	1.000	1.000
EOF-SU-5-2-1	19.10	1.0	0.00	781	---	SHEAR	---	---
EOF-SU-5-2-2	19.10	1.0	0.00	781	---	SHEAR	---	---
EOF-SU-5-3-1	19.10	1.0	0.50	813	---	SHEAR	---	---
EOF-SU-5-3-2	19.10	1.0	0.50	788	---	SHEAR	---	---
EOF-SU-5-4-1	19.10	1.0	0.70	775	---	SHEAR	---	---
EOF-SU-5-4-2	19.10	1.0	0.70	781	---	SHEAR	---	---
EOF-SU-5-5-1	19.10	1.0	1.00	769	---	SHEAR	---	---
EOF-SU-5-5-2	19.10	1.0	1.00	781	---	SHEAR	---	---
EOF-SU-5-6-1	19.10	1.0	1.50	781	---	SHEAR	---	---
EOF-SU-5-6-2	19.10	1.0	1.50	769	---	SHEAR	---	---
EOF-SU-5-7-1	23.10	3.0	0.50	731	---	SHEAR	---	---
EOF-SU-5-7-2	23.10	3.0	0.50	781	---	SHEAR	---	---
EOF-SU-6-1-1	19.16	1.0	SOLID	475	100.0	WEB CRIPPLING	1.000	1.000

Table VIII: Unreinforced EOF Test Results (cont.)

Specimen Number[(2)]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	PSW_{adj}	Limit State	Reduction Factor	
							Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-6-1-2	19.16	1.0	SOLID	475	100.0	WEB CRIPPLING	1.000	1.000
EOF-SU-6-2-1	19.16	1.0	0.00	288	---	SHEAR	---	---
EOF-SU-6-2-2	19.16	1.0	0.00	288	---	SHEAR	---	---
EOF-SU-6-3-1	19.16	1.0	0.50	331	---	SHEAR	---	---
EOF-SU-6-3-2	19.16	1.0	0.50	344	---	SHEAR	---	---
EOF-SU-6-4-1	19.16	1.0	0.70	356	---	SHEAR	---	---
EOF-SU-6-4-2	19.16	1.0	0.70	325	---	SHEAR	---	---
EOF-SU-6-5-1	19.16	1.0	1.00	331	---	SHEAR	---	---
EOF-SU-6-5-2	19.16	1.0	1.00	325	---	SHEAR	---	---
EOF-SU-6-6-1	19.16	1.0	1.50	325	---	SHEAR	---	---
EOF-SU-6-6-2	19.16	1.0	1.50	325	---	SHEAR	---	---
EOF-SU-6-7-1	19.16	3.0	0.50	356	---	SHEAR	---	---
EOF-SU-6-7-2	19.16	3.0	0.50	331	---	SHEAR	---	---
EOF-SU-7-1-1	11.24	1.0	SOLID	994	96.6	WEB CRIPPLING	1.000	1.000

Table VIII: Unreinforced EOF Test Results (cont.)

Specimen Number[2]	L[1] (in.)	N[1] (in.)	α[1]	$(P_n)_{test}$ (lbs.)	PSW_{adj}	Limit State	Reduction Factor	
							Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-7-1-2	11.24	1.0	SOLID	1063	103.3	WEB CRIPPLING	1.000	1.000
EOF-SU-7-2-1	15.24	1.0	0.00	850	82.6	WEB CRIPPLING	0.883	0.852
EOF-SU-7-2-2	15.24	1.0	0.00	800	77.7	WEB CRIPPLING	0.883	0.852
EOF-SU-7-3-1	15.24	1.0	0.50	994	96.6	WEB CRIPPLING	0.883	0.912
EOF-SU-7-3-2	15.24	1.0	0.50	944	91.7	WEB CRIPPLING	0.883	0.912
EOF-SU-7-4-1	15.24	1.0	0.70	988	96.0	WEB CRIPPLING	0.883	0.936
EOF-SU-7-4-2	15.24	1.0	0.70	956	92.9	WEB CRIPPLING	0.883	0.936
EOF-SU-7-5-1	15.24	1.0	1.00	963	93.6	WEB CRIPPLING	0.883	0.973
EOF-SU-7-5-2	15.24	1.0	1.00	994	96.6	WEB CRIPPLING	0.883	0.973
EOF-SU-7-6-1	15.24	1.0	1.50	988	96.0	WEB CRIPPLING	0.883	1.000
EOF-SU-7-6-2	15.24	1.0	1.50	988	96.0	WEB CRIPPLING	0.883	1.000
EOF-SU-8-1-1	15.33	1.0	SOLID	406	98.3	WEB CRIPPLING	1.000	1.000
EOF-SU-8-1-2	15.33	1.0	SOLID	419	101.5	WEB CRIPPLING	1.000	1.000
EOF-SU-8-2-1	15.33	1.0	0.00	388	93.9	WEB CRIPPLING	0.887	0.856

Table VIII: Unreinforced EOF Test Results (cont.)

Specimen Number(2)	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	PSW_{adj}	Limit State	Reduction Factor	
							Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-8-2-2	15.33	1.0	0.00	394	95.4	WEB CRIPPLING	0.887	0.856
EOF-SU-8-3-1	15.33	1.0	0.50	400	96.9	WEB CRIPPLING	0.887	0.916
EOF-SU-8-3-2	15.33	1.0	0.50	406	98.3	WEB CRIPPLING	0.887	0.916
EOF-SU-8-4-1	15.33	1.0	0.70	419	101.5	WEB CRIPPLING	0.887	0.940
EOF-SU-8-4-2	15.33	1.0	0.70	419	101.5	WEB CRIPPLING	0.887	0.940
EOF-SU-8-5-1	15.33	1.0	1.00	406	98.3	WEB CRIPPLING	0.887	0.976
EOF-SU-8-5-2	15.33	1.0	1.00	406	98.3	WEB CRIPPLING	0.887	0.976
EOF-SU-8-6-1	15.33	1.0	1.50	400	96.9	WEB CRIPPLING	0.887	1.000
EOF-SU-8-6-2	15.33	1.0	1.50	406	98.3	WEB CRIPPLING	0.887	1.000
EOF-SU-8-7-1	19.33	3.0	0.50	550	---	WEB CRIPPLING	0.949	0.916
EOF-SU-8-7-2	19.33	3.0	0.50	538	---	WEB CRIPPLING	0.949	0.916
EOF-SU-9-1-1	19.54	1.0	SOLID	669	99.1	WEB CRIPPLING	1.000	1.000
EOF-SU-9-1-2	19.54	1.0	SOLID	681	100.9	WEB CRIPPLING	1.000	1.000
EOF-SU-9-2-1	19.54	1.0	0.00	481	71.3	WEB CRIPPLING	0.705	0.790

Table VIII: Unreinforced EOF Test Results (cont.)

Specimen Number(2)	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	PSW_{adj}	Limit State	Reduction Factor	
							Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-9-2-2	19.54	1.0	0.00	475	70.4	WEB CRIPPLING	0.705	0.790
EOF-SU-9-3-1	19.54	1.0	0.50	585	86.7	WEB CRIPPLING	0.705	0.851
EOF-SU-9-3-2	19.54	1.0	0.50	619	91.7	WEB CRIPPLING	0.705	0.851
EOF-SU-9-4-1	19.54	1.0	0.70	619	91.7	WEB CRIPPLING	0.705	0.875
EOF-SU-9-4-2	19.54	1.0	0.70	619	91.7	WEB CRIPPLING	0.705	0.875
EOF-SU-9-5-1	19.54	1.0	1.00	681	100.9	WEB CRIPPLING	0.705	0.911
EOF-SU-9-5-2	19.54	1.0	1.00	656	97.2	WEB CRIPPLING	0.705	0.911
EOF-SU-9-6-1	24.81	1.0	1.00	638	94.5	WEB CRIPPLING	0.705	0.911
EOF-SU-9-6-2	24.81	1.0	1.00	675	100.0	WEB CRIPPLING	0.705	0.911
EOF-SU-9-7-1	24.81	1.0	1.50	681	100.9	WEB CRIPPLING	0.705	0.971
EOF-SU-9-7-2	24.81	1.0	1.50	619	91.7	WEB CRIPPLING	0.705	0.971
EOF-SU-9-8-1	23.54	3.0	0.50	819	---	WEB CRIPPLING	0.873	0.851
EOF-SU-9-8-2	23.54	3.0	0.50	831	---	WEB CRIPPLING	0.873	0.851
EOF-SU-9-9-1	25.54	4.0	0.50	919	---	WEB CRIPPLING	0.900	0.851
EOF-SU-9-10-1	27.54	5.0	0.50	1125	---	SHEAR	---	---

Table VIII: Unreinforced EOF Test Results (cont.)

Specimen Number[2]	L[1] (in.)	N[1] (in.)	α[1]	$(P_n)_{test}$ (lbs.)	PSW_{adj}	Limit State	Reduction Factor	
							Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-9-11-1	29.54	6.0	0.50	919	---	SHEAR	---	---
EOF-SU-9-11-2	29.54	6.0	0.50	938	---	SHEAR	---	---
EOF-SU-10-1-1	19.54	1.0	SOLID	2000	100.0	WEB CRIPPLING	1.000	1.000
EOF-SU-10-2-1	24.81	1.0	0.00	1338	66.9	WEB CRIPPLING	0.669	0.788
EOF-SU-10-2-2	24.81	1.0	0.00	1350	67.5	WEB CRIPPLING	0.669	0.788
EOF-SU-10-3-1	24.81	1.0	0.50	1606	80.3	WEB CRIPPLING	0.669	0.848
EOF-SU-10-3-2	24.81	1.0	0.50	1650	82.5	WEB CRIPPLING	0.669	0.848
EOF-SU-10-4-1	24.81	1.0	0.70	1888	94.4	WEB CRIPPLING	0.669	0.872
EOF-SU-10-4-2	24.81	1.0	0.70	1706	85.3	WEB CRIPPLING	0.669	0.872
EOF-SU-10-5-1	34.81	6.0	0.00	2406	---	SHEAR	---	---
EOF-SU-10-6-1	34.81	6.0	0.50	2750	---	SHEAR	---	---
EOF-SU-10-6-2	34.81	6.0	0.50	2750	---	SHEAR	---	---
EOF-SU-10-7-1	34.81	6.0	1.00	2506	---	SHEAR	---	---
EOF-SU-10-7-2	34.81	6.0	1.00	2606	---	SHEAR	---	---

Table VIII: Unreinforced EOF Test Results (cont.)

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	PSW_{adj}	Limit State	Reduction Factor	
							Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-12-1-1	21.62	1.0	SOLID	556	96.4	WEB CRIPPLING	1.000	1.000
EOF-SU-12-1-2	21.62	1.0	SOLID	598	103.6	WEB CRIPPLING	1.000	1.000
EOF-SU-12-2-1	21.62	1.0	0.00	531	92.0	WEB CRIPPLING	0.907	0.909
EOF-SU-12-2-2	21.62	1.0	0.00	506	87.7	WEB CRIPPLING	0.907	0.909
EOF-SU-12-3-1	21.62	1.0	0.50	544	94.3	WEB CRIPPLING	0.907	0.969
EOF-SU-12-3-2	21.62	1.0	0.50	556	96.4	WEB CRIPPLING	0.907	0.969
EOF-SU-12-4-1	24.20	1.0	1.00	556	96.4	WEB CRIPPLING	0.907	1.000
EOF-SU-12-4-2	24.20	1.0	1.00	563	97.6	WEB CRIPPLING	0.907	1.000
EOF-SU-12-5-1	30.00	1.0	1.50	581	100.7	WEB CRIPPLING	0.907	1.000
EOF-SU-12-5-2	30.00	1.0	1.50	569	98.6	WEB CRIPPLING	0.907	1.000
EOF-SU-13-1-1	27.62	1.0	SOLID	850	100.4	WEB CRIPPLING	1.000	1.000
EOF-SU-13-1-2	27.62	1.0	SOLID	844	99.6	WEB CRIPPLING	1.000	1.000
EOF-SU-13-2-1	27.62	1.0	0.00	800	94.5	WEB CRIPPLING	0.951	0.954

Table VIII: Unreinforced EOF Test Results (cont.)

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	PSW_{adj}	Limit State	Reduction Factor	
							Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-13-2-2	27.62	1.0	0.00	794	93.7	WEB CRIPPLING	0.951	0.954
EOF-SU-13-3-1	27.62	1.0	0.50	831	98.1	WEB CRIPPLING	0.951	1.000
EOF-SU-13-3-2	27.62	1.0	0.50	844	99.6	WEB CRIPPLING	0.951	1.000

Notes: 1. See Figures 2 and 3 for definition of dimensions.
2. Cross-section designations:
EOF: End-One-Flange loading condition, SU: Single Unreinforced web
EOF-SU-cross section number-specimen designation

Table IX: Analysis of Unreinforced EOF Test Results

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 30 & 31)	Reduced Capacity		AISI Provisions (Eqs. 30 & 31)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-1-1-1	905	905	905	1.10	1.10	1.10
EOF-SU-1-1-2	905	905	905	1.16	1.16	1.16
EOF-SU-1-2-1	905	887	902	1.30	1.32	1.30
EOF-SU-1-2-2	905	887	902	1.22	1.24	1.22
EOF-SU-2-1-1	540	540	540	1.31	1.31	1.31
EOF-SU-2-1-2	540	540	540	1.29	1.29	1.29
EOF-SU-2-2-1	540	375	424	0.90	1.30	1.15
EOF-SU-2-2-2	540	375	424	0.94	1.35	1.19
EOF-SU-2-3-1	540	375	457	1.08	1.55	1.27
EOF-SU-2-3-2	540	375	457	1.09	1.57	1.29
EOF-SU-2-4-1	540	375	470	1.11	1.60	1.28
EOF-SU-2-4-2	540	375	470	1.14	1.63	1.30

Table IX: Analysis of Unreinforced EOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 30 & 31)	Reduced Capacity		AISI Provisions (Eqs. 30 & 31)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-2-5-1	540	375	489	1.23	1.77	1.35
EOF-SU-2-5-2	540	375	489	1.20	1.73	1.33
EOF-SU-2-6-1	540	375	522	1.27	1.83	1.32
EOF-SU-2-6-2	540	375	522	1.26	1.82	1.30
EOF-SU-2-7-1	740	644	626	1.12	1.29	1.33
EOF-SU-2-7-2	740	644	626	1.05	1.20	1.24
EOF-SU-3-1-1	306	306	306	1.51	1.51	1.51
EOF-SU-3-1-2	306	306	306	1.49	1.49	1.49
EOF-SU-3-2-1	306	213	241	1.18	1.71	1.51
EOF-SU-3-2-2	306	213	241	1.10	1.59	1.40
EOF-SU-3-3-1	306	213	259	1.41	2.02	1.66
EOF-SU-3-3-2	306	213	259	1.33	1.91	1.57

Table IX: Analysis of Unreinforced EOF Test Results (cont.)

Specimen Number(1)	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 30 & 31)	Reduced Capacity		AISI Provisions (Eqs. 30 & 31)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-3-4-1	306	213	278	1.45	2.09	1.60
EOF-SU-3-4-2	306	213	278	1.45	2.09	1.60
* EOF-SU-4-1-1	1920	1920	1920	1.26	1.26	1.26
* EOF-SU-4-1-2	1920	1920	1920	1.25	1.25	1.25
* EOF-SU-4-2-1	1920	1316	1501	0.92	1.34	1.17
* EOF-SU-4-2-2	1920	1316	1501	0.92	1.35	1.18
* EOF-SU-4-3-1	1920	1316	1617	1.06	1.55	1.26
* EOF-SU-4-3-2	1920	1316	1617	1.05	1.53	1.25
* EOF-SU-4-4-1	1920	1316	1663	1.09	1.60	1.26
* EOF-SU-4-4-2	1920	1316	1663	1.07	1.57	1.24
* EOF-SU-4-5-1	1920	1316	1733	1.16	1.69	1.28
* EOF-SU-4-5-2	1920	1316	1733	1.18	1.71	1.30

Table IX: Analysis of Unreinforced EOF Test Results (cont.)

Specimen Number(1)	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 30 & 31)	Reduced Capacity		AISI Provisions (Eqs. 30 & 31)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
* EOF-SU-4-6-1	1920	1316	1849	1.18	1.72	1.23
* EOF-SU-4-6-2	1920	1316	1849	1.22	1.79	1.27
EOF-SU-5-1-1	1229	1229	1229	1.08	1.08	1.08
EOF-SU-5-1-2	1229	1229	1229	1.02	1.02	1.02
* EOF-SU-6-1-1	279	279	279	1.70	1.70	1.70
* EOF-SU-6-1-2	279	279	279	1.70	1.70	1.70
EOF-SU-7-1-1	1152	1152	1152	0.86	0.86	0.86
EOF-SU-7-1-2	1152	1152	1152	0.92	0.92	0.92
EOF-SU-7-2-1	1152	1018	982	0.74	0.84	0.87
EOF-SU-7-2-2	1152	1018	982	0.69	0.79	0.81

Table IX: Analysis of Unreinforced EOF Test Results (cont.)

Specimen Number(1)	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 30 & 31)	Reduced Capacity		AISI Provisions (Eqs. 30 & 31)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-7-3-1	1152	1018	1051	0.86	0.98	0.95
EOF-SU-7-3-2	1152	1018	1051	0.82	0.93	0.90
EOF-SU-7-4-1	1152	1018	1079	0.86	0.97	0.92
EOF-SU-7-4-2	1152	1018	1079	0.83	0.94	0.89
EOF-SU-7-5-1	1152	1018	1121	0.84	0.95	0.86
EOF-SU-7-5-2	1152	1018	1121	0.86	0.98	0.89
EOF-SU-7-6-1	1152	1018	1152	0.86	0.97	0.86
EOF-SU-7-6-2	1152	1018	1152	0.86	0.97	0.86
EOF-SU-8-1-1	319	319	319	1.27	1.27	1.27
EOF-SU-8-1-2	319	319	319	1.31	1.31	1.31
EOF-SU-8-2-1	319	283	273	1.22	1.37	1.42
EOF-SU-8-2-2	319	283	273	1.24	1.39	1.44

Table IX: Analysis of Unreinforced EOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 30 & 31)	Reduced Capacity		AISI Provisions (Eqs. 30 & 31)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-8-3-1	319	283	292	1.25	1.41	1.37
EOF-SU-8-3-2	319	283	292	1.27	1.44	1.39
EOF-SU-8-4-1	319	283	300	1.31	1.48	1.40
EOF-SU-8-4-2	319	283	300	1.31	1.48	1.40
EOF-SU-8-5-1	319	283	311	1.27	1.44	1.30
EOF-SU-8-5-2	319	283	311	1.27	1.44	1.30
EOF-SU-8-6-1	319	283	319	1.25	1.41	1.25
EOF-SU-8-6-2	319	283	319	1.27	1.44	1.27
EOF-SU-8-7-1	449	426	411	1.22	1.29	1.34
EOF-SU-8-7-2	449	426	411	1.20	1.26	1.31
EOF-SU-9-1-1	513	513	513	1.30	1.30	1.30
EOF-SU-9-1-2	513	513	513	1.33	1.33	1.33

Table IX: Analysis of Unreinforced EOF Test Results (cont.)

Specimen Number[(1)]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 30 & 31)	Reduced Capacity		AISI Provisions (Eqs. 30 & 31)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-9-2-1	513	362	406	0.94	1.33	1.19
EOF-SU-9-2-2	513	362	406	0.93	1.31	1.17
EOF-SU-9-3-1	513	362	437	1.14	1.62	1.34
EOF-SU-9-3-2	513	362	437	1.21	1.71	1.42
EOF-SU-9-4-1	513	362	449	1.21	1.71	1.38
EOF-SU-9-4-2	513	362	449	1.21	1.71	1.38
EOF-SU-9-5-1	513	362	468	1.33	1.88	1.46
EOF-SU-9-5-2	513	362	468	1.28	1.81	1.40
EOF-SU-9-6-1	513	362	468	1.24	1.76	1.36
EOF-SU-9-6-2	513	362	468	1.31	1.87	1.44
EOF-SU-9-7-1	513	362	499	1.33	1.88	1.37
EOF-SU-9-7-2	513	362	499	1.21	1.71	1.24

Table IX: Analysis of Unreinforced EOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 30 & 31)	Reduced Capacity		AISI Provisions (Eqs. 30 & 31)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
EOF-SU-9-8-1	704	614	598	1.16	1.33	1.37
EOF-SU-9-8-2	704	614	598	1.18	1.35	1.39
EOF-SU-9-9-1	799	719	679	1.15	1.28	1.35
EOF-SU-10-1-1	2315	2315	2315	0.86	0.86	0.86
EOF-SU-10-2-1	2315	1619	1824	0.58	0.83	0.73
EOF-SU-10-2-2	2315	1619	1824	0.58	0.83	0.74
EOF-SU-10-3-1	2315	1619	1964	0.69	0.99	0.82
EOF-SU-10-3-2	2315	1619	1964	0.71	1.02	0.84
EOF-SU-10-4-1	2315	1619	2020	0.82	1.17	0.93
EOF-SU-10-4-2	2315	1619	2020	0.74	1.05	0.84

Table IX: Analysis of Unreinforced EOF Test Results (cont.)

Specimen Number(1)	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 30 & 31)	Reduced Capacity		AISI Provisions (Eqs. 30 & 31)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
* EOF-SU-12-1-1	217	217	217	2.56	2.56	2.56
* EOF-SU-12-1-2	217	217	217	2.75	2.75	2.75
* EOF-SU-12-2-1	217	197	198	2.44	2.69	2.69
* EOF-SU-12-2-2	217	197	198	2.33	2.57	2.56
* EOF-SU-12-3-1	217	197	211	2.50	2.76	2.58
* EOF-SU-12-3-2	217	197	211	2.56	2.82	2.64
* EOF-SU-12-4-1	217	197	217	2.56	2.82	2.56
* EOF-SU-12-4-2	217	197	217	2.59	2.86	2.59
* EOF-SU-12-5-1	217	197	217	2.67	2.95	2.67
* EOF-SU-12-5-2	217	197	217	2.62	2.89	2.62
* EOF-SU-13-1-1	478	478	478	1.78	1.78	1.78

Table IX: Analysis of Unreinforced EOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 30 & 31)	Reduced Capacity		AISI Provisions (Eqs. 30 & 31)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
* EOF-SU-13-1-2	478	478	478	1.77	1.77	1.77
* EOF-SU-13-2-1	478	454	456	1.67	1.76	1.76
* EOF-SU-13-2-2	478	454	456	1.66	1.75	1.74
* EOF-SU-13-3-1	478	454	478	1.74	1.83	1.74
* EOF-SU-13-3-2	478	454	478	1.77	1.86	1.77

Statistical analysis is given on the next two pages.

Table IX: Analysis of Unreinforced EOF Test Results (cont.)

	$(P_n)_{test}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 30 & 31)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 68)
STATISTICS: ALL TEST SPECIMENS: $n^{(3)} = 108$			
MEAN	1.2928	1.5455	1.3917
STANDARD DEVIATION	0.4759	0.4995	0.4608
COEFFICIENT OF VARIATION	0.3681	0.3232	0.3311
Φ	0.7079	0.9293	0.8234
$(F.S.)_{LRFD}$	2.1661	1.6500	1.8623
STATISTICS: F_y less than or equal to 66.5 ksi: $n^{(3)} = 78$			
MEAN	1.1139	1.3686	1.2202
STANDARD DEVIATION	0.2211	0.3330	0.2320
COEFFICIENT OF VARIATION	0.1985	0.2433	0.1901
Φ	0.8435	0.9589	0.9366
$(F.S.)_{LRFD}$	1.8178	1.5990	1.6371
STATISTICS: Solid web specimens with F_y less than or equal to 66.5 ksi: $n^{(3)} = 15$			
MEAN	1.1881	1.1881	1.1881
STANDARD DEVIATION	0.2004	0.2004	0.2004
COEFFICIENT OF VARIATION	0.1687	0.1687	0.1687
Φ	0.9268	0.9268	0.9268
$(F.S.)_{LRFD}$	1.6545	1.6545	1.6545

Table IX: Analysis of Unreinforced EOF Test Results (cont.)

Notes: 1. Cross-section designations: EOF: End-One-Flange loading condition SU: Single Unreinforced web EOF-SU-cross section number-specimen designation 2. * signifies specimens with F_y values greater than 66.5 ksi. 3. n = number of tests.

specimen configuration, but in practice, they have no meaning for web crippling behavior. Furthermore, the parameter x' did not apply to the previous web crippling research on sections with web openings by Yu and Davis (1973) and Sivakumaran and Zielonka (1989). Both of these investigations were performed for the IOF loading condition with the web opening centered on the mid-span IOF loading plate as discussed in Section II.C.

Diagnostic tests were conducted to ensure variations in L and x' did not affect the web crippling behavior in the absence of bending moment. These tests were performed by using test specimens which were identical except for the L and x' values. For a given cross section, this was accomplished by fixing the value of N at 1.0 inch, α at 0.50, and the mid-span load bearing length at 3.0 inches. The value of x' was varied in three increments of zero, 0.5h, and 1.0h (Table VII).

The results of the diagnostic tests are given in Table VII. None of the diagnostic tests for evaluating L and x' exhibited severe bending deformation, and each test specimen failed in EOF web crippling. The failure load of the test specimens, which were in the absence of bending, are given as the failure load per web, $(P_n)_{test}$.

Specimens EOF-SU-9-12a, b, and c exhibited no significant difference with the variance of only L and x′ as shown in Table VII. Also, although not performed as part of the diagnostic procedure, two pairs of specimens with web openings, EOF-SU-9-5-(1 and 2) and EOF-SU-9-6-(1 and 2), exhibited no significant difference in failure load as shown in Table VIII. These tests for specimens EOF-SU-9-5-(1 and 2) and EOF-SU-9-6-(1 and 2) were performed with N equal to 1.0 inch, α equal to 1.00, and a mid-span bearing length of 3.0 inches. The L value for specimens EOF-SU-9-6-(1 and 2) was 27 percent higher than for specimens EOF-SU-9-5-(1 and 2).

This verification proved that the extraneous parameters L and x′ did not affect web crippling behavior, and therefore do not require inclusion into any design recommendations to account for the effect of web openings on web crippling behavior.

The effect of the parameter L does have application in practice to the effect of web openings on combined bending and web crippling behavior, because the length of sections is typically related to the internal bending. However, the magnitude of the bending is the critical parameter affecting the web crippling behavior, whereas L in not.

2. Test Setup. To stabilize the specimens against lateral-torsional buckling, each test specimen consisted of two C-shaped sections inter-connected by 3/4 x 3/4 x 1/8 inch angles using self-drilling screws. This 'dual-section' test specimen configuration was used in previous web crippling research for sections with or without web openings as conducted by Yu and Davis (1973), Hetrakul and Yu (1978), and Sivakumaran and Zielonka (1989). To prevent web crippling beneath the load point, a stiffener was attached vertically on the webs of both sections.

Using a Tinius-Olson testing machine (Fig. 11), a concentrated load was applied at mid-span to a three inch bearing plate in contact with the top flanges of the test specimen. The reactions creating the EOF loading were introduced to the specimen by bearing plates flush with the ends of the specimen (Figs. 3 and 10a). Therefore, the value of d_1 (Fig. 1) was equal to zero for all tests.

The EOF tests by Hetrakul and Yu (1978) (Section II.E) were performed with the EOF reaction plates flush with the ends of the specimen. Hence, the current design provisions were developed using this condition. Furthermore, as explained in the review of the AISI ASD (1986) and LRFD (1991a) Specification web crippling provisions (Section II.F), this is the worst case situation for the EOF loading condition, i.e. this provides the least EOF web crippling capacity, and ignores the additional capacity that will be realized as the value of d_1 increases. The value of d_1

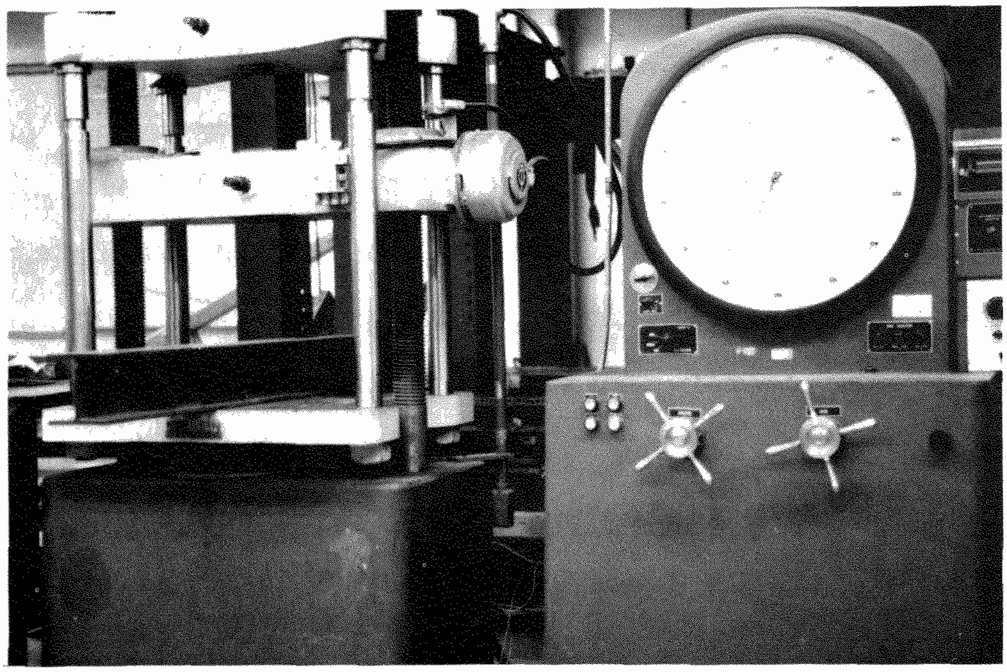


Figure 11: Tinius-Olson Testing Machine

could reach a maximum value of 1.5h while maintaining the requirements for the end loading condition (Fig. 1). Rollers were placed at the centerline of the bearing reactions to achieve a simple support condition for the specimen (Figs. 3 and 10a).

3. Test Procedure. The load was applied to the test specimens in a quasi-static manner until the specimen failed. Failure was defined when the specimen could carry no additional load. For many tests, the load was maintained for a duration after failure as the testing machine continued to cause the specimen to deflect. None of the specimens exhibited a subsequent increase in stiffness due to any post-buckling strength or strain hardening. Two identical tests were conducted for most of the test

specimens. Duplicate tests on identical specimens are identified by the specimen number designations in Tables VIII and IX.

As part of the evaluation of the test procedure, the rate of application of the load was evaluated to ensure that the web crippling behavior, using a constantly and gradually increasing quasi-static load application procedure, corresponds with that used in previous investigations. The primary comparison was performed with the load application procedure used by Hetrakul and Yu (1978) (Section II.E).

Hetrakul and Yu (1978) stated that the specimens were loaded in 15% increments of the expected failure load, and the load maintained for five minutes at each increment. However, for the current investigation, all tests were loaded slowly at a constant rate. The rate of load application for the current investigation was not quantified because it varied depending upon the stiffness of the test specimen, i.e. on the load versus deflection characteristics of the test specimen.

To ascertain the difference between the loading procedure used by Hetrakul and Yu (1978) and the procedure used during the current investigation, six identical solid web specimens from cross-section EOF-SU-11 were tested. Three specimens were tested using each of the loading procedures. The results are shown in Table VII for cross-section EOF-SU-11. The EOF web crippling capacity is given as the failure load per web, $(P_n)_{test}$. Both loading rates resulted in web crippling failure loads within the realm of experimental error. Hence, the web crippling behavior is essentially the same under both methods of load application, and thus, both loading procedures are acceptable.

D. TEST RESULTS

1. General. One-hundred-fifty-seven unreinforced EOF tests were conducted. Of these, 108 failed in web crippling, 34 failed in shear, four failed by flexure at mid-span in the compression flange, and 11 were conducted to perform diagnostic tests to ensure validity of the testing procedure. Six of the diagnostic tests were performed to ascertain the validity of the load application procedure, and five of the diagnostic tests were performed to study the effect of the parameters L and x′ (Fig. 3).

The tested failure load per web, $(P_n)_{test}$, for specimens exhibiting either a web crippling or a shear failure are given in Table VIII. The results of the diagnostic tests are given in Table VII. The specimens with web openings were not symmetric about the mid-span load due to the presence of a web opening in one half of the specimen. However, from a first order static analysis of the determinate simply supported test specimens, it is assumed that the value of $(P_n)_{test}$ is equal to 1/4 of the mid-span applied load, i.e. each section of the dual-section test specimens equally shared one-half of the load applied to the mid-span load plate, and the load on each of the two sections was equally shared by both ends of the sections. Therefore, each of the test specimen's four contact points with the EOF loading plates is assumed to equally support the applied loading. Furthermore, because of the quasi-static nature of the loading, none of the applied load is assumed to be resisted by inertial forces.

2. Typical Failures. Typical web crippling and shear failures of the unreinforced EOF test specimens are shown in Figures 10, and 12 thru 18. For Figures 12 thru 17, one of the two C-shaped sections comprising the specimen is shown after testing with the mid-span load point stiffener removed. The figures state the specimen number, therefore, Tables I, VIII and IX can be referenced for the specimen parameters.

Figure 12 shows a solid web specimen, with a typical EOF web crippling failure. Figure 13 shows a typical EOF web crippling failure for a specimen with a web opening that has a high α value. Figure 14 shows a typical EOF web crippling failure for a specimen with a web opening with a moderate α value. Figure 15 shows a typical EOF web crippling failure for a specimen with a web opening at an α value of zero. Figure 16 shows a typical shear failure that is attributed to a high N value. Figure 17 shows a typical shear failure that is attributed to a high a/h. Figure 18 shows a web crippling failure for a deep web section which exhibited elastic bifurcation. For the specimen of Figure 18, the failure load is still applied. Due to the elastic

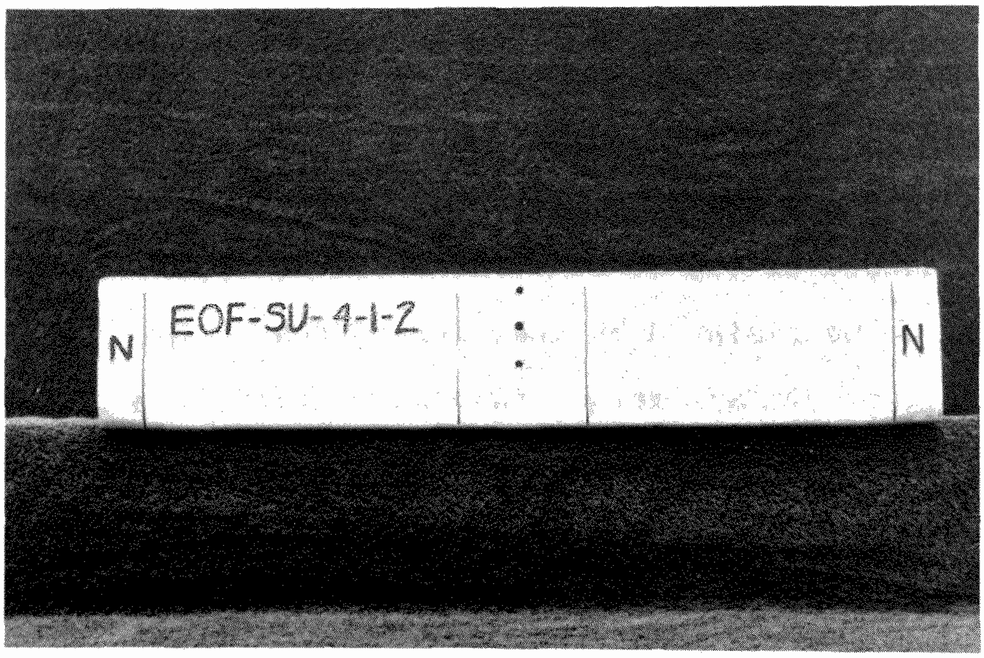


Figure 12: Typical Unreinforced EOF Solid Web Crippling Failure, EOF-SU-4-1-2

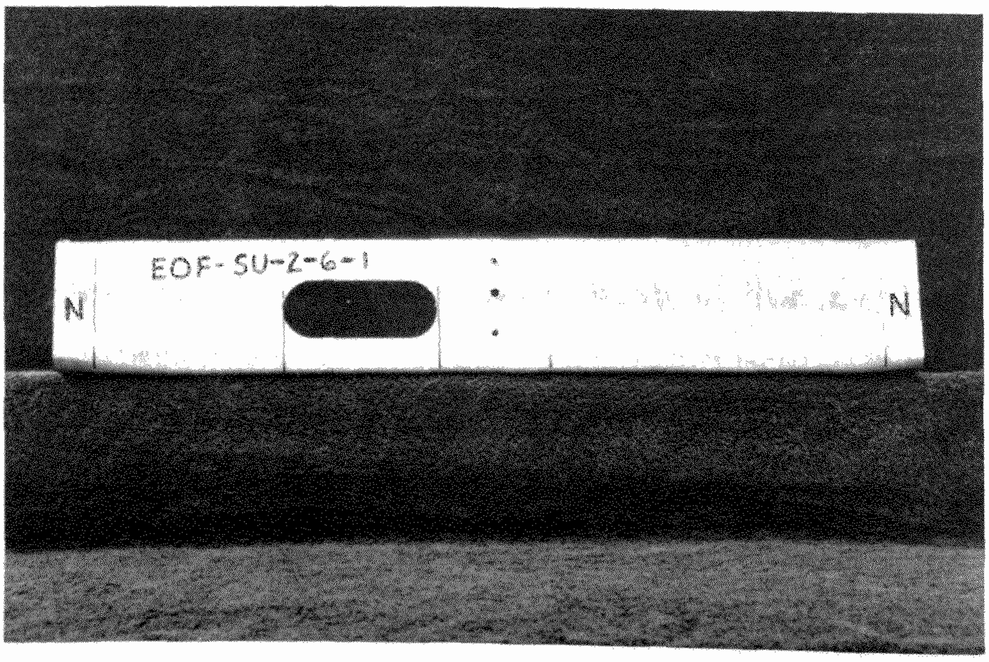
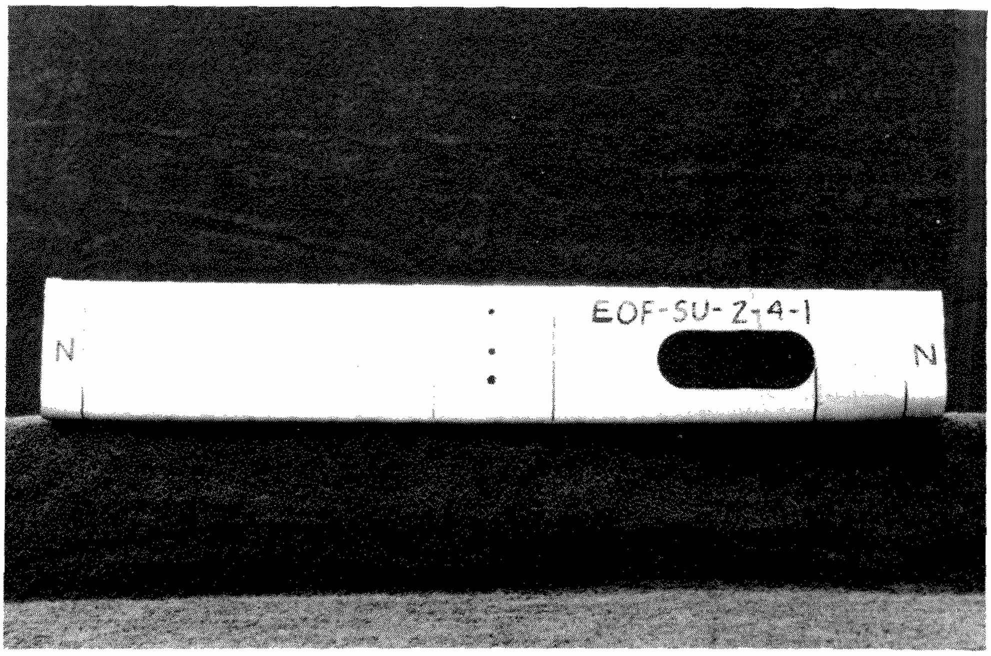


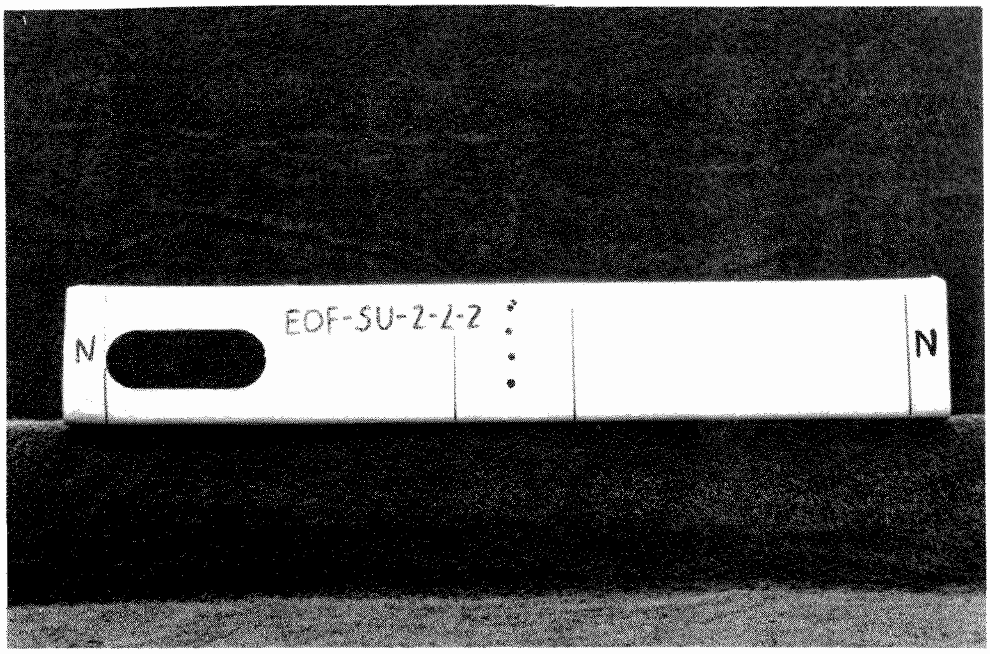
Figure 13: Typical Unreinforced EOF Web Crippling Failure, EOF-SU-2-6-1



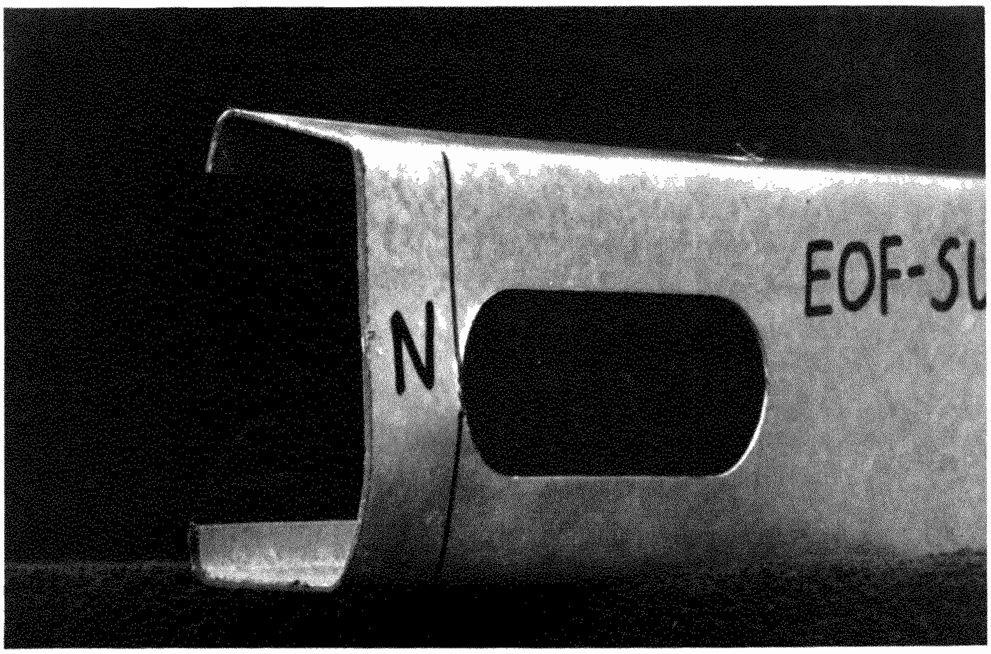
(a)

(b)

Figure 14: Typical Unreinforced EOF Web Crippling Failure, EOF-SU-2-4-1

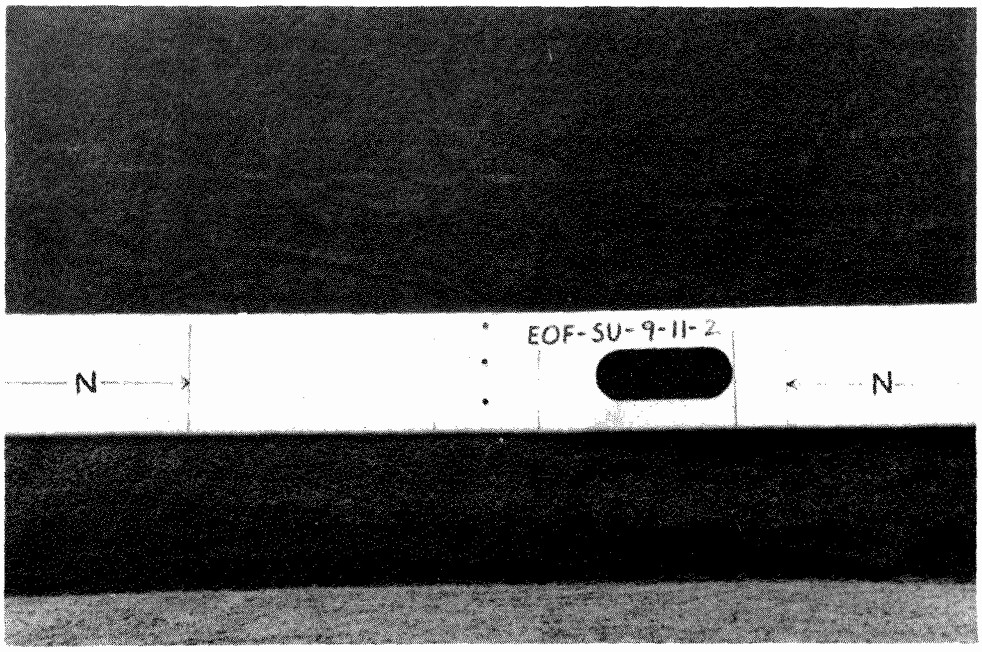


(a)

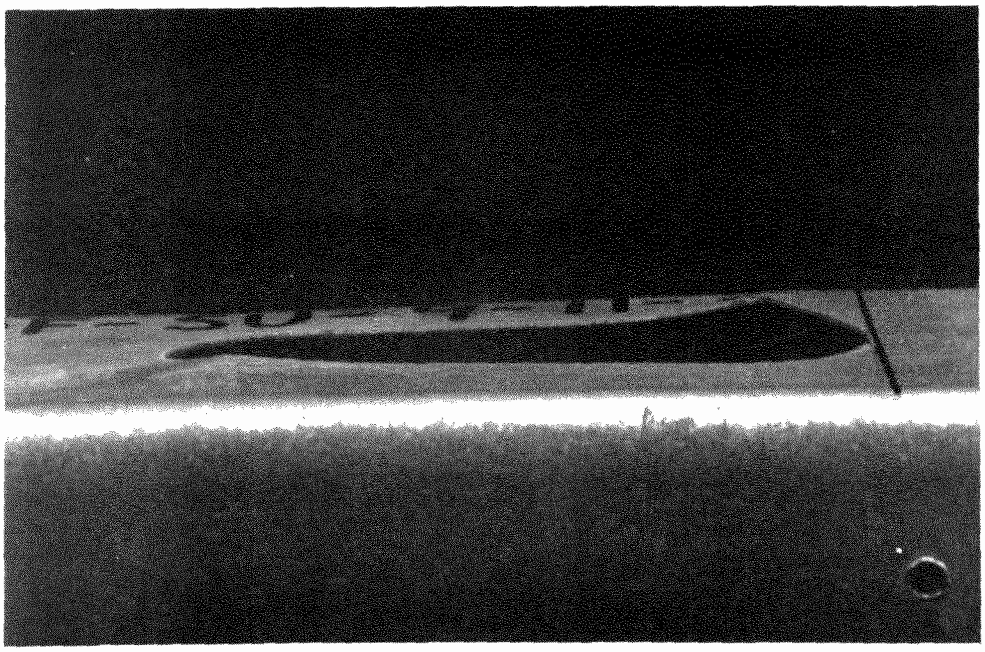


(b)

Figure 15: Typical Unreinforced Web Crippling Failure, EOF-SU-2-2-2

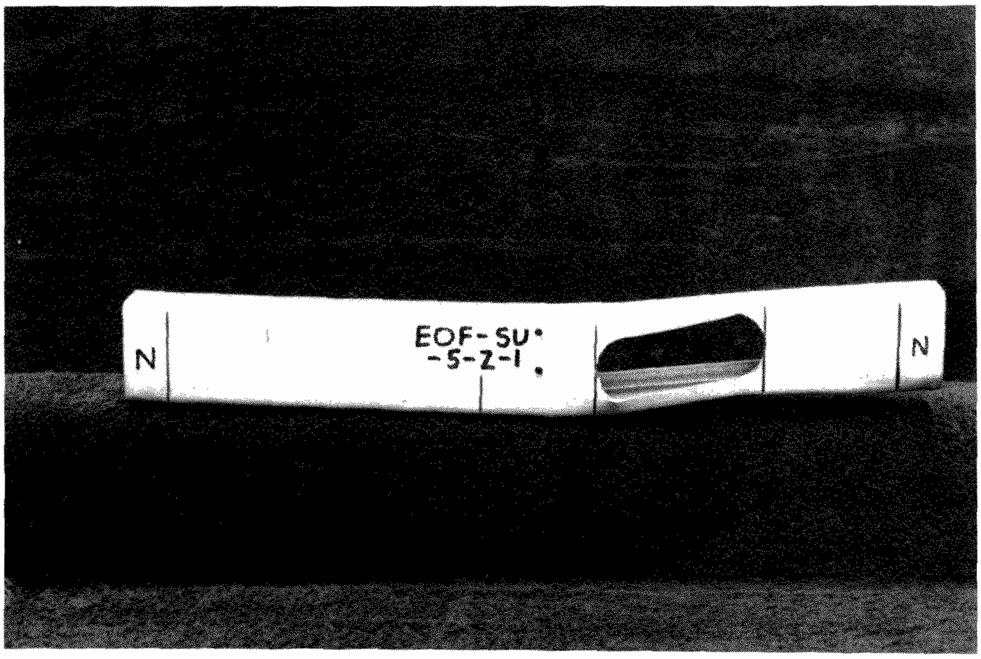


(a)

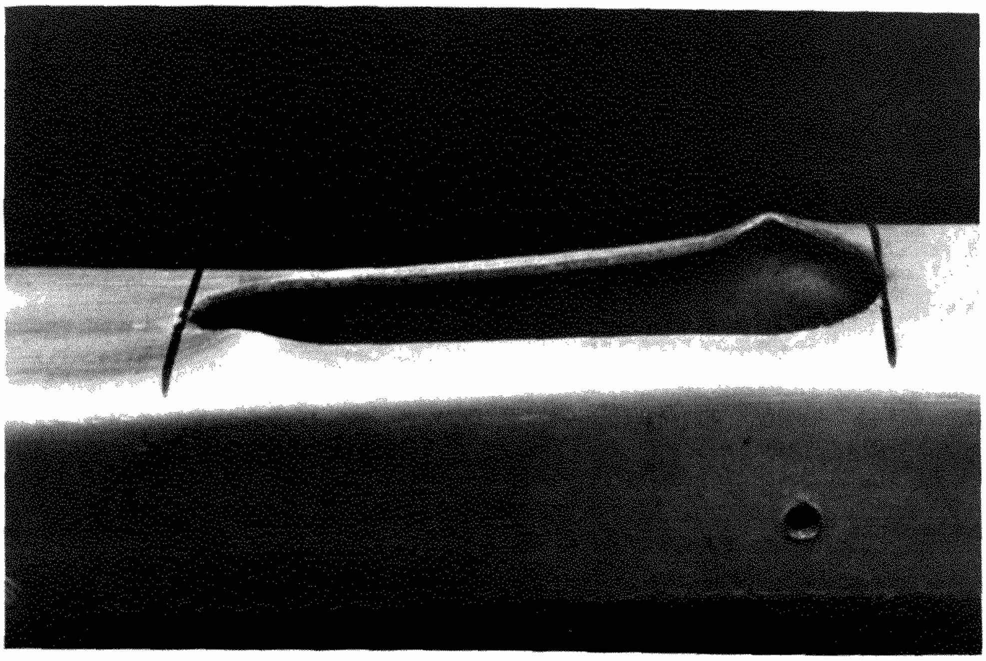


(b)

Figure 16: Typical Unreinforced EOF High N Value Shear Failure, EOF-SU-9-11-2



(a)



(b)

Figure 17: Typical Unreinforced EOF High a/h Value Shear Failure, EOF-SU-5-2-1

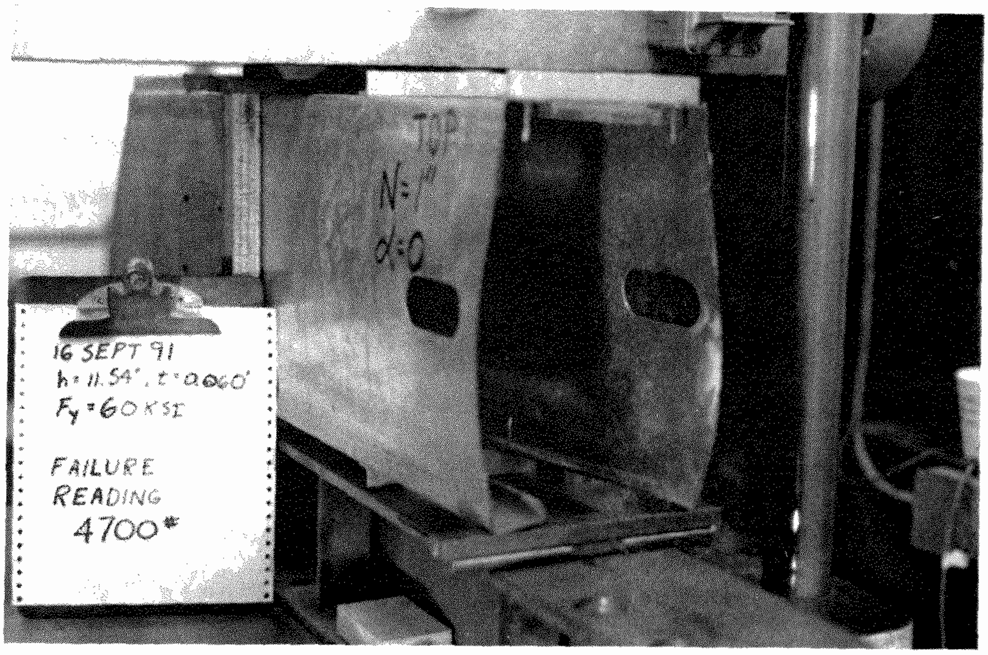


Figure 18: Typical Unreinforced EOF Web Crippling Failure, EOF-SU-1-2-1

behavior of the specimen, it returned to its undeformed geometry after the load was removed.

3. Bending Failures. Four of the test specimens failed at mid-span because of either yielding in the flanges or compression flange buckling. Bending failures occurred when the flexural capacity was less than the internal bending moment, $(M_n)_{test}$ as given by:

$$(M_n)_{test} = \frac{P \times L_{span}}{8} \quad \textbf{(61)}$$

where P = the load applied to the mid-span loading plate = 2 times the load applied to each section of the test specimen = $4(P_n)_{test}$, and; $L_{span} = L - 2(N/2) = L - N$, (Fig. 3).

Bending failures were readily identified because of their mid-span failure location, and therefore were distinguishable from EOF web crippling failures which occurred near the end reaction plate. Each of the four specimens which failed in flexure exhibited insignificant EOF web crippling deformation.

4. Shear.

a. General. Thirty-four test specimens failed in shear. The shear failures were very pronounced at the location of the web opening. As can be seen in Table VIII, the shear failures resulted from tests performed at high N values (Fig. 16) and high a/h values (Fig. 17). The effect of these parameters on the shear behavior of the test specimens is discussed in the evaluation of the test results.

b. Shear Deformation. Shear failures usually occurred with little or no web crippling deformation at the end reaction. Because of the pronounced shear deformation, shear failures were readily identified, and the data was used by Shan (1994) for studies on flexural members with web openings subjected primarily to shear. An additional observation is that many of the specimens that failed due to web crippling had a slight amount of shear deformation. The location of the shear 'bulges' protruding from the diagonal compression corners of the web opening were the same as the distinct shear failures, but the magnitude of the deformation was negligible.

5. Web Crippling Deformation at Failure. At failure, most specimens were severely deformed and would be considered unserviceable under most applications. This is an important consideration in the selection of the ASD Specification factor of safety and the LRFD Specification resistance factor. These specifications do not place a serviceability limit on web crippling. The AISI Specification does not place a serviceability limit on web crippling due to the difficulty in establishing a standard for quantifying the deformation and the difficulty of implementing the results in practice.

This phenomenon adds further credibility to the use of the AISI ASD web crippling safety factor of 1.85 and the AISI LRFD web crippling resistance factor of 0.75 for single web sections which, as discussed herein, are generally conservative from a strength aspect. Although, Hetrakul and Yu (1978) state that the primary justification for the high ASD factor of safety is caused by the high variance of web crippling tests results, and hence is not based on the amount of deformation. The relationships between the variance of the test results, the ASD factor of safety, and the LRFD resistance factor was provided in Section II.J.

The web crippling deformation for tests with low α values extended from the region of the web near the load plate to the corner of the web opening closest to the load plate (Fig. 15). As α increased, the visually noticeable deformation eventually ceased to reach the web opening, as shown in Figure 13.

The web crippling deformation at the allowable web crippling load was negligible. Evaluation of the deformation at the allowable web crippling load was accomplished by visual observation of the second test specimen from pairs of two identical specimens. The allowable load was not computed from the existing AISI Specification web crippling provisions in conjunction with a reduction factor equation. Instead, the allowable load was computed from the failure load of the first test of a pair of identical specimens by dividing the failure load of the first specimen by the ASD factor of safety of 1.85. As the second of two identical specimens was loaded, the test specimen was observed as the load reached the allowable capacity.

E. EVALUATION OF TEST RESULTS

1. General. The PSW and PSW_{adj} values were computed using the procedure stated in Section I.D, Terminology. For this study, the values of PSW and PSW_{adj} are equal because all of the EOF web crippling failures occurred in the absence of significant bending degradation of the web crippling strength. Therefore, EOF web crippling capacity could be considered directly without consideration of the combined behavior of bending and web crippling.

The magnitude of bending moment at the centerline of the rollers is assumed to be equal to zero. The region of the span near the rollers is also located in the vicinity of the EOF web crippling failures. Hence, the bending moment is assumed to be insignificant in the region of the web crippling failures. In general, the EOF condition may have significant bending moment. This could arise if the value of d_1 (Fig. 1) approaches the value of 1.5h, or under certain support conditions for cantilever beams.

The primary measure of the effect of web openings on web crippling behavior is the failure load of the test specimens and the resulting PSW_{adj} values. Therefore, the effect of web openings on web crippling behavior is measured by the effect of the parameters associated with the web openings on the PSW_{adj} values. These web opening parameters were found to be the a/h and α values.

2. <u>Effect of Web Openings on Web Crippling Behavior.</u>

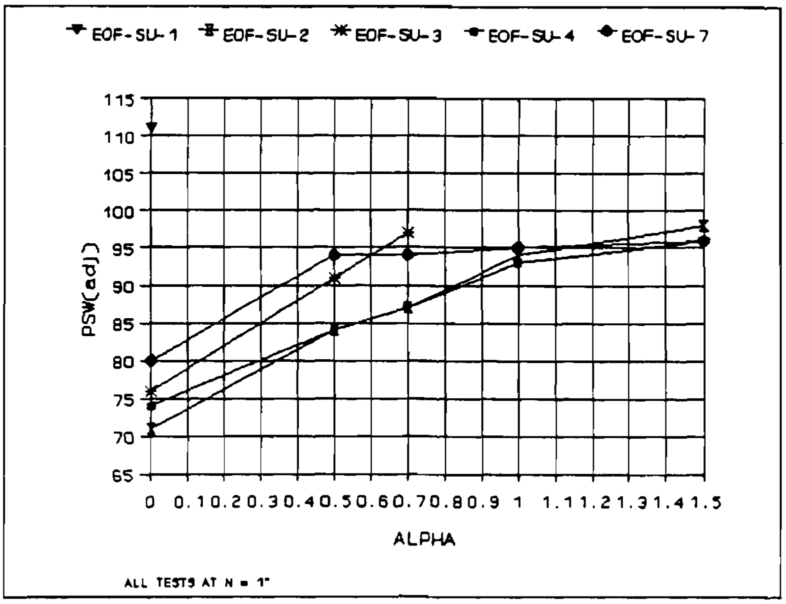
a. <u>General.</u> Based on the results of the EOF test specimens, the following observations concerning the effect of the web opening parameters α and a/h can be made. These findings add specificity to the trends stated in Section I.C concerning the effect of web opening parameters on the web crippling capacity. Specifically, as the value of a/h increased, the resulting value of PSW_{adj} values decreased, and as the value of α increased, the value of PSW_{adj} increased. The effect of the web opening parameters of α

and a/h, based on evaluation of the test results, are discussed separately in this paragraph.

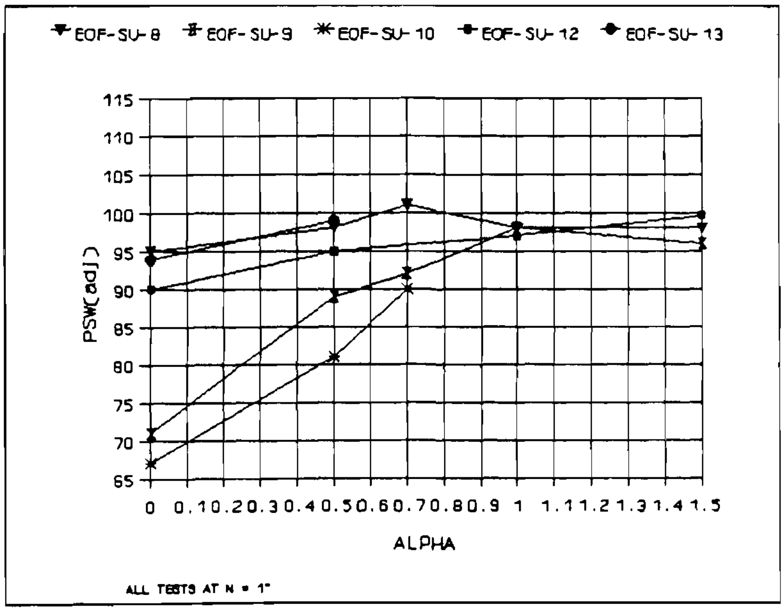
In accordance with the procedure used to determine the design equations, i.e. the reduction factor equations, as provided in Section I.D, Terminology, both α and a/h are ultimately accounted for herein as parameters in the reduction factor equation for the EOF loading condition of single unreinforced webs.

b. <u>Effect of α on Web Crippling Behavior.</u> A notable trend exists within the test results. As α increased from zero to 1.5, the values of PSW_{adj} increased (Figs. 19 and 20). The PSW_{adj} values pertain only to tests performed at N equal to one inch. A few tests with web openings were conducted at N values greater than one inch, and many of these tests failed in shear (Table VIII and Fig. 16).

Figure 19 graphically shows the trend of increasing PSW_{adj} values as α increased for ten of the 13 cross sections used in the EOF unreinforced web phase of the investigation. The data points in Figure 19 are the average PSW_{adj} values for all test specimens from the same cross section, tested at the same α value, and at N equal to one inch. For visual clarity, five cross sections are shown on both Figures 19a and 19b. The PSW_{adj} values for each cross section were averaged at each α value to provide a single data point for the graph, thereby facilitating the plotting of a curve for each cross section and thereby readily showing the aforementioned PSW_{adj} vs. α trend for each cross section.

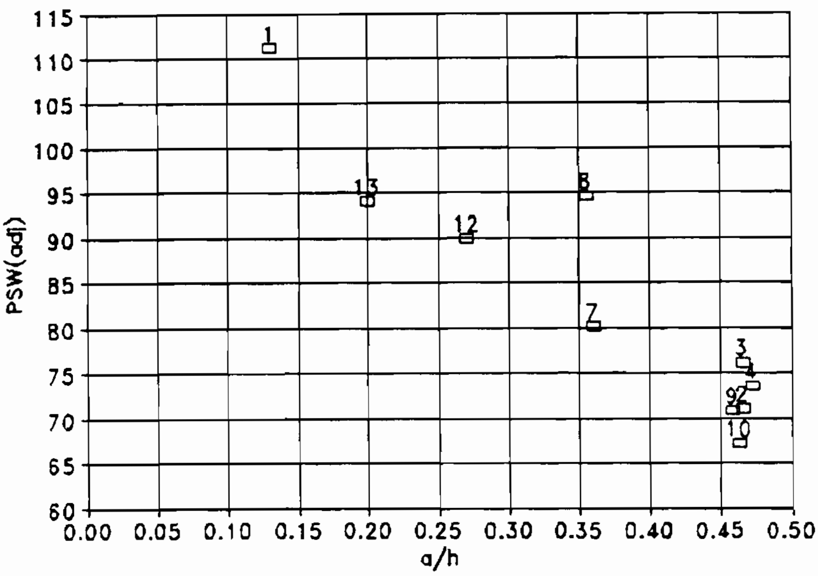


(a)

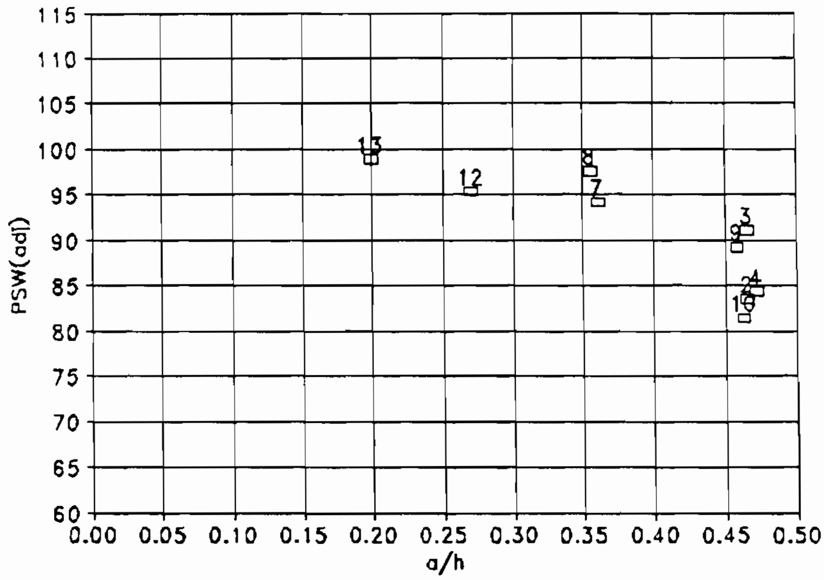


(b)

Figure 19: Unreinforced EOF Tests, α vs. PSW_{adj}

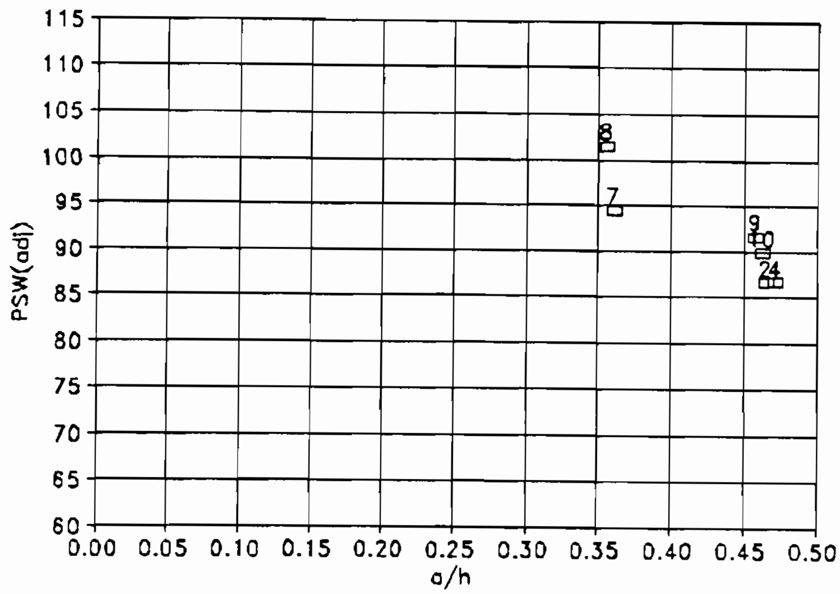


(a) α = 0



(b) α = 0.50

Figure 20: PSW_{adj} vs. a/h for EOF Tests



(c) α = 0.70

Figure 20: PSW_{adj} vs. a/h for EOF Tests (cont.)

Three of the thirteen cross sections used during this phase of the study were not shown in Figure 19 for the following reasons. Unreinforced web cross-sections EOF-SU-5 and EOF-SU-6 were excluded from Figure 19 because they failed in shear for all tests with web openings. Cross-section EOF-SU-11 was excluded from Figure 19 because it was a solid web cross section which was only used in diagnostic tests (Table VII). Figures 20a, b, and c show the results of Figure 19 at α values of 0, 0.5, and 0.7, respectively.

c. <u>Effect of a/h on Web Crippling Behavior.</u>

i. <u>General.</u> The parameter a/h distinctly affected the web crippling behavior. A distinct trend existed in which the value of a/h is inversely proportional to the PSW_{adj}

values (Figs. 19 and 20). The effect of a/h is responsible for the different curves shown in Figure 19, i.e. a/h influenced the magnitude of PSW_{adj} for each fixed α value. In general, cross sections with lower a/h values had higher PSW_{adj} values at each fixed value of α, and as shown in Figure 19 had curves which are closer to the top of the graphs, i.e. closer to the line defined by PSW_{adj} is equal to 100 percent. This result has considerable significance; specifically, if the web crippling behavior was not influenced by a/h, then a web opening of any size would have the same effect on web crippling behavior. As a consequence, a web opening of infinitesimal size, where a/h is approximately equal to zero and hence is essentially a solid web section, would therefore have the same effect on web crippling behavior as a large web opening.

ii. <u>Analysis of Test Results for the Effect of a/h on Web Crippling Behavior.</u> The parameters that define the web opening size are a/h and b (Fig. 3). Examining the PSW_{adj} values for all ten cross sections shown in Figures 19 and 20 at fixed values of α shows the distinct inverse proportionality in the relationship between PSW_{adj} and the a/h parameter. For example, considering the fixed value of α equal to zero on Figure 19, this trend is evident by examining the progression of the PSW_{adj} values along the PSW_{adj} axis, i.e. along the vertical line defined by α is equal to zero, and associating the applicable a/h value for each cross section. Cross sections with lower a/h values had higher PSW_{adj} values. Figure 20a isolates the test results for α is equal to zero and shows the relationship between PSW_{adj} and a/h.

An anomaly exists for this trend of a/h versus PSW_{adj} values and therefore on web crippling behavior. This deviation from the trend pertains to cross-section EOF-SU-8, which had an a/h value of 0.36. Cross-section EOF-SU-8 had an average PSW_{adj} value at α is equal to zero which exceeds the PSW_{adj} value for two cross sections with smaller a/h values (Fig. 20a). The two cross sections with the smaller a/h values were EOF-SU-12, which had an a/h value of 0.27, and EOF-SU-13, which had an a/h value of 0.20. At α is equal to zero, cross-section EOF-SU-8 had an average PSW_{adj} value of 94.7 percent, whereas cross-sections EOF-SU-12 and EOF-SU-13 had an average PSW_{adj} value of 89.9 and 94.1 percent, respectively.

Cross-section EOF-SU-8 had a smaller b value than cross-sections EOF-SU-12 and EOF-SU-13. As discussed in the next paragraph for the effect of the parameter b on web crippling, the effect of b was determined not to have produced the higher PSW_{adj} values for cross-section EOF-SU-8 than were obtained for cross-sections EOF-SU-12 and EOF-SU-13.

Two tests were conducted for cross-section EOF-SU-1 at α is equal to zero (Figs. 19a and 20a). The two tests produced an average PSW_{adj} value of 111 percent. The a/h value of 0.13 for cross-section EOF-SU-1 was the smallest tested, and it produced the only PSW_{adj} results significantly above 100 percent. The behavior of cross-section EOF-SU-1 could be considered as an additional anomaly from the stated trend of the effect of a/h on PSW_{adj} values. This is because this cross section with web openings had higher PSW_{adj} values than would be expected from a cross section with an a/h value of zero, i.e. a solid web cross section.

These observations for cross-sections EOF-SU-1 and EOF-SU-8 are considered to be within the realm of experimental error and the variability associated with web crippling experiments, and do not refute the aforementioned trend stated for the effect of a/h on PSW_{adj}. Furthermore, no conclusive relationships are found which account for the atypical behavior of these two cross sections.

This trend of an inversely proportional relationship between PSW_{adj} and a/h clearly continued for the higher α values of 0.5 (Fig. 20b) and 0.7 (Fig. 20c). At α is equal to 1.0 and 1.5 all cross sections shown on Figure 19 exhibited very little difference in their PSW_{adj} values, as the PSW_{adj} values approached 100 percent. The small percentage difference in PSW_{adj} values between these points of intersection and the PSW_{adj} value of 100 percent is within the realm of experimental error for web crippling analysis.

Limiting the highest α value tested to 1.5 did not restrict the worthiness of the results. For example, although α values of 2.0 would have resulted in a likely preponderance of flexural failures, the PSW_{adj} values for the test results at α is equal to 2.0 would have been approximately 100 percent, as existed at α is equal to 1.5. At α values equal to 1.0 and 1.5, the trend curves for each value of a/h of Figures 19 frequently intersected each other.

d. Effect of b on Web Crippling Behavior. All web crippling failures were located between the end of the specimen and the nearest edge of the web opening. Only a minor portion of the horizontal length of the web opening appeared to influence the failure (Figs. 13, 14, and 15). Hence a small b value, i.e., slightly less than the minimum tested value of two inches, will have essentially the same effect as b values within the range of those tested. The parameter b is accounted for as a maximum allowable b value for use of the design recommendations corresponding to the maximum b value used in standard industry practice.

An increase in strength may exist for situations where α and b are both small, and the load can dissipate in roughly a 45 degree angle over the web opening. For example, this could occur when a narrow vertical slit of height a is located near or adjacent to the load plate. However, this phenomenon was not studied because of the smallest web opening b value of two inches. In practice, b will typically not be less than two inches for providing passage of services.

Based on the web crippling behavior of cross-section EOF-SU-8, the web opening parameter b is worthy of additional examination for its effect on web crippling behavior. Cross-section EOF-SU-8 had a b value of 2.00 inches, whereas cross-sections EOF-SU-12 and EOF-SU-13 both had a b value of 4.00 inches (Table I). Therefore, it could be concluded that the higher b value for the latter two cross sections was responsible for the lower PSW_{adj} values exhibited by cross-section EOF-SU-12 and EOF-SU-13 (Figs. 19a and 20a). However, cross-section EOF-SU-7 had the same b value as cross-section EOF-SU-8, of 2.00 inches, and approximately the same a/h value as cross-section EOF-SU-8, of 0.36. Yet, cross-sections EOF-SU-7 and EOF-SU-8 had significantly different web crippling behavior.

Cross-section EOF-SU-7 had a PSW_{adj} value of 80.2 percent at α is equal to zero (Figs. 19a and 20a). This value was significantly less than the PSW_{adj} value of cross-section EOF-SU-8 at α is equal to zero of 94.7 percent. Furthermore, the PSW_{adj} value at α is equal to zero for cross-section EOF-SU-7 was less than for cross-sections EOF-SU-12 and EOF-SU-13. The behavior of cross-section EOF-SU-7 as compared to that of cross-sections EOF-SU-12 and EOF-SU-13, shows that for these cross sections, the lower value for b in cross-section EOF-SU-7 was not useful in overcoming the degradation caused by the higher a/h value for cross-section EOF-SU-7. Hence, it is concluded that the parameter b did not affect web crippling behavior for the range of b values tested, and that the behavior of cross-section EOF-SU-8 is an anomaly.

e. Effect of Non-Web Opening Parameters on Web Crippling Behavior. This paragraph is included in the discussion of the effect of the web opening parameters on web crippling behavior because it is concluded from the test results that the web opening parameters of α and a/h are the only cross-section parameters which have a distinct effect on the PSW_{adj} values. Specifically, the cross-section parameters not related to web openings, t, F_y, h/t, N/t, and R/t, did not affect the PSW_{adj} values.

As provided in the previous paragraphs, the parameters α and a/h had a distinct effect on the PSW_{adj} values, and therefore on the web crippling behavior for sections with web openings. However, although the effect of a/h is distinct, cross sections with the same a/h value had notably different PSW_{adj} values for the same α value.

Most notably, five of the cross sections had approximately the same a/h value of 0.47. These cross sections and their a/h values are: EOF-SU-2, EOF-SU-3, EOF-SU-4, EOF-SU-9, and EOF-SU-10, with a/h values of 0.466, 0.465, 0.472, 0.459, and 0.462, respectively (Table I). The consistency of the a/h values for the five cross sections resulted from a constant value of a, where a is equal to 1.5 inches, and approximately the same h values. The h values ranged from 3.18 to 3.27 inches for these five cross sections (Table I). Hence the values of a/h ranged from:

$$1.5/3.27 \leq a/h \leq 1.5/3.18 \tag{62}$$

or,

$$0.459 \leq a/h \leq 0.472 \tag{63}$$

In addition to the a/h value, the test specimens from the five cross sections had several other important parameters which were equal. These cross sections each had R values equal to 5/32 inch, and each cross section was tested at common α values of 0.0, 0.5, 0.7, 1.0, and 1.5, and at a N value of 1.0 inch. Finally, the last characteristic common of the five cross sections and their test specimens is a consistent bending magnitude assumed equal to zero at the end reaction plate.

Because of the constant values of these key parameters, and a constant value of b equal to 4.00 inches, the situation was ideal to examine the results of the five cross sections to determine if variable parameters clearly affect the web crippling behavior of the sections with web openings. This was accomplished by considering PSW_{adj} as a dependent variable and the non-constant parameters separately as independent variables. The average PSW_{adj} values of the five cross sections at α is equal to zero, listed in order of increasing values of PSW_{adj}, are EOF-SU-10 (67.2%), EOF-SU-9 (70.9%), EOF-SU-2 (71.0%), EOF-SU-4 (73.8%), and EOF-SU-3 (76.2%). The PSW_{adj} values for these five cross sections at α is equal to zero is given on Figure 20a.

The variable or dissimilar parameters among the five cross sections were t, h/t, N/t, F_y, and R/t. Each of these parameters affect web crippling behavior, as is evident from their inclusion in the current Specification web crippling provisions (Eqs. 30 thru 35). However, as discussed in the following, none of the dissimilar parameters of t, h/t, N/t, F_y, and R/t had a distinct effect on the values of PSW_{adj}. This is because these dissimilar parameters equally affect the strength of the test specimens with web openings and the strength of their solid web counterparts.

i. Effect of t on PSW_{adj} Values. The t values for the five cross sections, listed in the same order stated for increasing PSW_{adj} values at α equal to zero, were: EOF-SU-10 (0.077 in.), EOF-SU-9 (0.044 in.), EOF-SU-2 (0.044 in.), EOF-SU-4 (0.071 in.), and EOF-SU-3 (0.036 in.). The relationship between t and PSW_{adj} is shown as Figure 21.

A linear regression analysis was performed to isolate the effect of t on PSW_{adj} for the results shown in Figure 21. The results of the linear regression of PSW_{adj} versus t yields the equation:

$$PSW_{adj} = 77.27 - 99.9t \tag{64}$$

The coefficient of correlation for the regression was 0.292.

As can be seen from the low coefficient of correlation for PSW_{adj} versus t, which quantifies the high degree of scatter of the data shown in Figure 21, there is no notable correlation between PSW_{adj} and thickness.

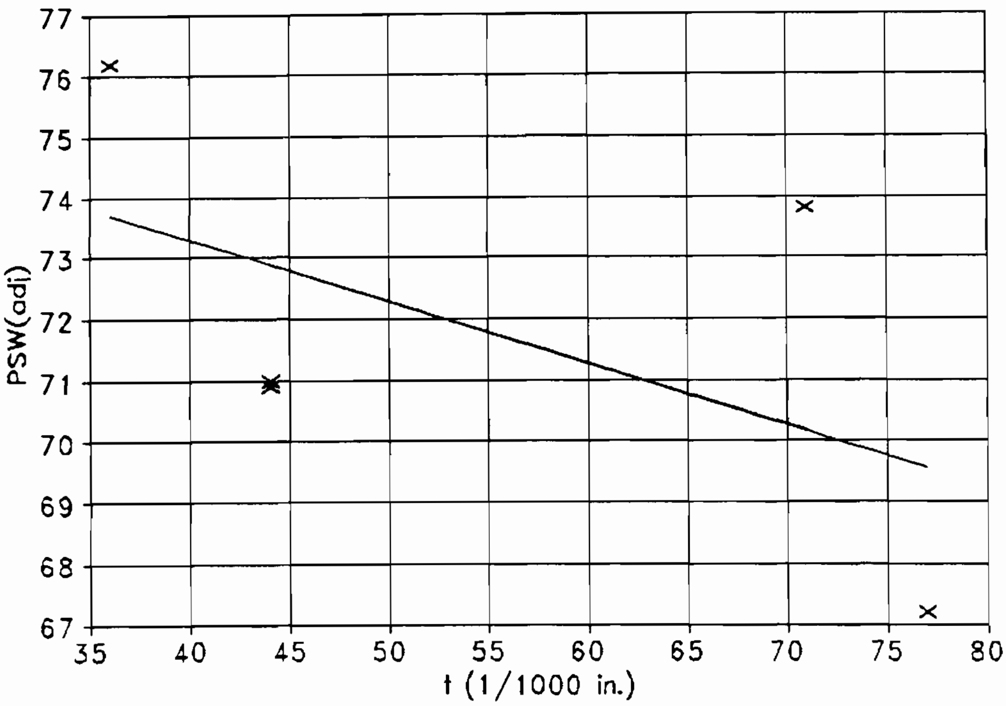


Figure 21: PSW_{adj} vs. t for EOF Tests at a/h = 0.47

ii. <u>Effect of F_y on PSW_{adj} Values.</u> The F_y values for the five cross sections were EOF-SU-10 (64 ksi), EOF-SU-9 (47 ksi), EOF-SU-2 (53 ksi), EOF-SU-4 (81 ksi), and EOF-SU-3 (64 ksi). The relationship between F_y and PSW_{adj} is shown as Figure 22.

A linear regression analysis was performed to isolate the effect of F_y on PSW_{adj} for the results shown in Figure 22. The results of the linear regression of F_y yields the equation:

$$PSW_{adj} = 66.48 + 0.090F_y \tag{65}$$

The coefficient of correlation for the regression was 0.110.

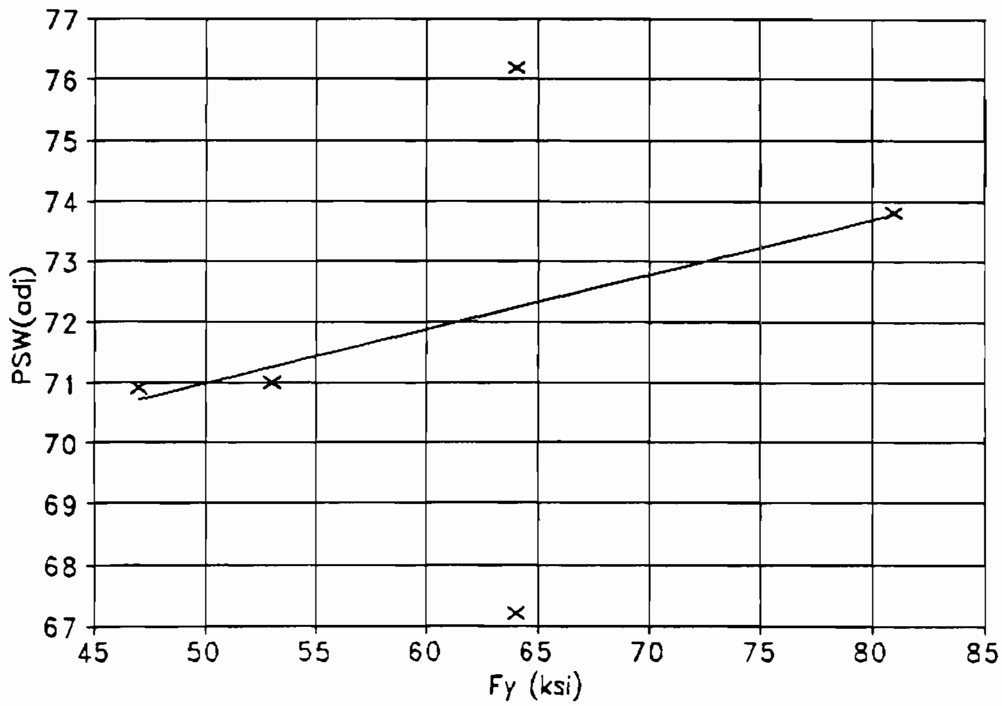


Figure 22: PSW_{adj} vs. F_y for EOF Tests at a/h = 0.47

As can be seen from the low coefficient of correlation for PSW_{adj} versus F_y, which quantifies the high degree of scatter of the data shown in Figure 22, there is no notable correlation between PSW_{adj} and yield stress.

iii. <u>Effect of h/t, N/t, and R/t on PSW_{adj} Values.</u> The three remaining dissimilar parameters among the five cross sections discussed in this paragraph are h/t, N/t, and R/t. However, these three parameters did not receive separate consideration because the effect of these three parameters is directly related to the effect of the thickness. This resulted from the constant values of h, N, and R among the five cross sections. Therefore, for example, the effect of h/t would have the same effect on PSW_{adj} as the effect of thickness only because the five cross sections essentially had the same h value. A graph of PSW_{adj} versus h/t, N/t, or R/t would show the same high degree of scatter as shown in Figure 21.

f. Summary of the Effect of α and a/h on Web Crippling Behavior. The web opening parameters of α and a/h provided the only conclusive correlation with PSW_{adj}. As a result of the above findings, PSW_{adj} and therefore the reduction factor equation, are dependent only upon these web opening parameters. The reduction factor equation will therefore not include any parameters intrinsic to the solid web specimens. Many of the parameters associated with solid web sections are included in the existing Specification web crippling provisions, Equations 30 thru 35.

The cross-section parameters shown in Table I, with the exception of the web opening parameters of α, b, a, and therefore a/h, proportionally affected both the $(P_n)_{test,\ solid\ web}$ and $(P_n)_{test,\ web\ opening}$ values. The values of $(P_n)_{test,\ solid\ web}$ and $(P_n)_{test,\ web\ opening}$ comprise the denominator and numerator, respectively, of the relationship defining PSW_{adj}. Therefore, the effect of the parameters intrinsic to solid web sections of t, F_y, h/t, N/t and R/t, is nullified by their having the same effect on both the numerator and denominator of the PSW_{adj} relationship. Conversely, the parameters α and a/h influenced PSW_{adj} since these two parameters influenced only the numerator of the PSW_{adj} relationship, $(P_n)_{test,\ web\ opening}$.

The influence of the remaining web opening parameter, b, is addressed by imposing a maximum limit on b according to that which exists in standard practice as provided in Section III.F.

3. <u>Nominal Tested vs. Computed Capacity for Tests with Web Crippling Failures</u>. For all test specimens identified as having an EOF web crippling failure, the $(P_n)_{test}$ value was compared to the computed nominal web crippling load, $(P_n)_{comp}$, from ASD Equation 30 multiplied by the ASD factor of safety of 1.85 or directly from the LRFD Equation 31. The comparison was accomplished by computing the value of $(P_n)_{test}/(P_n)_{comp}$ for each test specimen. This comparison of $(P_n)_{test}/(P_n)_{comp}$ values was performed for the results of all test specimens which had a web crippling failure, to include those with web openings and those with solid webs. The values of $(P_n)_{test}/(P_n)_{comp}$ and the statistical results of $(P_n)_{test}/(P_n)_{comp}$ values, to include the mean and the coefficient of variation, are given in Table IX.

The primary findings for the values of $(P_n)_{test}/(P_n)_{comp}$ are: they had a mean value significantly above unity and they had a high variation. For all 108 test specimens exhibiting a web crippling failure, the mean was 1.29, and the coefficient of variation was 0.368. Both of these statistical results for the $(P_n)_{test}/(P_n)_{comp}$ values are significant, and require investigation to determine the contributing factors. The high mean value of $(P_n)_{test}/(P_n)_{comp}$ equal to 1.29 is due to two factors: testing of cross sections with high F_y values, and testing of specimens with low $(P_n)_{comp}$ values. The high coefficient of variation of $(P_n)_{test}/(P_n)_{comp}$ values equal to 0.368 was due to the testing of specimens with different a/h values and different α values. Further discussion of the high mean and the coefficient of variation of $(P_n)_{test}/(P_n)_{comp}$ values and the contributing factors are subsequently discussed separately in Parts (a) and (b) below.

a. Mean of $(P_n)_{test}/(P_n)_{comp}$ Values for Web Crippling Failures.

i. General. The two factors that attributed to the high mean value of the $(P_n)_{test}/(P_n)_{comp}$ results of 1.29 for all web crippling failures are the high F_y values of several cross sections and the low $(P_n)_{comp}$ values of several cross sections. To isolate the effect of these two factors, the discussion is limited to the results from tests performed on solid web specimens.

Limiting the discussion to tests performed with constant a/h and α values removes the effect of these two web opening parameters from further consideration. Furthermore, limiting the discussion to solid web tests is a special case of considering tests with constant a/h and α values. Also, strictly analyzing the solid web test results has two important advantages. First, this facilitates the direct use of $(P_n)_{comp}$ as the predicted capacity of the test specimens. Secondly, this provides the largest set of test data available which has an unique set of α and a/h values. Twenty-six percent of the 108 web crippling failures were performed on solid web tests, and this percentage greatly exceeds the percent for any single set of a/h and α values.

ii. Nominal Tested vs. Computed Capacity for Solid Web Tests to Evaluate the Mean Value of $(P_n)_{test}/(P_n)_{comp}$.

(a) General. As shown in Table IX, the values of $(P_n)_{test}/(P_n)_{comp}$ for solid web tests performed on most of the cross sections were above unity. Exceptions are the values of $(P_n)_{test}/(P_n)_{comp}$ for the solid web tests for cross-sections EOF-SU-7 and EOF-SU-10 which were slightly less than unity. The results from the solid web tests performed on these two cross sections are discussed subsequently in this paragraph as Part (e).

The $(P_n)_{test}/(P_n)_{comp}$ values of the 23 solid web tests (Table IX) are shown in Figure 23. The results shown on Figure 23 were compared to the data of Figure 24 (Fig. 34 of Hetrakul and Yu, 1978). Because the results summarized by Figure 23 for all tests are close to the line defined by $(P_n)_{test}$ is equal to $(P_n)_{comp}$, there is good correlation with the existing AISI provisions.

Figure 23 shows that the magnitude of $(P_n)_{test}/(P_n)_{comp}$ cannot be solely considered to judge the conservatism of the solid web test results, i.e. results are traditionally considered more conservative as the value of $(P_n)_{test}/(P_n)_{comp}$

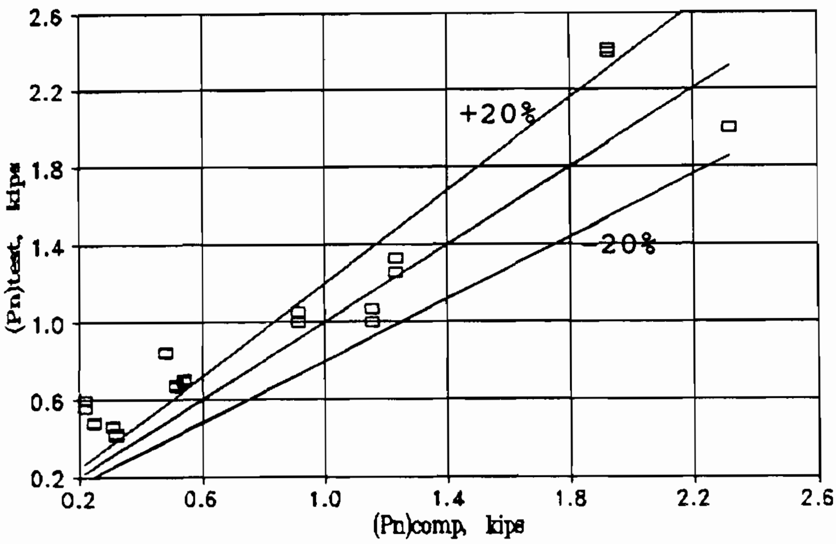


Figure 23: $(P_n)_{test}$ vs. $(P_n)_{comp}$ for Unreinforced Solid Web EOF Tests

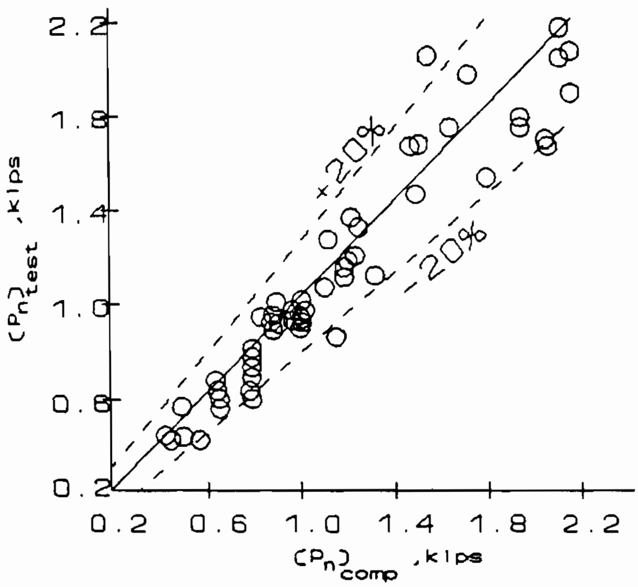


Figure 24: $(P_n)_{test}$ vs. $(P_n)_{comp}$ for Unreinforced EOF Tests as Given by Hetrakul and Yu (1978, Fig. 34)

increases from unity. However, in addition to the magnitude of $(P_n)_{test}/(P_n)_{comp}$, the distance between the $(P_n)_{test}/(P_n)_{comp}$ results and the line defined by $(P_n)_{test}$ is equal to $(P_n)_{comp}$ must be considered. The distance is given by:

$$DIST = \frac{|(P_n)_{comp} - (P_n)_{test}|}{\sqrt{2}} \tag{66}$$

The most notable example of using this additional criteria for judging conservatism is seen from the behavior of cross-sections EOF-SU-12 and EOF-SU-4. The tests with the greatest $(P_n)_{test}/(P_n)_{comp}$ values were from test specimens EOF-SU-12-1-(1 and 2) which had $(P_n)_{test}/(P_n)_{comp}$ values of 2.56 and 2.75 respectively. Hence, these two results can be considered 156 and 175 percent conservative, respectively. These $(P_n)_{test}/(P_n)_{comp}$ values are shown on Figure 23 with a $(P_n)_{comp}$ value of 0.217 kips and $(P_n)_{test}$ values of 0.556 and 0.598 kips.

Although considered extremely conservative using the traditional definition of conservatism, these two results are closer to the line defined by $(P_n)_{test}$ equal to $(P_n)_{comp}$ than are the results of tests EOF-SU-4-1-(1 and 2) which had much lower $(P_n)_{test}/(P_n)_{comp}$ values of 1.26 and 1.25, respectively. The two values for cross-section EOF-SU-4 exhibited the greatest distance from the $(P_n)_{test}$ is equal to $(P_n)_{comp}$ line, and yet are only 25 percent conservative. The test results for cross-section EOF-SU-4 result from a $(P_n)_{comp}$

value of 1.920 kips and $(P_n)_{test}$ values of 2.413 and 2.394 kips (Fig. 23).

Using Equation 66, the distance of the $(P_n)_{test}/(P_n)_{comp}$ values for the solid web tests of cross-section EOF-SU-12 were at an average distance of 0.255 kips from the line defined by $(P_n)_{test}$ is equal to $(P_n)_{comp}$. The distance of the $(P_n)_{test}/(P_n)_{comp}$ values for the solid web tests of cross-section EOF-SU-4 were at an average distance of 0.342 kips from the line defined by $(P_n)_{test}$ is equal to $(P_n)_{comp}$.

In general, the high values of $(P_n)_{test}/(P_n)_{comp}$ were caused by the low $(P_n)_{comp}$ values (Part b) and high F_y values (Part c) of several cross sections.

(b) Low $(P_n)_{comp}$ Values. As shown by Figure 24, the Hetrakul and Yu (1978) study did not include any specimens with $(P_n)_{comp}$ values lower than 0.4 kips, and few specimens with $(P_n)_{comp}$ values lower than 0.6 kips. However, 14 of the 23 solid web tests conducted during the current investigation had $(P_n)_{comp}$ less than 0.6 kips.

The highest $(P_n)_{test}/(P_n)_{comp}$ values from the current study resulted from sections with low $(P_n)_{comp}$ values. Most notably, all solid web tests with $(P_n)_{test}/(P_n)_{comp}$ values greater than 1.35 had $(P_n)_{comp}$ values less than 600 pounds. In Figure 23, tests with low $(P_n)_{comp}$ values plotted close to the origin, and therefore close to the line defined by $(P_n)_{test}$ is equal to $(P_n)_{comp}$. This finding diminishes the validity of using the magnitude of $(P_n)_{test}/(P_n)_{comp}$ as the sole judge of conservatism.

(c) High F_y Values. Several cross sections were tested that had F_y values (Table I) exceeding the maximum value of 54 ksi used in the development of the existing provisions (Hetrakul and Yu, 1978). Furthermore, several cross sections were tested with F_y values greater than 66.5 ksi. As provided in the review of the AISI Specification web crippling provisions (Section II.F), explicit use of Equations 30 thru 33 for F_y values greater than 66.5 ksi results in a decrease in web crippling capacity as F_y increases from 66.5 ksi. This is due to the parabolic nature of the web crippling capacity equation with respect to the variable F_y. Hence, this warrants that a F_y value of 66.5 ksi be used for cross sections with F_y values greater than 66.5 ksi. This has the effect of artificially suppressing the values of $(P_n)_{comp}$ and therefore artificially increasing the $(P_n)_{test}/(P_n)_{comp}$ value by constraining the denominator of this relationship.

For cross sections with F_y values greater than 54 ksi, the solid web test results were analyzed using Equations 44 and 45 for the situation where Z is equal to zero and e is greater than or equal to 0.5h (Fig. 9). The results of this analysis and a comparison with the analysis using the current AISI Specification web crippling provisions are shown in Table X for the solid web tests.

The $(P_n)_{test}/(P_n)_{comp}$ values for each cross section given in Table X were significantly closer to unity than resulted from the current provisions. This includes one

Table X: Comparison of EOF Results with Equations from Santaputra, Parks, and Yu (1989)

	F_y (ksi)	Santaputra, Parks, and Yu Equations (lbs.) P_{cy} (Eq.44)	P_{cb} (Eq.45)	$(P_n)_{comp}$ (lbs.) Lesser of P_{cy} and P_{cb}	Eqs. 30 & 31	Average $(P_n)_{test}$ (lbs.)	$(P_n)_{test}/(P_n)_{comp}$ Lesser of P_{cy} and P_{cb}	Eqs. 30 & 31
For F_y is greater than 66.5 ksi								
EOF-SU-4	81	2162	3068	2162	1920	2404	1.11	1.25
EOF-SU-6	67	317	615	317	279	475	1.50	1.70
EOF-SU-12	93	440	347	347	217	577	1.66	2.65
EOF-SU-13	72	587	647	587	478	847	1.44	1.77
For F_y values between 54 and less than 66.5 ksi								
EOF-SU-1	60	918	912	912	905	1022	1.12	1.73
EOF-SU-3	64	352	644	352	306	460	1.31	1.50
EOF-SU-10	64	2171	3649	2171	2315	2000	0.921	0.864
						AVERAGE:	1.29	1.58

Notes: 1. All tests performed on solid web sections at N is equal to 1.00 inch.
2. Cross-section designations:
EOF: End-One-Flange loading condition, SU: Single Unreinforced web
EOF-SU-cross section number-specimen designation

cross-section, EOF-SU-10, which exhibited an increase in the $(P_n)_{test}/(P_n)_{comp}$ value equal to 0.86 from the existing Specification web crippling equations to 0.92 using Equations 44 and 45. Cross-section EOF-SU-10 exhibited the lowest $(P_n)_{test}/(P_n)_{comp}$ value from the current provision equations. The average $(P_n)_{test}/(P_n)_{comp}$ value of the cross sections shown in Table X was 1.58 using the current AISI provisions and was 1.29 using the equations of Santaputra, Parks, and Yu (1989).

(d) <u>High α and a/h Values.</u> It has been shown herein that the testing of cross sections with high F_y values and/or low $(P_n)_{comp}$ values is responsible for the mean of $(P_n)_{test}/(P_n)_{comp}$ being greater than unity. Also, it has been clearly shown that web openings reduce the values of $(P_n)_{test}$ and therefore reduce the value of $(P_n)_{test}/(P_n)_{comp}$. Hence, the testing of specimens with web openings should decrease the mean value of $(P_n)_{test}/(P_n)_{comp}$ to less than unity. Furthermore, the testing of specimens with high a/h values or low α values should cause the mean value of $(P_n)_{test}/(P_n)_{comp}$ to further decrease from unity.

The average $(P_n)_{test}/(P_n)_{comp}$ value of 1.29 apparently contradicts this. However, as previously stated, the low $(P_n)_{comp}$ values and high F_y values were responsible for the mean value of $(P_n)_{test}/(P_n)_{comp}$ exceeding unity, and the effect of a/h and α in reducing $(P_n)_{test}/(P_n)_{comp}$ was not powerful enough to counteract this effect.

(e) $(P_n)_{test}/(P_n)_{comp}$ Less Than Unity. Equations 30 and 31 overestimated the strength for cross-sections EOF-SU-7 and EOF-SU-10, as evidenced by $(P_n)_{test}/(P_n)_{comp}$ values less than unity. Hence, the solid web test specimens of these cross sections did not obtain their predicted nominal capacity. EOF-SU-7 and EOF-SU-10 had average $(P_n)_{test}/(P_n)_{comp}$ values of 0.89 and 0.86 for the solid web test specimens, respectively. However, these values are within the variance for web crippling analysis. Consequently, the $(P_n)_{test}/(P_n)_{comp}$ values from these cross sections were significantly less than unity for test specimens with web openings. This most notably applies to the specimens with α is equal to zero. Hence, disregarding the reduction in web crippling strength to account for web openings for these two cross sections could produce a dangerous condition in practice.

At α is equal to zero, these two cross section had inadequate capacity beyond service load. This can be observed by comparing the $(P_n)_{test}/(P_n)_{comp}$ values for the cross sections to the reciprocal of the ASD factor of safety, 1/1.85 which is equal to 0.54. Cross-sections EOF-SU-7 and EOF-SU-10 had average $(P_n)_{test}/(P_n)_{comp}$ values of 0.71 and 0.58, respectively, for the web opening tests at α is equal to zero. These two cross sections exceeded their allowable capacity, at α is equal to zero, by only 31 and seven percent, respectively.

Examination of the cross-section parameters of these two cross sections produces no conclusive trends to provide the reasons for their low $(P_n)_{test}/(P_n)_{comp}$ values. However, the two aforementioned factors which produce high $(P_n)_{test}/(P_n)_{comp}$ in solid web sections with low $(P_n)_{comp}$ values and high F_y values did not apply to either cross-sections EOF-SU-7 or EOF-SU-10.

Specifically, cross-section EOF-SU-7 had a F_y value of 37 ksi and a $(P_n)_{comp}$ value of 1152 pounds at N is equal to one inch. Therefore, the F_y value of this cross section was the second lowest F_y value tested and the $(P_n)_{comp}$ value was relatively high as compared to the other cross sections used in the current investigation. Cross-section EOF-SU-10 had a F_y value of 64 ksi, which is just below the maximum value of 66.5 ksi, and a $(P_n)_{comp}$ value of 2315 pounds at N equal to one inch, which was the highest $(P_n)_{comp}$ value for a test specimen. Because no distinct trends can be determined which defines the amount of the conservatism or unconservatism of Equations 30 and 31 for cross-sections EOF-SU-7 and EOF-SU-10, no recommendation is made to change the current Specification provisions for solid webs.

(f) <u>Summary for the Mean of $(P_n)_{test}/(P_n)_{comp}$.</u> It could be incorrectly and unsafely deduced that because the average $(P_n)_{test}/(P_n)_{comp}$ value was greater than unity, no reduction in web crippling strength is needed to account for web openings. Although the mean value of $(P_n)_{test}/(P_n)_{comp}$ was significantly greater than unity, it appears that the existing equations are very conservative, and therefore allow for the existence of a web opening. However, the intent of a factor of safety, or resistance factor, is to account for uncertainty. The intent is not to account for a reduction in ultimate strength such as the presence of web openings. This reduction of the web crippling capacity of the solid web sections was clearly illustrated by the effect of the web opening parameters.

b. Coefficient of Variation of $(P_n)_{test}/(P_n)_{comp}$ Values for Web Crippling Failures. The coefficient of variation of 0.368 for all test specimens which exhibited a web crippling failure is significantly greater than the typical coefficient of variation of $(P_n)_{test}/(P_n)_{comp}$ for web crippling. This includes previous web crippling investigations, which typically, as stated in the review of Hetrakul and Yu (1978) (Section II.E), have a high coefficient of variation. The coefficient of variation of the EOF $(P_n)_{test}/(P_n)_{comp}$ results used in the development of the current AISI Specification web crippling provisions was equal to 0.117 for sections with edge-stiffened flanges, (Hetrakul and Yu, 1978). Furthermore, Hetrakul and Yu (1978) stated that the justification of the ASD factor of safety of 1.85 is based on the high variation in $(P_n)_{test}/(P_n)_{comp}$ values. The tests performed by Hetrakul and Yu (1978) were performed only on solid web test specimens. The mean value of the $(P_n)_{test}/(P_n)_{comp}$ results from Hetrakul and Yu (1978) was equal to unity. This result was obtained because the equation for $(P_n)_{comp}$ was developed from the test results.

The web opening parameters of a/h and α are the contributing factors for the high coefficient of variation of the $(P_n)_{test}/(P_n)_{comp}$ values, because $(P_n)_{test}$ is dependent on the a/h and α values. However, the values of $(P_n)_{comp}$ from the existing provisions is not dependent on the a/h or α values. Therefore, only the numerator of the relationship $(P_n)_{test}/(P_n)_{comp}$ is affected by the a/h and α values. Hence, any variations in a/h and α will ultimately increase the variation of $(P_n)_{test}/(P_n)_{comp}$ values because these parameters only affect the numerator of this expression. Furthermore, this variation is superimposed on the variation associated with web crippling.

If the testing procedure was limited to a single set of a/h and α values, to include a solid web situation, where a/h and α are trivial parameters, then the variation in $(P_n)_{test}/(P_n)_{comp}$ values would have been significantly reduced. The variation would ideally equal that associated with web crippling only. However, numerous combinations of a/h and α values were used in this investigation, and these distinctly affected the $(P_n)_{test}$ values by increasing their variance, and therefore increasing the variance of $(P_n)_{test}/(P_n)_{comp}$.

As discussed in Section III.G, use of the reduction factor equation given in Section III.F significantly reduces the variance of $(P_n)_{test}/(P_n)_{comp}$. This is because the reduction factor equation ideally transforms the $(P_n)_{test}/(P_n)_{comp}$ results to the values that would have been obtained if all of the tests were performed at a single set of a/h and α values. Specifically, this set of a/h and α values corresponds to those of the solid web condition where a/h is equal to zero, and α is infinite.

4. <u>Evaluation of Shear Failures.</u>

a. <u>General.</u> Thirty-four test specimens failed in shear (Table VIII). Ten of the shear failures were caused by high N values. It is concluded that high N values were the major contributing factor in these shear failures, because test specimens from the same cross sections that failed in shear at high N values, failed in web crippling at lower N values. Twenty-four of the shear failures were caused by high a/h values (Table VIII). It is concluded that high a/h values were the major contributing factor in these shear failures, because these specimens failed in shear at the lowest N value tested of one inch.

b. <u>Evaluation of Shear Failures Due to High N Values.</u> Shear failures generally occurred at higher end bearing lengths, N, because an increase in N provides an increase in the web crippling strength of the section. Numerical examples of this behavior can be seen from the values of $(P_n)_{comp}$ in Table VIII by comparing the $(P_n)_{comp}$ values for various N values. However, as can be seen by the AISI Specification shear provisions (Eqs. 49, 50, and 52), shear capacity is independent of N. Figure 16 shows a typical shear failure attributed to a high N value.

To examine a transition of failure mode from web crippling to shear as the value of N was increased, tests were conducted on cross-section EOF-SU-9, with varying values of N. For cross-section EOF-SU-9, the transition occurred distinctly between N equal to 4.0 and 5.0 inches. The value of α was arbitrarily maintained at a constant value of 0.50 for these tests.

In cross sections with different web opening sizes, and possibly at other values of α, this transition will occur at different N values. For example, for cross-section EOF-SU-4, the transition occurred between N equal to 1.0 and 3.0 inches. These tests were also conducted at α equals 0.50. No generalized equations were developed to determine the parameters that will determine the transition. In keeping with the usual procedure for the situation where several limit states may govern, each limit state must be checked separately.

c. Evaluation of Shear Failures Due to High a/h Values. Shear failures also occurred at high a/h values. Cross-sections EOF-SU-5 and EOF-SU-6 demonstrate this phenomenon for a/h values of 0.74 and 0.73, respectively. These two cross sections were the only cross sections that failed in shear at N equal to one inch. Figure 17 shows a typical shear failure attributed to a high a/h value.

F. DESIGN RECOMMENDATIONS

1. Bending Interaction. Because the test specimens were configured as simply supported spans, zero moment is considered to have been present at the EOF failure

locations. Therefore, the interaction of bending was not considered for the test specimens. Due to the absence of bending interaction on the EOF web crippling capacity of the test specimens, the PSW_{adj} values are equal to their PSW counterparts.

2. Reduction Factor Equation. The procedure for the development of the reduction factor equation was provided in Section I.D, Terminology. Seventy-eight tests conducted at N equal to one inch failed in web crippling. A bivariate linear regression was performed on the 78 test results with α and a/h as the independent variables and PSW_{adj} as the dependant variable. The resulting equation, with a maximum limit of 100 percent was found to be:

$$RF = 107.91 - (62.95\frac{a}{h}) + (12.06\alpha) \leq 100\% \quad \mathbf{(67)}$$

or,

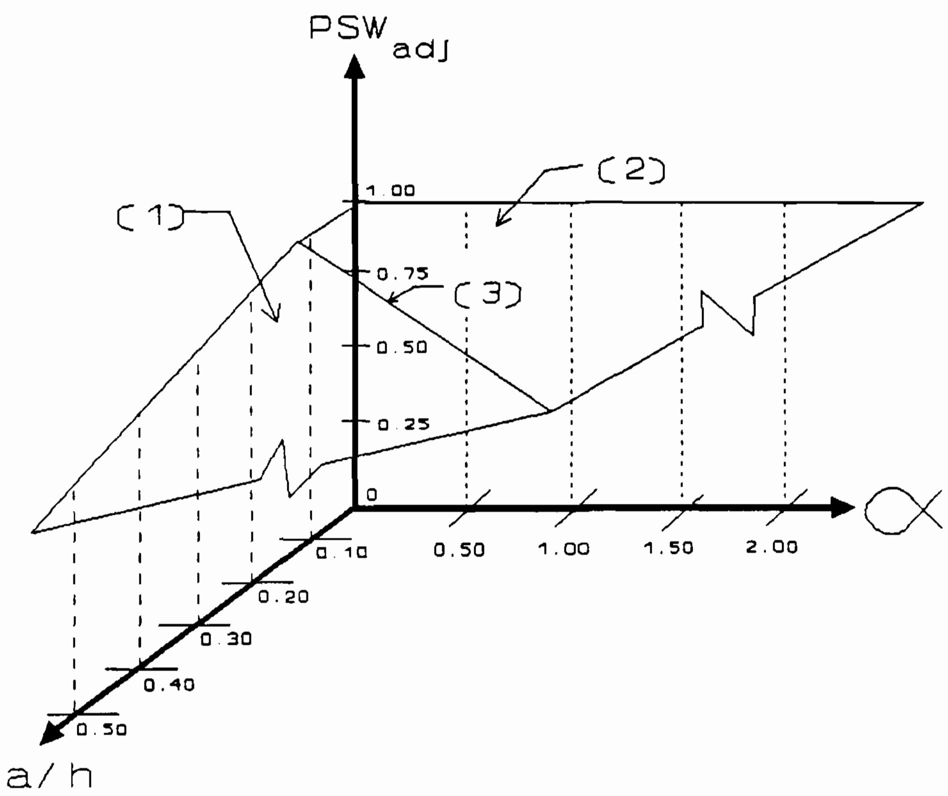
$$RF = 1.08 - (0.630\frac{a}{h}) + (0.120\alpha) \leq 1.00 \quad \mathbf{(68)}$$

Equation 68 is represented graphically by the least y-squares plane, ((1), Fig. 25) for the 78 data points. The horizontal plane ((2), Fig. 25) corresponds to a PSW value of 100 percent.

A PSW value of 100 percent signifies that no strength reduction is required. The reduction factor equation yields, at 100 PSW:

$$\alpha \geq 5.25(a/h) - 0.67 \geq 0 \quad \mathbf{(69)}$$

Equation 69 is shown as (3) in Figure 25. This implies that, for any positive value of α, no strength reduction is required for any cross section with an a/h value less than 0.13. The total joint region of α and a/h which requires no strength reduction is shown as (2) of Figure 25.



(1) $PSW_{adj} = 1.08 - 0.630(a/h) + 0.120\alpha$
(2) $PSW_{adj} = 1.00$ (3) $\alpha = 5.25(a/h) - 0.67$

Figure 25: EOF, PSW_{adj} vs. α and a/h

The correlation coefficient of the bivariate linear regression was 0.6442, which is acceptable for the case of two independent variables. A higher order regression will not significantly improve the correlation coefficient primarily because of the inconsistent influence of the a/h parameter. As was shown by Figures 19 and 20, cross sections with approximately the same a/h value often exhibit different PSW_{adj} values at identical α values.

3. Limitations of Reduction Factor. The ASD Specification (1986) allowable web crippling capacity and the LRFD Specification (1991a) nominal web crippling capacity for sections with web openings can be obtained by applying Equation 68 to Equations 30 thru 33, as given by Equations 2 and 3.

Use of the reduction factor equation provides the web crippling strength of the section with web openings in the absence of bending moment. To consider the interaction of bending and EOF web crippling of single web unreinforced members, Equation 42 or 43 must be used, with the web crippling capacity and bending capacity reduced to account for the strength reduction caused by the web openings.

Equation 68 is applicable to all cross sections and conditions that meet the ranges of applicability. The justification for these ranges is based on four factors: 1. the limits imposed on the existing Specification web crippling provisions as given in Section II.F. 2. the industry imposed limits on web opening parameters, 3. engineering judgement, and 4. the range of parameters for the test specimens (Table IV).

The use of engineering judgement was frequently used to extrapolate the limits for the test specimens to correspond with those of the current AISI Specification web crippling provisions and with those of the industry imposed limits on web opening parameters. The following discussion applies in the application of the reduction factor equation as a design recommendation.

i. Current AISI Web Crippling Provisions (Eqs. 30 thru 33): Although the testing was limited to specimens with edge-stiffened flanges (Eqs. 30 and 31), the same percent reduction in strength is expected for sections with unstiffened flanges (Eqs. 32 and 33). Therefore, Equation 68 is applicable to both flange stiffening conditions. If Equation 68 is used to reduce the allowable strength of Equations 30 thru Equation 33, the limits on h/t, R/t, N/t, and N/h ratios stated in the AISI Specifications (1986, and 1991a) web crippling provisions must be met.

(1) h/t: Although the maximum h/t ratio tested was 192, this can be extended to the maximum allowable prescribed for Equations 30 thru 33 of 200 for use of Equation 68. No minimum h/t is prescribed although the minimum h/t tested was 34.

(2) R/t: The tested range was 2.03 to 4.74. However, all R/t values less than or equal to 6.0 are valid for use of Equation 68, because this is the maximum limit imposed for Equations 30 thru 33.

(3) N/t: The tested range was 13.0 to 181.8. However, all N/t values less than or equal to 210 are valid for use of Equation 68, because this is the maximum limit imposed for Equations 30 thru 33.

(4) N/h: The tested range was 0.087 to 2.96. However, all N/h values less than or equal to 3.5 are valid for use of Equation 68, because this is the maximum limit imposed for Equations 30 thru 33.

(5) θ: Theta equalled 90° for all tests. However, it is assumed that all θ values within the allowable limits of Equations 30 thru 33 of 45° to 90° are valid for use of Equation 68.

ii. a/h: Although the maximum a/h value tested which failed in web crippling was 0.47, Equation 68 is assumed to be valid for a/h values less than or equal to 0.50. This limit corresponds to the maximum a/h value employed for industry standard sections.

High a/h values greatly increase the probability of a shear failure. Therefore, shear must be checked separately using results from the concurrent UMR study of shear behavior of sections with web openings (Shan, 1994).

An example of establishing a maximum value for the a/h ratio for web crippling reduction factor equations was given in Section II.C for the reduction factor equations developed by Yu and Davis (1973) and Sivakumaran and Zielonka (1989).

iii. α: The value of α has a lower limit of zero in keeping with the standard practice of providing web reinforcement when any portion of a web opening is located above or below the EOF load plate. The value of α has no upper limit. As α is increased, Equation 68 will eventually obtain its maximum limit of 100 percent for every a/h value. Furthermore, the upper limit on α is constrained by the web opening spacing of the member.

iv. Bearing Length, N: Although Equation 68 is based on test data exclusively at N equal to one inch, it is applicable for all N values greater than or equal to one inch. This occurs for four reasons:

1. The test results strongly support the generalization of Equation 68 to all N values. Table VIII shows seven test specimens which failed in web crippling for N values greater than one inch. The average $(P_n)_{test}/(P_n)_{comp}$ value, based on the reduced strength from the reduction factor equation (Eq. 68), was 1.333 for the seven higher N value tests (Table IX). The average $(P_n)_{test}/(P_n)_{comp}$, based on the reduced strength from the reduction factor equation for the corresponding tests, i.e. at the same α value, at N equal to one inch was 1.347. Therefore, these seven higher N value tests had the same average reduced $(P_n)_{test}/(P_n)_{comp}$ value as their N is equal to one inch counterparts.

2. The current EOF provision equations (Eqs. 30 thru 33) incorporate the N value. Therefore, N has a strong influence on the reduced allowable and nominal capacity, even though N is not included in Equation 68. Table VIII

shows examples of the effect of N on the value of $(P_n)_{comp}$ for Equations 30 and 31.

3. The same trend in increasing web crippling strength with increasing α and decreasing a/h values is expected at higher N values. Specifically, the same reduction factor equation would have been expected if a N value other than one inch formed the basis of the test program.

4. The web crippling reduction factor equations provided by Yu and Davis (Eqs. 4 and 5) and by Sivakumaran and Zielonka (Eq. 6) were developed based on tests performed at a single N value. Neither of these previous investigations restricted the use of the reduction factor equations to that of the N value used in the testing.

Although a maximum limit is not given explicitly for N, the value of N will be limited by the maximum allowable values of N/t and N/h of 210 and 3.5, respectively, as applies to Equations 30 thru 33.

A cross section limit state will change from web crippling to shear failure at a particular N value inherent to the cross-section properties. Therefore, Equation 68 can be used in conjunction with Equations 30 thru 33 for all N values if shear strength is checked separately using the design recommendations of Shan (1994).

v. Flat Portion of the Web, h: The tested range of the flat portion of the web was 2.03 to 11.54 inches. However, all h values are valid for use with Equation 68 if the h/t maximum limit of 200 is not exceeded.

vi. Base Metal Thickness, t: The base metal thickness is determined after removing the coating from the cross-section material. The tested thickness range was 0.033 to 0.077 inches. However, all t values which meet the material requirements of the AISI Specification (1986, and 1991a) are valid if the h/t maximum limit of 200 is not exceeded.

vii. Yield Strength, F_y: The tested range of F_y was 34 to 93 ksi. Therefore, all F_y are valid for use of Equation 68. For cross sections with F_y greater than 66.5 ksi, 66.5 ksi may be used in the Specification provision equations (Eqs. 30 thru 33). However, for Grade E materials, the F_y and F_u values must be in accordance with Section A3.2.2 of the Specification.

vii. Maximum Web Opening Size:

(1) Opening Height, a: No maximum limit is prescribed for a. However, the industry standard maximum allowable a/h ratio of 0.50 must be adhered to.

(2) Opening Width, b: Although the maximum b value tested was four inches, it is recommended that the maximum limit for b be extended to the industry standard maximum of 4.5 inches. The parameter b is not included in the reduction factor equation, hence no variation in allowable load for b values between zero and 4.5 inches is recommended.

Establishing a maximum value for the length of the web opening has precedence for web crippling reduction factor equations, as discussed in the review of the Yu and Davis

(1973) and Sivakumaran and Zielonka (1989) reduction factor equations, (Section II.C). Although Yu and Davis (1973) did not explicitly state a maximum web opening length for use in Equations 4 and 5, a limit for this parameter does indirectly exist. Their study was limited to square or circular web openings, and they gave a maximum limit on the ratio of the depth of the web opening to the height of the section.

Conservative consideration for irregularly shaped or eccentric web openings is given in Figures 5 and 6 as discussed in Section I.D., Terminology.

G. EVALUATION OF DESIGN RECOMMENDATIONS

The nominal tested versus computed capacity based on inclusion of Equation 68 was used as the measure of the effectiveness of the reduction factor equation. Table VIII shows the reduction values from the Sivakumaran and Zielonka study (Eq. 6) and the current study (Eq. 68) for each test specimen which had a web crippling failure. Table IX shows three different values for $(P_n)_{comp}$ for each test specimen. These three values correspond to the nominal web crippling strength from Equations 30 and 31, and the reduced nominal web crippling strengths, based on Equations 30 and 31, multiplied separately by the numerical value given by Equations 6 and 68.

Table IX also shows the $(P_n)_{test}/(P_n)_{comp}$ values using the three $(P_n)_{comp}$ values for all tests that failed in web crippling. Also listed in Table IX are the required statistical values of the mean and coefficient of variation which are needed to compute the resistance factor, Φ, and the factor of safety. The Φ factor and the factor of safety, based on each of the three $(P_n)_{comp}$ values, was computed using Equations 55 and 56, respectively.

Comparison of the results from Table IX show that employing Equation 68 will increase the conservatism exhibited by some cross sections, i.e. cross sections with $(P_n)_{test}/(P_n)_{comp}$ value consistently greater than unity even for test specimens with web openings. However, for other cross sections, disregarding Equation 68 will increase the existing unconservatism inherent in the solid web cross section. This is demonstrated by cross-sections EOF-SU-7 and EOF-SU-10, which were examined previously because of the $(P_n)_{test}/(P_n)_{comp}$ values from their solid web tests being less than unity (Section III.E.3.a.ii.(e)). Also, three cross-sections, EOF-SU-2, EOF-SU-4, and EOF-SU-9 had $(P_n)_{test}/(P_n)_{comp}$ values greater than unity for the solid web specimens, but $(P_n)_{test}/(P_n)_{comp}$ values less than unity at low α values. Therefore, of the ten cross sections with web openings that exhibited web crippling failures, five require the use of Equation 68 to ensure that a portion of the safety factor of 1.85 and the Φ value of 0.75 is not depreciated solely by the existence of web openings.

Table IX show the $(F.S.)_{LRFD}$ values resulting from Equation 56. A notable observation is that the $(F.S.)_{LRFD}$

value resulting from use of Equation 68 equals 1.86 when all 108 test specimens which failed in web crippling are considered. This is approximately equal to the factor of safety of 1.85 which is currently applied to Equations 30 and 32.

Because of the high variance of test results, the $(F.S.)_{LRFD}$ value based on the unreduced $(P_n)_{comp}$ values was 2.17. This value of 2.17 imposes 16 percent more conservatism than the $(F.S.)_{LRFD}$ resulting from Equation 68 and the currently accepted value of 1.85. However, an increase in the factor of safety is commonplace for the inclusion of an additional source of uncertainty such as the effect of web openings.

The use of Equation 68 to modify the values of $(P_n)_{comp}$ removes the effect of the web opening parameters of a/h and α, and therefore provides a set of $(P_n)_{test}$ values that ideally equal the results that would have been obtained if all tests were performed on solid web specimens. As a result, Equation 68 significantly reduces the coefficient of variation of the $(P_n)_{test}/(P_n)_{comp}$ values by normalizing the tests for different web opening parameters. Consequently, this reduction in variance increases the value of Φ for the tests with web openings.

The value of Φ for all tests was equal to 0.708 without use of Equation 68, and was equal to 0.823 after use of the Equation 68. Because the value of 0.823 is greater than Φ_w of 0.75 for single unreinforced webs (AISI, 1991a), the Φ_w

value of 0.75 does not require augmentation to satisfy the β_0 value of 2.5 (Eq. 55).

If Equation 68 is not used in design, the value of Φ_w equal to 0.75 must be reduced to account for the increase in variance, i.e. it should be reduced to 0.71 as given earlier. This has a similar effect of reducing the web crippling capacity because of the presence of web openings by using a reduction factor equation. However, not using a reduction factor equation, and instead reducing the Φ_w value, would equally penalize the web crippling capacity for all cross sections, regardless of the a/h and α values. This could create a dangerous condition for high a/h values and low α values, and conversely would be uneconomical for sections with low a/h values and/or high α values.

H. SUMMARY OF THE EOF UNREINFORCED WEB OPENING STUDY

A total of 157 specimens were tested for the EOF loading condition. Analysis of EOF test data provided a reduction factor equation (Eq. 68) to be applied to AISI Equation C3.4-1 (Eqs. 30 and 31) and AISI Equation C3.4-2 (Eqs. 32 and 33). The reduction factor equation applies to single web unreinforced sections when the web opening in not located above or below the EOF concentrated load plate. Additionally, bending and web crippling interaction must be checked using AISI Equation C3.5-1 (Eqs. 42 and 43) using the web opening reduced web crippling and bending capacities in the absence of each other. Use of the reduction factor equation can readily be implemented in practice to ensure that the design for the limit states of web crippling and combined bending and web crippling can be accomplished with adequate strength, stability, and serviceability. The reduction factor equation is a function of the α and a/h values of the design situation. A joint region of α and a/h was identified that requires no strength reduction. The reduction factor is valid for all bearing lengths, N, greater than or equal to one inch and for all sections that satisfy the ranges of applicability stated herein. Other failure modes, i.e. shear, flexure, and combinations thereof, must be checked separately.

SECTION IV. INTERIOR-ONE-FLANGE UNREINFORCED WEB OPENING STUDY

A. INTRODUCTION

This section comprises the complete findings of the UMR study on the web crippling behavior of single unreinforced webs for cold-formed steel flexural members with web openings subjected to the interior-one-flange, IOF, loading condition (Fig. 1). The experimental investigation, test results, evaluation of test results, and design recommendations provided in this section are independent of those of Section III, End-One-Flange Unreinforced Web Opening Study, and Section V, End-One-Flange and Interior-One-Flange Reinforced Web Opening Study.

Previous investigations by Yu and Davis (1973) and Sivakumaran and Zielonka (1989) studied IOF web crippling behavior, in the absence of bending moment, for thin-walled flexural members with web openings. In both of these investigations, the web opening was centered on the load plate. The current UMR investigation is the first known research performed using the IOF loading condition which considers the effect of the web opening when it is not centered on the load plate.

The primary results of the study are design recommendations which quantify the IOF web crippling behavior in a manner suitable for implementation in practice. The design recommendations provided in this section are in the form of a reduction factor equation, as defined in Section I.D, Terminology, and the limits of applicability of the reduction factor equation, based on the parameters of the design situation. The design recommendations are also summarized in Section VI.

The numerical value from the reduction factor equation can be used in Equations 2 or 3 to provide the reduced IOF web crippling capacity for sections with single unreinforced webs with web openings. Furthermore, for sections with web openings, these capacities are required entries for the AISI ASD Specification (1986) and the LRFD Specification (1991a) equations for combined bending and web crippling interaction for sections with single unreinforced webs, Equations 42 and 43, respectively.

B. <u>PURPOSE</u>

The purposes of the overall investigation for the IOF loading condition for unreinforced single web sections are, respectively:

1. To study the web crippling behavior and combined bending and web crippling behavior of single unreinforced webs of cold-formed steel flexural members with web openings subjected to the IOF loading condition, and, if necessary, to develop appropriate design recommendations based on these two behaviors as exhibited by the test specimens.

2. To evaluate the existing AISI IOF web crippling provisions for single web unreinforced sections by comparing

the following two sets of test results with the AISI Specification web crippling provisions: results of unreinforced solid web IOF tests, and results of the unreinforced IOF tests performed on test specimens with web openings.

The existing AISI Specification web crippling provisions provide the capacities of solid web sections in the absence of bending moment. Therefore, a necessary condition for an useful comparison is that the test results be limited to those results that were performed in the absence of significant bending moment. As discussed herein, many IOF tests obtained during the investigation had bending moment degradation of the web crippling capacity. Therefore, established relationships from the current AISI Specification were used to compute the equivalent web crippling capacity of the test results to account for bending interaction on the web crippling behavior. Therefore, use of the relationships permitted comparison of the results from solid web sections and sections with web openings with the current AISI Specification web crippling provisions. The applicable AISI Specification web crippling provisions for unreinforced single web sections are Equations 34 and 35, which provide the web crippling capacity in the absence of bending moment.

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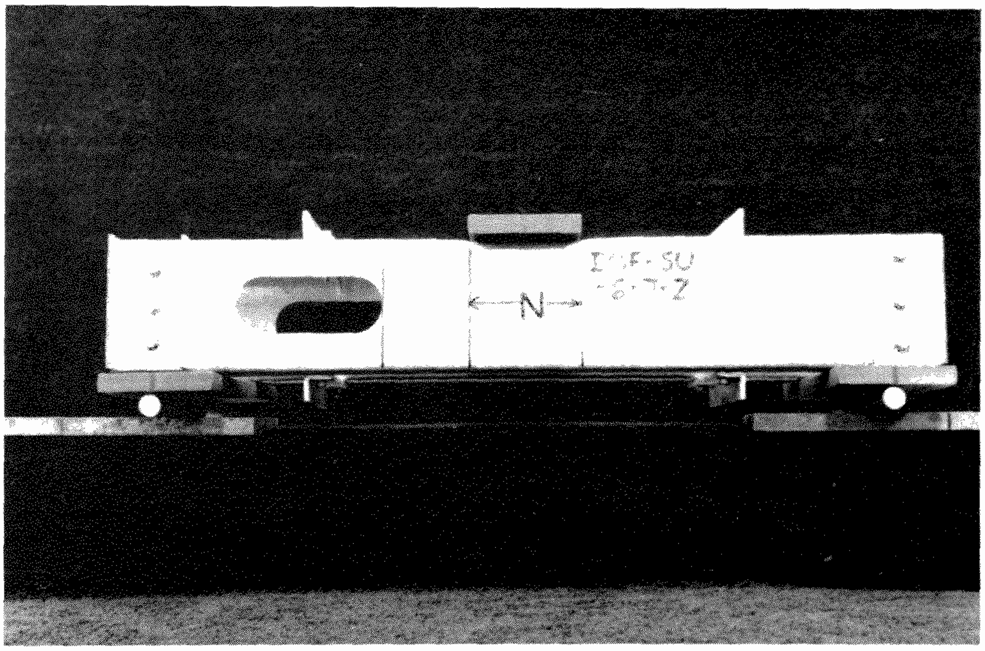
C. EXPERIMENTAL INVESTIGATION

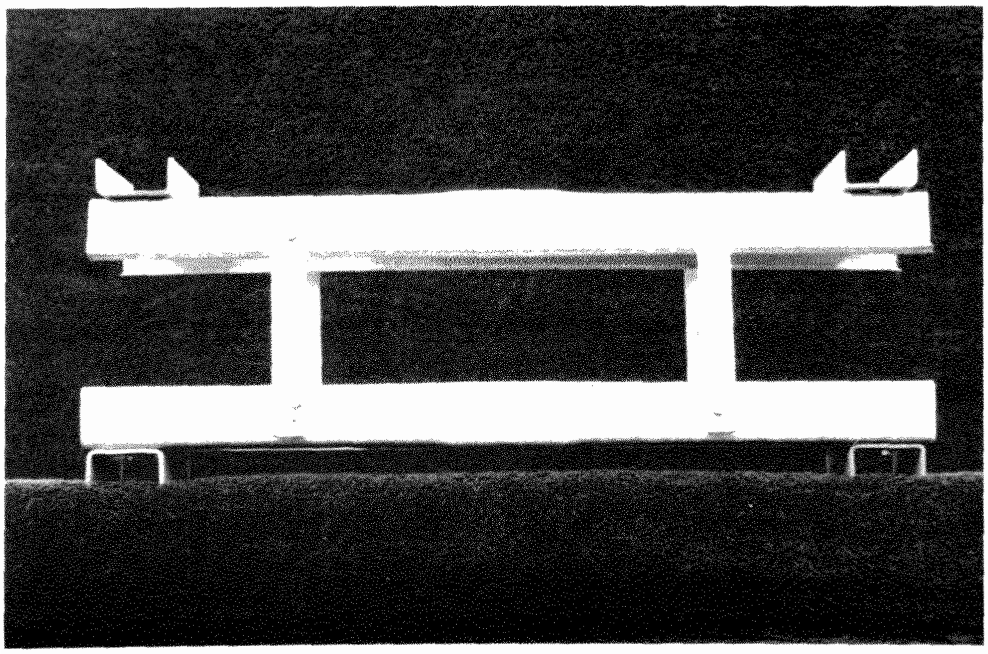
1. Test Specimens. The test specimens were fabricated from industry standard C-sections with edge-stiffened flanges. Therefore, the flanges are classified as partially-stiffened in accordance with the AISI Specification (1986, and 1991a). The web openings were rectangular with fillet corners and were located at mid-height of the web. See Figures 2 and 4 for the cross-section and longitudinal geometry of the test specimens, respectively. Figure 26 shows a typical test specimen. Ten cross-section types were tested with cross-section properties as listed in Table II. The tested range of cross-section parameters are given in Table V. Two sizes of web openings were used in this test program, 0.75 x 4 inches and 1.50 x 4 inches, and are designated by dimensions a and b as shown in Figure 4.

The sections were fabricated to ensure that the web opening in each test specimen was at the desired distance x (Fig. 4) from the IOF load plate. The major parameter varied within each common cross section was the horizontal clear distance between the web opening and the near edge of the IOF load application plate, x, (Fig. 4). The value of x was converted to a non-dimensional parameter α, which is equal to x/h. Tests were conducted for α values in increments of 0, 0.5, 0.7, 1.0, and 1.5.

The length of the IOF load application plate, N, affected the test specimen configuration because it is



(a) Side View



(b) Top View

Figure 26: Typical Unreinforced IOF Specimen

included in the overall specimen length, L. Tests were performed at N values of 3.0, 4.0, 5.0, and 6.0 inches. The minimum required length, L_{min}, of the specimens, was equal to the value necessary to satisfy the requirement of the one-flange loading condition (Fig. 1). However, the value of L was often longer than that required to satisfy the one-flange loading condition requirement. This is because of the imposition of the additional requirement that the value of x′ (Fig. 4) be greater than or equal to zero. This requirement was imposed in order to prevent reinforcement of the web opening by the end reaction stiffener. Therefore, this requirement ensured that the entire length of the web opening, b, (Fig. 4) was located in the clear distance between the end reaction bearing plate and the mid-span IOF load application plate.

The L_{min} of each test specimen was the greater of:

$$L_{min} = (2\,(1.5h)) + N + 6,\ \textit{inches} \tag{70}$$

and,

$$L_{min} = (2\,(x+b)) + N + 6,\ \textit{inches} \tag{71}$$

Equation 70 results from the requirements of one-flange loading (Fig. 1). Equation 71 results from the requirement that x′ is greater than or equal to zero. For both equations, the coefficient of two in the first term results from the application of the load at mid-span. The value of six inches in both equations is equal to the sum of the two end bearing lengths, which each were three inches in length. The length of each test specimen, L, is the greater of:

$$L = 2\,(1.5h) + N + 6,\ inches \tag{72}$$

and,

$$L = (2\,(x + b + x')) + N + 6,\ inches \tag{73}$$

The parameters which comprise the value of L can be seen in Figure 4.

The value of b is a cross-section parameter and invariant for a given cross section as defined in Section I.D, Terminology. For a given cross section, and therefore a given b value, at high α, or x/h, values, Equation 73 governs the L value. Hence, for specimens with high α and b values, the requirement that x′ be greater than or equal to zero controlled the specimen length, by providing a L value greater than required for an one-flange loading condition. Tables XI and XII contain a summary of the overall specimen length, L, bearing length, N, and α value of each test specimen.

Equation 73 does not apply to solid web test specimens. The current investigation is the first known IOF web crippling research where the specimen length was governed by a factor other than the requirement for one-flange loading (Eq. 72). Because of the simply supported configuration of the test specimens, this situation often resulted in test specimens with significant bending moment in the interior region of the test specimen.

Table XI: Unreinforced IOF Test Results

Specimen Number(2)	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State(3)	$(M_n)_{test}$ (K in) (Eq. 75)	$\frac{(M_n)_{test}}{(M_n)_{comp}{}^{(5)}}$	Reduction Factor: S&Z(4) (Eq. 6)	Reduction Factor: Current UMR Study (Eq.77)
IOF-SU-1-1-1	44.00	3.0	SOLID	5785	5785	97.6	97.6	W.C.	59.30	0.330	1.000	1.000
IOF-SU-1-1-2	44.00	3.0	SOLID	6075	6075	102.4	102.4	W.C.	62.27	0.346	1.000	1.000
IOF-SU-1-2-1	44.00	3.0	0.00	6100	6100	102.9	102.9	W.C.	62.53	0.348	0.985	0.929
IOF-SU-1-2-2	44.00	3.0	0.00	6000	6000	101.2	101.2	W.C.	61.50	0.342	0.985	0.929
IOF-SU-2-1-1	17.00	3.0	SOLID	925	997	101.3	101.9	W.C.	3.24	0.427	1.000	1.000
IOF-SU-2-1-2	17.00	3.0	SOLID	900	959	98.6	98.0	W.C.	3.15	0.415	1.000	1.000
IOF-SU-2-2-1	17.00	3.0	0.00	825	849	90.4	86.9	W.C.	2.89	0.381	0.872	0.868
IOF-SU-2-2-2	17.00	3.0	0.00	838	868	91.8	88.7	W.C.	2.93	0.387	0.872	0.868
IOF-SU-2-3-1	28.80	3.0	0.00	588	684	64.4	69.9	W.C.	3.79	0.500	0.872	0.868
IOF-SU-2-3-2	28.80	3.0	0.00	575	661	63.0	67.6	W.C.	3.71	0.489	0.872	0.868
IOF-SU-2-4-1	20.00	3.0	0.50	800	881	87.6	90.1	W.C.	3.40	0.448	0.872	0.899
IOF-SU-2-4-2	20.00	3.0	0.50	813	902	89.0	92.2	W.C.	3.46	0.456	0.872	0.899
IOF-SU-2-5-1	22.00	3.0	1.00	813	955	89.0	97.7	W.C.	3.86	0.509	0.872	0.931

Table XI: Unreinforced IOF Test Results (cont.)

Specimen Number[2]	L[1] (in.)	N[1] (in.)	α[1]	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State[3]	$(M_n)_{test}$ (K in) (Eq. 75)	$\frac{(M_n)_{test}}{(M_n)_{comp}}$[5]	Reduction Factor S&Z[4] (Eq. 6)	Reduction Factor Current UMR Study (Eq.77)
IOF-SU-2-5-2	22.00	3.0	1.00	813	955	89.0	97.7	W.C.	3.86	0.509	0.872	0.931
IOF-SU-2-6-1	24.00	3.0	1.50	788	964	86.3	98.6	W.C.	4.14	0.546	0.872	0.962
IOF-SU-2-6-2	24.00	3.0	1.50	800	988	87.6	101.1	W.C.	4.20	0.554	0.872	0.962
IOF-SU-2-7-1	17.00	4.0	SOLID	1050	1201	99.3	99.1	W.C.	3.68	0.485	1.000	1.000
IOF-SU-2-7-2	17.00	4.0	SOLID	1063	1224	100.6	100.9	W.C.	3.72	0.491	1.000	1.000
IOF-SU-2-8-1	18.00	4.0	0.00	950	---	---	---	SHEAR	---	---	---	---
IOF-SU-2-8-2	18.00	4.0	0.00	950	---	---	---	SHEAR	---	---	---	---
IOF-SU-2-9-1	18.50	6.0	SOLID	1338	1945	101.9	103.6	W.C.	5.18	0.684	1.000	1.000
IOF-SU-2-9-2	18.50	6.0	SOLID	1288	1809	98.1	96.4	W.C.	4.99	0.658	1.000	1.000
IOF-SU-2-10-1	20.00	6.0	0.00	1038	---	---	---	SHEAR	---	---	---	---
IOF-SU-2-10-2	20.00	6.0	0.00	1050	---	---	---	SHEAR	---	---	---	---
IOF-SU-3-1-1	17.00	3.0	SOLID	1975	2168	101.3	101.8	W.C.	6.91	0.445	1.000	1.000
IOF-SU-3-1-2	17.00	3.0	SOLID	1925	2089	98.7	98.1	W.C.	6.74	0.434	1.000	1.000

Table XI: Unreinforced IOF Test Results (cont.)

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State[3]	$(M_n)_{test}$ (K in) (Eq. 75)	$\frac{(M_n)_{test}}{(M_n)_{comp}}$[5]	Reduction Factor	
											S&Z[4] (Eq. 6)	Current UMR Study (Eq.77)
IOF-SU-3-2-1	17.00	3.0	0.00	1775	1862	91.0	87.5	W.C.	6.21	0.400	0.872	0.868
IOF-SU-3-2-2	17.00	3.0	0.00	1763	1845	90.4	86.7	W.C.	6.17	0.397	0.872	0.868
IOF-SU-3-3-1	28.80	3.0	0.00	1063	1162	54.5	54.6	W.C.	6.86	0.441	0.872	0.868
IOF-SU-3-3-2	28.80	3.0	0.00	1050	1142	53.8	53.6	W.C.	6.77	0.436	0.872	0.868
IOF-SU-3-4-1	20.00	3.0	0.50	1788	2056	91.7	96.6	W.C.	7.60	0.489	0.872	0.899
IOF-SU-3-4-2	20.00	3.0	0.50	1788	2056	91.7	96.6	W.C.	7.60	0.489	0.872	0.899
IOF-SU-3-5-1	22.00	3.0	1.00	1588	1819	81.4	85.4	W.C.	7.54	0.486	0.872	0.931
IOF-SU-3-5-2	22.00	3.0	1.00	1575	1796	80.8	84.4	W.C.	7.48	0.482	0.872	0.931
IOF-SU-3-6-1	24.00	3.0	1.50	1638	2023	84.0	95.1	W.C.	8.60	0.554	0.872	0.962
IOF-SU-3-6-2	24.00	3.0	1.50	1588	1924	81.4	90.4	W.C.	8.34	0.537	0.872	0.962
IOF-SU-3-7-1	17.00	4.0	SOLID	2300	2729	100.8	101.3	W.C.	8.05	0.518	1.000	1.000
IOF-SU-3-7-2	17.00	4.0	SOLID	2263	2661	99.2	98.7	W.C.	7.92	0.510	1.000	1.000
IOF-SU-3-8-1	18.00	4.0	0.00	2013	2306	88.2	85.6	W.C.	7.55	0.486	0.907	0.868
IOF-SU-3-8-2	18.00	4.0	0.00	1975	2241	86.5	83.1	W.C.	7.41	0.477	0.907	0.868

Table XI: Unreinforced IOF Test Results (cont.)

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State[3]	$(M_n)_{test}$ (K in) (Eq. 75)	$\frac{(M_n)_{test}}{(M_n)_{comp}}$ [5]	Reduction Factor: S&Z[4] (Eq. 6)	Reduction Factor: Current UMR Study (Eq.77)
IOF-SU-3-9-1	18.50	6.0	SOLID	2763	4046	100.0	100.0	W.C.	10.71	0.689	1.000	1.000
IOF-SU-3-9-2	18.50	6.0	SOLID	2763	4046	100.0	100.0	W.C.	10.71	0.689	1.000	1.000
IOF-SU-3-10-1	20.00	6.0	0.00	2075	---	---	---	SHEAR	---	---	---	---
IOF-SU-3-10-2	20.00	6.0	0.00	2063	---	---	---	SHEAR	---	---	---	---
IOF-SU-4-1-1	16.00	3.0	SOLID	1150	1218	102.2	103.1	W.C.	3.74	0.410	1.000	1.000
IOF-SU-4-1-2	16.00	3.0	SOLID	1100	1145	97.8	96.9	W.C.	3.58	0.392	1.000	1.000
IOF-SU-4-2-1	17.00	3.0	0.00	750	---	---	---	SHEAR	---	---	---	---
IOF-SU-4-2-2	17.00	3.0	0.00	750	---	---	---	SHEAR	---	---	---	
IOF-SU-4-3-1	19.00	6.0	SOLID	1550	2241	100.8	101.5	W.C.	6.20	0.680	1.000	1.000
IOF-SU-4-3-2	19.00	6.0	SOLID	1525	2173	99.2	98.4	W.C.	6.10	0.669	1.000	1.000
IOF-SU-4-4-1	20.00	6.0	0.00	850	---	---	---	SHEAR	---	---	---	---
IOF-SU-4-4-2	20.00	6.0	0.00	825	---	---	---	SHEAR	---	---	---	---

Table XI: Unreinforced IOF Test Results (cont.)

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State[3]	$(M_n)_{test}$ (K in) (Eq. 75)	$\frac{(M_n)_{test}}{(M_n)_{comp}}$[5]	Reduction Factor: S&Z[4] (Eq. 6)	Reduction Factor: Current UMR Study (Eq.77)
IOF-SU-5-1-1	18.69	3.0	SOLID	925	925	100.0	100.0	W.C.	3.63	0.258	1.000	1.000
IOF-SU-5-1-2	18.69	3.0	SOLID	925	925	100.0	100.0	W.C.	3.63	0.258	1.000	1.000
IOF-SU-5-2-1	18.69	3.0	0.00	838	838	90.6	90.6	W.C.	3.29	0.234	0.871	0.838
IOF-SU-5-2-2	18.69	3.0	0.00	825	825	89.2	89.2	W.C.	3.24	0.230	0.871	0.838
IOF-SU-5-3-1	28.80	3.0	0.00	675	675	73.0	73.0	W.C.	4.35	0.310	0.871	0.838
IOF-SU-5-3-2	28.80	3.0	0.00	675	675	73.0	73.0	W.C.	4.35	0.310	0.871	0.838
IOF-SU-5-4-1	21.00	3.0	0.50	838	838	90.6	90.6	W.C.	3.77	0.268	0.871	0.869
IOF-SU-5-4-2	21.00	3.0	0.50	863	863	93.3	93.3	W.C.	3.88	0.276	0.871	0.869
IOF-SU-5-5-1	22.00	3.0	0.70	838	838	90.6	90.6	W.C.	3.98	0.283	0.871	0.882
IOF-SU-5-5-2	22.00	3.0	0.70	863	863	93.3	93.3	W.C.	4.10	0.292	0.871	0.882
IOF-SU-5-6-1	24.00	3.0	1.00	813	813	87.9	87.9	W.C.	4.27	0.304	0.871	0.901
IOF-SU-5-6-2	24.00	3.0	1.00	788	788	85.2	85.2	W.C.	4.14	0.294	0.871	0.901
IOF-SU-5-7-1	27.00	3.0	1.50	688	688	74.4	94.4	W.C.	4.13	0.294	0.871	0.932
IOF-SU-5-7-2	27.00	3.0	1.50	738	738	79.8	79.8	W.C.	4.43	0.315	0.871	0.932

Table XI: Unreinforced IOF Test Results (cont.)

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State[3]	$(M_n)_{test}$ (K in) (Eq. 75)	$\frac{(M_n)_{test}}{(M_n)_{comp}^{(5)}}$	Reduction Factor: S&Z[4] (Eq. 6)	Reduction Factor: Current UMR Study (Eq.77)
IOF-SU-5-8-1	20.00	4.0	SOLID	963	963	99.4	99.4	W.C.	4.09	0.291	1.000	1.000
IOF-SU-5-8-2	20.00	4.0	SOLID	975	975	100.6	100.6	W.C.	4.14	0.295	1.000	1.000
IOF-SU-5-9-1	20.00	4.0	0.00	863	863	89.1	89.1	W.C.	3.67	0.261	0.898	0.838
IOF-SU-5-9-2	20.00	4.0	0.00	888	888	91.6	91.6	W.C.	3.77	0.268	0.898	0.838
IOF-SU-5-10-1	25.00	4.0	0.00	850	850	87.7	87.7	W.C.	4.68	0.332	0.898	0.838
IOF-SU-5-10-2	25.00	4.0	0.00	825	825	85.1	85.1	W.C.	4.54	0.323	0.898	0.838
IOF-SU-5-11-1	21.69	6.0	SOLID	1125	1151	98.9	98.4	W.C.	5.26	0.374	1.000	1.000
IOF-SU-5-11-2	21.69	6.0	SOLID	1150	1186	100.1	101.4	W.C.	5.37	0.382	1.000	1.000
IOF-SU-5-12-1	22.00	6.0	0.00	1100	1123	96.7	96.0	W.C.	5.23	0.372	0.925	0.838
IOF-SU-5-12-2	22.00	6.0	0.00	1075	1088	94.5	93.1	W.C.	5.11	0.363	0.925	0.838
IOF-SU-6-1-1	18.78	3.0	SOLID	1438	1438	102.6	102.6	W.C.	5.67	0.302	1.000	1.000
IOF-SU-6-1-2	18.78	3.0	SOLID	1363	1363	97.3	97.3	W.C.	5.38	0.287	1.000	1.000
IOF-SU-6-2-1	18.78	3.0	0.00	1188	1188	84.8	84.8	W.C.	4.69	0.250	0.872	0.839

Table XI: Unreinforced IOF Test Results (cont.)

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State[3]	$(M_n)_{test}$ (K in) (Eq. 75)	$\frac{(M_n)_{test}}{(M_n)_{comp}}$[5]	Reduction Factor	
											S&Z[4] (Eq. 6)	Current UMR Study (Eq.77)
IOF-SU-6-2-2	18.78	3.0	0.00	1200	1200	85.7	85.7	W.C.	4.73	0.252	0.872	0.839
IOF-SU-6-3-1	25.00	3.0	0.00	1150	1150	82.1	82.1	W.C.	6.33	0.337	0.872	0.839
IOF-SU-6-3-2	25.00	3.0	0.00	1138	1138	81.2	81.2	W.C.	6.26	0.334	0.872	0.839
IOF-SU-6-4-1	28.80	3.0	0.00	988	988	70.5	70.5	W.C.	6.37	0.340	0.872	0.839
IOF-SU-6-4-2	28.80	3.0	0.00	988	988	70.5	70.5	W.C.	6.37	0.340	0.872	0.839
IOF-SU-6-5-1	21.00	3.0	0.50	1225	1225	87.4	87.4	W.C.	5.51	0.294	0.872	0.870
IOF-SU-6-5-2	21.00	3.0	0.50	1205	1205	86.0	86.0	W.C.	5.42	0.289	0.872	0.870
IOF-SU-6-6-1	25.00	3.0	0.50	1188	1188	84.8	84.8	W.C.	6.53	0.348	0.872	0.870
IOF-SU-6-6-2	25.00	3.0	0.50	1163	1163	83.0	83.0	W.C.	6.40	0.341	0.872	0.870
IOF-SU-6-7-1	22.00	3.0	0.70	1250	1250	89.2	89.2	W.C.	5.94	0.317	0.872	0.883
IOF-SU-6-7-2	22.00	3.0	0.70	1238	1238	88.4	88.4	W.C.	5.88	0.314	0.872	0.883
IOF-SU-6-8-1	25.00	3.0	0.70	1188	1188	84.8	84.8	W.C.	6.53	0.348	0.872	0.883
IOF-SU-6-8-2	25.00	3.0	0.70	1138	1138	81.2	81.2	W.C.	6.26	0.334	0.872	0.883
IOF-SU-6-9-1	24.00	3.0	1.00	1225	1225	87.4	87.4	W.C.	6.43	0.343	0.872	0.902

Table XI: Unreinforced IOF Test Results (cont.)

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State[3]	$(M_n)_{test}$ (K in) (Eq. 75)	$\frac{(M_n)_{test}}{(M_n)_{comp}}$[5]	Reduction Factor S&Z[4] (Eq. 6)	Reduction Factor Current UMR Study (Eq.77)
IOF-SU-6-9-2	24.00	3.0	1.00	1250	1250	89.2	89.2	W.C.	6.56	0.350	0.872	0.902
IOF-SU-6-10-1	27.00	3.0	1.50	1213	1258	86.6	89.8	W.C.	7.28	0.388	0.872	0.933
IOF-SU-6-10-2	27.00	3.0	1.50	1238	1294	88.4	92.3	W.C.	7.43	0.396	0.872	0.933
IOF-SU-6-11-1	20.00	4.0	SOLID	1375	1375	100.4	100.4	W.C.	5.84	0.312	1.000	1.000
IOF-SU-6-11-2	20.00	4.0	SOLID	1363	1363	99.6	99.6	W.C.	5.79	0.309	1.000	1.000
IOF-SU-6-12-1	20.00	4.0	0.00	1338	1338	97.7	97.7	W.C.	5.69	0.303	0.900	0.839
IOF-SU-6-12-2	20.00	4.0	0.00	1313	1313	95.9	95.9	W.C.	5.58	0.298	0.900	0.839
IOF-SU-6-13-1	25.00	4.0	0.00	1238	1253	90.4	91.5	W.C.	6.81	0.363	0.900	0.839
IOF-SU-6-13-2	25.00	4.0	0.00	1250	1270	91.3	92.7	W.C.	6.88	0.367	0.900	0.839
IOF-SU-6-14-1	21.78	6.0	SOLID	1725	1868	100.5	102.1	W.C.	8.10	0.434	1.000	1.000
IOF-SU-6-14-2	21.78	6.0	SOLID	1675	1791	98.5	97.9	W.C.	7.86	0.419	1.000	1.000
IOF-SU-6-15-1	22.00	6.0	0.00	1638	1744	96.4	95.3	W.C.	7.78	0.415	0.926	0.839
IOF-SU-6-15-2	22.00	6.0	0.00	1600	1687	94.1	92.2	W.C.	7.60	0.405	0.926	0.839

Table XI: Unreinforced IOF Test Results (cont.)

Specimen Number[2]	L[1] (in.)	N[1] (in.)	α[1]	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State[3]	$(M_n)_{test}$ (K in) (Eq. 75)	$\frac{(M_n)_{test}}{(M_n)_{comp}}$[5]	Reduction Factor S&Z[4] (Eq. 6)	Reduction Factor Current UMR Study (Eq.77)
IOF-SU-7-1-1	18.76	3.0	SOLID	1888	1888	N/A	N/A	W.C.	7.44	0.348	1.000	1.000
IOF-SU-7-1-2	18.76	3.0	SOLID	1938	1952	N/A	N/A	W.C.	7.64	0.357	1.000	1.000
IOF-SU-7-2-1	20.00	3.0	SOLID	1913	1969	N/A	N/A	W.C.	8.13	0.381	1.000	1.000
IOF-SU-7-2-2	20.00	3.0	SOLID	1875	1916	N/A	N/A	W.C.	7.97	0.373	1.000	1.000
IOF-SU-7-3-1	22.00	3.0	SOLID	1875	2000	N/A	N/A	W.C.	8.91	0.417	1.000	1.000
IOF-SU-7-3-2	22.00	3.0	SOLID	1800	1889	N/A	N/A	W.C.	8.55	0.400	1.000	1.000
IOF-SU-7-4-1	24.00	3.0	SOLID	2175	2628	N/A	N/A	W.C.	11.42	0.535	1.000	1.000
IOF-SU-7-4-2	24.00	3.0	SOLID	2175	2628	N/A	N/A	W.C.	11.42	0.535	1.000	1.000
IOF-SU-7-5-1	26.00	3.0	SOLID	2100	2629	N/A	N/A	W.C.	12.08	0.565	1.000	1.000
IOF-SU-7-5-2	26.00	3.0	SOLID	2138	2709	N/A	N/A	W.C.	12.29	0.576	1.000	1.000
IOF-SU-8-1-1	18.66	3.0	SOLID	2950	3124	98.7	98.2	W.C.	11.55	0.409	1.000	1.000
IOF-SU-8-1-2	18.66	3.0	SOLID	3025	3236	101.2	101.8	W.C.	11.84	0.420	1.000	1.000
IOF-SU-8-2-1	18.66	3.0	0.00	2675	2729	89.5	85.8	W.C.	10.47	0.371	0.870	0.837

Table XI: Unreinforced IOF Test Results (cont.)

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State[3]	$(M_n)_{test}$ (K in) (Eq. 75)	$\frac{(M_n)_{test}}{(M_n)_{comp}}$ [5]	Reduction Factor: S&Z[4] (Eq. 6)	Reduction Factor: Current UMR Study (Eq.77)
IOF-SU-8-2-2	18.66	3.0	0.00	2688	2747	90.0	86.4	W.C.	10.52	0.373	0.870	0.837
IOF-SU-8-3-1	28.80	3.0	0.00	1988	2203	66.5	69.3	W.C.	12.82	0.455	0.870	0.837
IOF-SU-8-3-2	28.80	3.0	0.00	1950	2142	65.3	67.4	W.C.	12.58	0.446	0.870	0.837
IOF-SU-8-4-1	21.00	3.0	0.50	2813	3099	94.1	97.5	W.C.	12.66	0.449	0.870	0.869
IOF-SU-8-4-2	21.00	3.0	0.50	2775	3038	92.9	95.5	W.C.	12.49	0.443	0.870	0.869
IOF-SU-8-5-1	22.00	3.0	0.70	2788	3139	93.3	98.7	W.C.	13.24	0.470	0.870	0.881
IOF-SU-8-5-2	22.00	3.0	0.70	2738	3055	91.6	96.1	W.C.	13.01	0.461	0.870	0.881
IOF-SU-8-6-1	24.00	3.0	1.00	2713	3172	90.8	99.8	W.C.	14.24	0.505	0.870	0.900
IOF-SU-8-6-2	24.00	3.0	1.00	2738	3218	91.6	101.2	W.C.	14.37	0.510	0.870	0.900
IOF-SU-8-7-1	27.00	3.0	1.50	2650	3311	88.7	104.1	W.C.	15.90	0.564	0.870	0.932
IOF-SU-8-7-2	27.00	3.0	1.50	2600	3209	87.0	100.9	W.C.	15.60	0.553	0.870	0.932
IOF-SU-8-8-1	21.66	6.0	SOLID	3613	4700	99.3	98.8	W.C.	16.85	0.598	1.000	1.000
IOF-SU-8-8-2	21.66	6.0	SOLID	3663	4814	100.7	101.2	W.C.	17.09	0.606	1.000	1.000
IOF-SU-8-9-1	22.00	6.0	0.00	3213	3911	88.3	82.2	W.C.	15.26	0.541	0.925	0.837

Table XI: Unreinforced IOF Test Results (cont.)

Specimen Number[2]	L[1] (in.)	N[1] (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State[3]	$(M_n)_{test}$ (K in) (Eq. 75)	$(M_n)_{test}$ / $(M_n)_{comp}$[5]	Reduction Factor S&Z[4] (Eq. 6)	Reduction Factor Current UMR Study (Eq.77)
IOF-SU-8-9-2	22.00	6.0	0.00	3150	3789	86.6	79.7	W.C.	14.96	0.530	0.925	0.837
IOF-SU-9-1-1	25.62	3.0	SOLID	1800	1800	101.8	101.8	W.C.	10.18	0.328	1.000	1.000
IOF-SU-9-1-2	25.62	3.0	SOLID	1738	1738	98.2	98.2	W.C.	9.83	0.317	1.000	1.000
IOF-SU-9-2-1	25.62	3.0	0.00	1675	1675	94.7	94.7	W.C.	9.47	0.305	0.945	0.890
IOF-SU-9-2-2	25.62	3.0	0.00	1638	1638	92.6	92.6	W.C.	9.26	0.299	0.945	0.890
IOF-SU-9-3-1	25.62	3.0	0.50	1625	1625	91.9	91.9	W.C.	9.19	0.296	0.945	0.922
IOF-SU-9-3-2	25.62	3.0	0.50	1613	1613	91.2	91.2	W.C.	9.12	0.294	0.945	0.922
IOF-SU-9-4-1	28.40	3.0	1.00	1650	1650	93.3	93.3	W.C.	10.48	0.338	0.945	0.953
IOF-SU-9-4-2	28.40	3.0	1.00	1613	1613	91.2	91.2	W.C.	10.24	0.330	0.945	0.953
IOF-SU-10-1-1	31.62	3.0	SOLID	2263	2263	98.9	98.9	W.C.	16.19	0.278	1.000	1.000
IOF-SU-10-1-2	31.62	3.0	SOLID	2313	2313	101.1	101.1	W.C.	16.55	0.285	1.000	1.000
IOF-SU-10-2-1	31.62	3.0	0.00	2238	2238	97.8	97.8	W.C.	16.01	0.275	0.968	0.910

Table XI: Unreinforced IOF Test Results (cont.)

Specimen Number[2]	$L^{(1)}$ (in.)	$N^{(1)}$ (in.)	$\alpha^{(1)}$	$(P_n)_{test}$ (lbs.)	$(P_n)_{test,adj}$ (lbs.) (Eq. 74)	PSW	PSW_{adj}	Limit State[3]	$(M_n)_{test}$ (K in) (Eq. 75)	$\frac{(M_n)_{test}}{(M_n)_{comp}}$ [5]	Reduction Factor	
											S&Z[4] (Eq. 6)	Current UMR Study (Eq.77)
IOF-SU-10-2-2	31.62	3.0	0.00	2175	2175	95.1	95.1	W.C.	15.56	0.268	0.968	0.910
IOF-SU-10-3-1	31.62	3.0	0.50	2263	2263	98.9	98.9	W.C.	16.19	0.278	0.968	0.941
IOF-SU-10-3-2	31.62	3.0	0.50	2163	2163	94.5	94.5	W.C.	15.48	0.266	0.968	0.941

Notes:
1. See Figures 2 and 4 for definition of dimensions.
2. Cross-section designations:
   IOF: Interior-One-Flange loading condition, SU: Single Unreinforced web
   IOF-SU-cross section number-specimen number
3. Limit State: W.C. is Web Crippling
4. Reduction Factor: S&Z is Sivakumaran and Zielonka (1989)
5. $(M_n)_{comp}$ is from Procedure I: Initiation of Yielding. See Table II for values.

Table XII: Analysis of Unreinforced IOF Test Results

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-1-1-1	5425	5425	5425	1.066	1.066	1.066	1.471
IOF-SU-1-1-2	5425	5425	5425	1.120	1.120	1.120	1.545
IOF-SU-1-2-1	5425	5342	5038	1.124	1.142	1.211	1.643
IOF-SU-1-2-2	5425	5342	5038	1.106	1.123	1.191	1.617
IOF-SU-2-1-1	974	974	974	1.024	1.024	1.024	1.444
IOF-SU-2-1-2	974	974	974	0.985	0.985	0.985	1.405
IOF-SU-2-2-1	974	849	845	0.872	1.001	1.005	1.426
IOF-SU-2-2-2	974	849	845	0.891	1.023	1.027	1.448
IOF-SU-2-3-1	974	849	845	0.703	0.806	0.810	1.245
IOF-SU-2-3-2	974	849	845	0.679	0.779	0.782	1.217
IOF-SU-2-4-1	974	849	876	0.905	1.038	1.006	1.426
IOF-SU-2-4-2	974	849	876	0.927	1.063	1.030	1.449

Table XII: Analysis of Unreinforced IOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-2-5-1	974	849	906	0.981	1.126	1.054	1.469
IOF-SU-2-5-2	974	849	906	0.981	1.126	1.054	1.469
IOF-SU-2-6-1	974	849	937	0.990	1.136	1.029	1.445
IOF-SU-2-6-2	974	849	937	1.015	1.165	1.055	1.467
IOF-SU-2-7-1	1162	1162	1162	1.034	1.034	1.034	1.452
IOF-SU-2-7-2	1162	1162	1162	1.054	1.054	1.054	1.470
IOF-SU-2-9-1	1537	1537	1537	1.265	1.265	1.265	1.615
IOF-SU-2-9-2	1537	1537	1537	1.177	1.177	1.177	1.555
IOF-SU-3-1-1	2696	2696	2696	0.804	0.804	0.804	1.229
IOF-SU-3-1-2	2696	2696	2696	0.775	0.775	0.775	1.198
IOF-SU-3-2-1	2696	2350	2340	0.691	0.792	0.796	1.212
IOF-SU-3-2-2	2696	2350	2340	0.684	0.785	0.788	1.204

Table XII: Analysis of Unreinforced IOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-3-3-1	2696	2350	2340	0.431	0.495	0.497	0.928
IOF-SU-3-3-2	2696	2350	2340	0.424	0.486	0.488	0.916
IOF-SU-3-4-1	2696	2350	2425	0.762	0.875	0.848	1.278
IOF-SU-3-4-2	2696	2350	2425	0.762	0.875	0.848	1.278
IOF-SU-3-5-1	2696	2350	2510	0.675	0.774	0.725	1.163
IOF-SU-3-5-2	2696	2350	2510	0.666	0.764	0.716	1.153
IOF-SU-3-6-1	2696	2350	2595	0.750	0.861	0.780	1.229
IOF-SU-3-6-2	2696	2350	2595	0.714	0.819	0.742	1.192
IOF-SU-3-7-1	3024	3024	3024	0.902	0.902	0.902	1.332
IOF-SU-3-7-2	3024	3024	3024	0.880	0.880	0.880	1.311
IOF-SU-3-8-1	3024	2742	2624	0.763	0.841	0.879	1.307
IOF-SU-3-8-2	3024	2742	2624	0.741	0.817	0.854	1.282
IOF-SU-3-9-1	3805	3805	3805	1.064	1.064	1.064	1.466

Table XII: Analysis of Unreinforced IOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-3-9-2	3805	3805	3805	1.064	1.064	1.064	1.466
IOF-SU-4-1-1	1143	1143	1143	1.066	1.066	1.066	1.486
IOF-SU-4-1-2	1143	1143	1143	1.002	1.002	1.002	1.422
IOF-SU-4-3-1	1796	1796	1796	1.248	1.248	1.248	1.603
IOF-SU-4-3-2	1796	1796	1796	1.210	1.210	1.210	1.577
IOF-SU-5-1-1	1018	1018	1018	0.908	0.908	0.908	1.230
IOF-SU-5-1-2	1018	1018	1018	0.908	0.908	0.908	1.230
IOF-SU-5-2-1	1018	886	853	0.823	0.945	0.982	1.285
IOF-SU-5-2-2	1018	886	853	0.810	0.931	0.967	1.265
IOF-SU-5-3-1	1018	886	853	0.663	0.726	0.791	1.156
IOF-SU-5-3-2	1018	886	853	0.663	0.726	0.791	1.156

Table XII: Analysis of Unreinforced IOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-5-4-1	1018	886	885	0.823	0.945	0.947	1.281
IOF-SU-5-4-2	1018	886	885	0.848	0.974	0.975	1.319
IOF-SU-5-5-1	1018	886	898	0.823	0.945	0.933	1.282
IOF-SU-5-5-2	1018	886	898	0.848	0.974	0.961	1.320
IOF-SU-5-6-1	1018	886	917	0.798	0.917	0.886	1.252
IOF-SU-5-6-2	1018	886	917	0.774	0.889	0.859	1.213
IOF-SU-5-7-1	1018	886	949	0.676	0.776	0.725	1.069
IOF-SU-5-7-2	1018	886	949	0.725	0.833	0.777	1.147
IOF-SU-5-8-1	1212	1212	1212	0.794	0.794	0.794	1.141
IOF-SU-5-8-2	1212	1212	1212	0.804	0.804	0.804	1.155
IOF-SU-5-9-1	1212	1089	1015	0.712	0.793	0.850	1.170
IOF-SU-5-9-2	1212	1089	1015	0.733	0.816	0.874	1.204
IOF-SU-5-10-1	1212	1089	1015	0.701	0.781	0.837	1.228

Table XII: Analysis of Unreinforced IOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-5-10-2	1212	1089	1015	0.681	0.758	0.812	1.192
IOF-SU-5-11-1	1600	1600	1600	0.719	0.719	0.719	1.126
IOF-SU-5-11-2	1600	1600	1600	0.741	0.741	0.741	1.151
IOF-SU-5-12-1	1600	1479	1340	0.702	0.759	0.838	1.250
IOF-SU-5-12-2	1600	1479	1340	0.680	0.736	0.812	1.221
IOF-SU-6-1-1	1726	1726	1726	0.833	0.833	0.833	1.194
IOF-SU-6-1-2	1726	1726	1726	0.790	0.790	0.790	1.132
IOF-SU-6-2-1	1726	1506	1448	0.688	0.789	0.820	1.128
IOF-SU-6-2-2	1726	1506	1448	0.695	0.797	0.829	1.139
IOF-SU-6-3-1	1726	1506	1448	0.666	0.764	0.794	1.187
IOF-SU-6-3-2	1726	1506	1448	0.659	0.756	0.786	1.175
IOF-SU-6-4-1	1726	1506	1448	0.572	0.656	0.682	1.070

Table XII: Analysis of Unreinforced IOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-6-4-2	1726	1506	1448	0.572	0.656	0.682	1.070
IOF-SU-6-5-1	1726	1506	1502	0.710	0.814	0.815	1.166
IOF-SU-6-5-2	1726	1506	1502	0.698	0.800	0.802	1.147
IOF-SU-6-6-1	1726	1506	1502	0.688	0.789	0.791	1.195
IOF-SU-6-6-2	1726	1506	1502	0.674	0.772	0.774	1.169
IOF-SU-6-7-1	1726	1506	1524	0.724	0.830	0.820	1.194
IOF-SU-6-7-2	1726	1506	1524	0.717	0.822	0.812	1.183
IOF-SU-6-8-1	1726	1506	1524	0.688	0.789	0.779	1.182
IOF-SU-6-8-2	1726	1506	1524	0.659	0.756	0.747	1.133
IOF-SU-6-9-1	1726	1506	1557	0.710	0.814	0.787	1.185
IOF-SU-6-9-2	1726	1506	1557	0.724	0.830	0.803	1.209
IOF-SU-6-10-1	1726	1506	1611	0.729	0.835	0.781	1.194
IOF-SU-6-10-2	1726	1506	1611	0.750	0.859	0.803	1.218

Table XII: Analysis of Unreinforced IOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-6-11-1	2011	2011	2011	0.684	0.684	0.684	1.043
IOF-SU-6-11-2	2011	2011	2011	0.678	0.678	0.678	1.034
IOF-SU-6-12-1	2011	1809	1687	0.666	0.740	0.793	1.152
IOF-SU-6-12-2	2011	1809	1687	0.653	0.726	0.779	1.131
IOF-SU-6-13-1	2011	1809	1687	0.623	0.693	0.743	1.149
IOF-SU-6-13-2	2011	1809	1687	0.632	0.702	0.753	1.160
IOF-SU-6-14-1	2579	2579	2579	0.724	0.724	0.724	1.147
IOF-SU-6-14-2	2579	2579	2579	0.694	0.694	0.694	1.114
IOF-SU-6-15-1	2579	2388	2164	0.676	0.730	0.806	1.225
IOF-SU-6-15-2	2579	2388	2164	0.654	0.706	0.780	1.196
IOF-SU-7-1-1	1817	1817	1817	1.039	1.039	1.039	1.460
IOF-SU-7-1-2	1817	1817	1817	1.074	1.074	1.074	1.499

Table XII: Analysis of Unreinforced IOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-7-2-1	1817	1817	1817	1.084	1.084	1.084	1.507
IOF-SU-7-2-2	1817	1817	1817	1.055	1.055	1.055	1.477
IOF-SU-7-3-1	1817	1817	1817	1.101	1.101	1.101	1.521
IOF-SU-7-3-2	1817	1817	1817	1.040	1.040	1.040	1.460
IOF-SU-7-4-1	1817	1817	1817	1.447	1.447	1.447	1.815
IOF-SU-7-4-2	1817	1817	1817	1.447	1.447	1.447	1.815
IOF-SU-7-5-1	1817	1817	1817	1.447	1.447	1.447	1.802
IOF-SU-7-5-2	1817	1817	1817	1.491	1.491	1.491	1.835
IOF-SU-8-1-1	3571	3571	3571	0.875	0.875	0.875	1.293
IOF-SU-8-1-2	3571	3571	3571	0.906	0.906	0.906	1.326
IOF-SU-8-2-1	3571	3106	2990	0.764	0.879	0.913	1.329
IOF-SU-8-2-2	3571	3106	2990	0.769	0.884	0.919	1.335

Table XII: Analysis of Unreinforced IOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-8-3-1	3571	3106	2990	0.617	0.709	0.737	1.166
IOF-SU-8-3-2	3571	3106	2990	0.600	0.690	0.716	1.144
IOF-SU-8-4-1	3571	3106	3102	0.868	0.998	0.999	1.419
IOF-SU-8-4-2	3571	3106	3102	0.851	0.978	0.979	1.400
IOF-SU-8-5-1	3571	3106	3147	0.879	1.010	0.997	1.417
IOF-SU-8-5-2	3571	3106	3147	0.856	0.984	0.971	1.392
IOF-SU-8-6-1	3571	3106	3215	0.889	1.021	0.987	1.408
IOF-SU-8-6-2	3571	3106	3215	0.901	1.036	1.001	1.421
IOF-SU-8-7-1	3571	3106	3328	0.927	1.066	0.995	1.416
IOF-SU-8-7-2	3571	3106	3328	0.899	1.033	0.964	1.389
IOF-SU-8-8-1	4717	4717	4717	0.997	0.997	0.997	1.417
IOF-SU-8-8-2	4717	4717	4717	1.021	1.021	1.021	1.437
IOF-SU-8-9-1	4717	4361	3949	0.829	0.897	0.990	1.412

Table XII: Analysis of Unreinforced IOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-8-9-2	4717	4361	3949	0.803	0.869	0.959	1.384
IOF-SU-9-1-1	1036	1036	1036	1.738	1.738	1.738	2.188
IOF-SU-9-1-2	1036	1036	1036	1.678	1.678	1.678	2.112
IOF-SU-9-2-1	1036	979	922	1.617	1.711	1.816	2.249
IOF-SU-9-2-2	1036	979	922	1.582	1.673	1.776	2.199
IOF-SU-9-3-1	1036	979	955	1.569	1.660	1.702	2.117
IOF-SU-9-3-2	1036	979	955	1.557	1.648	1.689	2.102
IOF-SU-9-4-1	1036	979	988	1.593	1.686	1.671	2.126
IOF-SU-9-4-2	1036	979	988	1.557	1.648	1.633	2.078
IOF-SU-10-1-1	1711	1711	1711	1.322	1.322	1.322	1.693
IOF-SU-10-1-2	1711	1711	1711	1.351	1.351	1.351	1.731

Table XII: Analysis of Unreinforced IOF Test Results (cont.)

Specimen Number[1]	Nominal Capacity $(P_n)_{comp}$ (lbs.)			$(P_n)_{test\ adj}/(P_n)_{comp}$			Interaction Equation Value (Eq.43)
	AISI Provisions (Eqs. 34 & 35)	Reduced		AISI Provisions (Eqs. 34 & 35)	Reduced		
		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)		S&Z[2] (Eq. 6)	Current UMR Study (Eq. 77)	
IOF-SU-10-2-1	1711	1656	1557	1.308	1.352	1.437	1.813
IOF-SU-10-2-2	1711	1656	1557	1.271	1.314	1.397	1.762
IOF-SU-10-3-1	1711	1656	1611	1.322	1.367	1.405	1.781
IOF-SU-10-3-2	1711	1656	1611	1.264	1.306	1.342	1.703

Statistical analysis is given on the next two pages.

Table XII: Analysis of Unreinforced IOF Results (cont.)

	$(P_n)_{test\ adj}/(P_n)_{comp}$		
	AISI Provisions (Eqs. 34 & 35)	Reduced Capacity	
		Sivakumaran and Zielonka (Eq. 6)	Current UMR Study (Eq. 77)
STATISTICS: ALL TEST SPECIMENS: $n^{(3)}$= 138			
MEAN	0.907	0.972	0.976
STANDARD DEVIATION	0.275	0.261	0.265
COEFFICIENT OF VARIATION	0.303	0.268	0.272
Φ	0.569	0.652	0.650
$(F.S.)_{LRFD}$	2.696	2.351	2.359
STATISTICS: F_y less than 70 ksi: $n^{(3)}$ = 124			
MEAN	0.842	0.908	0.909
STANDARD DEVIATION	0.200	0.181	0.175
COEFFICIENT OF VARIATION	0.237	0.199	0.193
Φ	0.598	0.688	0.696
$(F.S.)_{LRFD}$	2.564	2.228	2.204
STATISTICS: Solid web specimens with F_y less than 70.0 ksi: $n^{(3)}$ = 44			
MEAN	1.001	1.001	1.001
STANDARD DEVIATION	0.210	0.210	0.210
COEFFICIENT OF VARIATION	0.210	0.210	0.210
Φ	0.741	0.741	0.741
$(F.S.)_{LRFD}$	2.070	2.070	2.070

Table XII: Analysis of Unreinforced IOF Results (cont.)

Statistical Analysis of Eq. 43 for the interaction value for all test specimens: Mean = 1.373 Standard deviation = 0.270 Coefficient of variation = 0.197 Mean / 1.42 = 0.967
Notes: 1. Cross section designations: IOF: Interior-One-Flange loading condition SU: Single Unreinforced web IOF-SU-cross section number-specimen designation 2. S&Z is Sivakumaran and Zielonka (1989) 3. n = number of tests

Mid-span flexural failures become significantly more likely as the value of α, and hence the value of L, is increased. Therefore, the highest α value used in the test procedure was limited to 1.5.

The length of the specimen, L, and the horizontal clear distance of the web opening to the mid-span loading plate, x', are extraneous parameters to IOF web crippling behavior. Specifically, they are required parameters for the test specimen configuration, but in practice, they have no influence on the web crippling behavior. Furthermore, the parameter x' did not apply to the previous IOF web crippling research on sections with web openings by Yu and Davis (1973) and Sivakumaran and Zielonka (1989). Both of these investigations were performed for the IOF loading condition with the web opening centered on the mid-span IOF loading plate. Furthermore, as provided in the review of the investigations by Yu and Davis (1973) and Sivakumaran and Zielonka (1989), (Section II.C), bending moment was not significant. This was primarily because of the short specimen lengths. The test specimens used in their investigations satisfied Equation 72, but did not have to satisfy Equation 73.

Based on the determination from the EOF diagnostic tests provided in Section III (Table VII), the effect of L and x′ was assumed not to effect the IOF web crippling behavior in the absence of bending moment.

2. Test Setup. To stabilize the specimens against lateral-torsional buckling, each test specimen consisted of two C-shaped sections inter-connected by 3/4 x 3/4 x 1/8 inch angles using self-drilling screws. This is the same 'dual-section' test specimen configuration used in previous web crippling research for single web sections with or without web openings as conducted by Yu and Davis (1973), Hetrakul and Yu (1978), Sivakumaran and Zielonka (1989), and in Section III for the EOF unreinforced web opening study.

To prevent web crippling at the ends of the span due to an end reaction loading, stiffeners were attached vertically on the webs of both sections at the ends of the span (Fig. 4). Using a Tinius-Olson testing machine (Fig. 11), a concentrated load was applied at mid-span to the IOF loading plate of length N in contact with the top flanges of the test specimen. The end-of-span reactions were introduced to the specimen by three inch bearing plates flush with the ends of the specimen. Rollers were placed at the centerline of the end bearing reactions to achieve a simple support condition.

3. Test Procedure. The load was applied to the test specimens in a quasi-static manner until the specimen failed. Failure was defined when the specimen could carry no additional load. For many tests, the load was maintained for a duration after failure as the testing machine continued to cause the specimen to deflect. None of the specimens exhibited a subsequent increase in stiffness due to any post-buckling strength or strain hardening. Two identical tests were conducted for each of the test specimens. Duplicate tests on identical specimens are identified by the specimen number designations in Tables XI and XII.

The evaluation of the load application rate performed for the EOF loading condition tests (Section III and Table VII) was assumed applicable to the IOF loading condition. Therefore, the load application procedure used by Hetrakul and Yu (1978) for the development of the existing AISI Specification web crippling provisions and the procedure used in the current investigation were assumed equivalent in their effect on IOF web crippling behavior.

D. TEST RESULTS

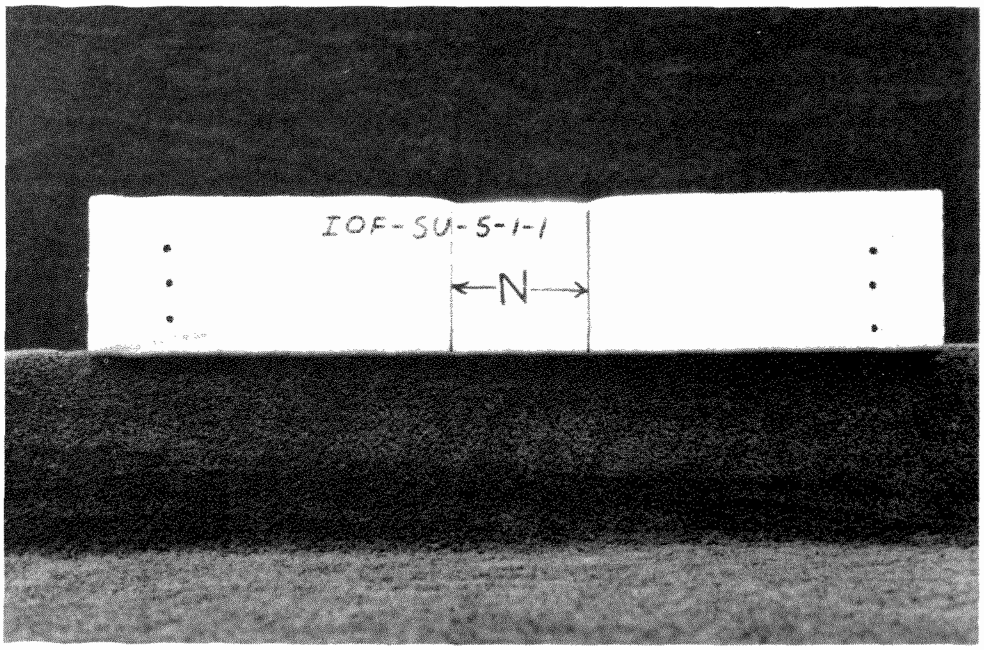
1. General. One-hundred-forty-eight unreinforced web IOF tests were conducted. Of these, 138 are valid for web

crippling analysis and 10 failed in shear. No specimens failed in pure bending without significant IOF web crippling deformation.

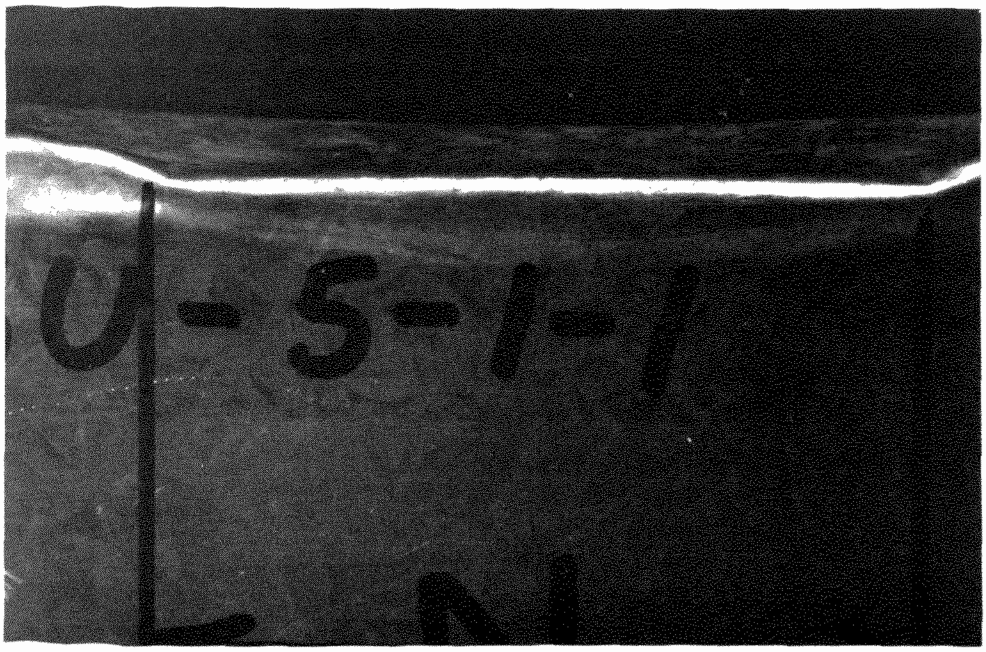
The tested failure load per web, $(P_n)_{test}$, for all tests is given in Table XI. The tested failure load per web is 1/2 of the applied mid-span load at failure. The specimens with web openings were not symmetric about the mid-span load due to the presence of a web opening in one-half of the specimen. However, from a first order static analysis of the determinate simply supported test specimens, it is assumed that the value of $(P_n)_{test}$ is equal to 1/2 of the mid-span applied load, i.e. each section of the dual-section test specimens equally shared one-half of the load applied to the mid-span load plate. Furthermore, because of the quasi-static nature of the loading, none of the applied load is assumed to be resisted by inertial forces.

2. Typical Failures. Typical web crippling and shear failures of the unreinforced IOF test specimens are shown in Figures 26 thru 36. For Figures 27 thru 36, one of the two C-shaped sections comprising the specimen is shown after testing with the end-of-span reaction web stiffeners removed. The figures state the specimen number, therefore, Tables I, XI, and XII can be referenced for the specimen parameters.

Figure 27 shows a typical web crippling failure of a solid web test specimen. Figures 28, 29, 30, and 31 show typical web crippling failures of test specimens with α



(a)



(b)

Figure 27: Typical Unreinforced IOF Solid Web Crippling Failure, IOF-SU-5-1-1

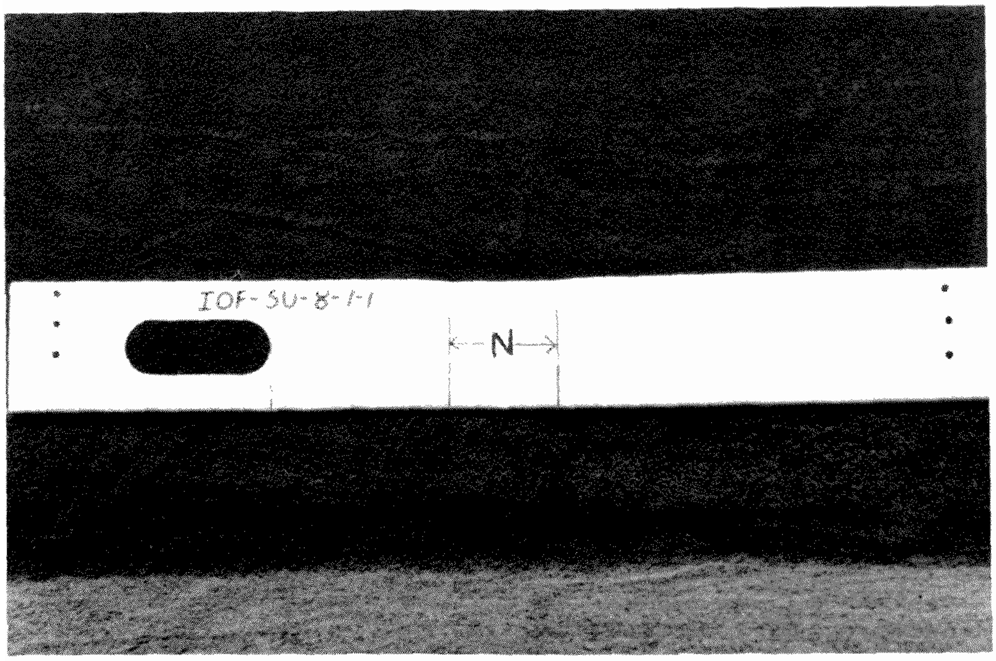


Figure 28: Typical Unreinforced IOF Web Crippling Failure, IOF-SU-8-7-1

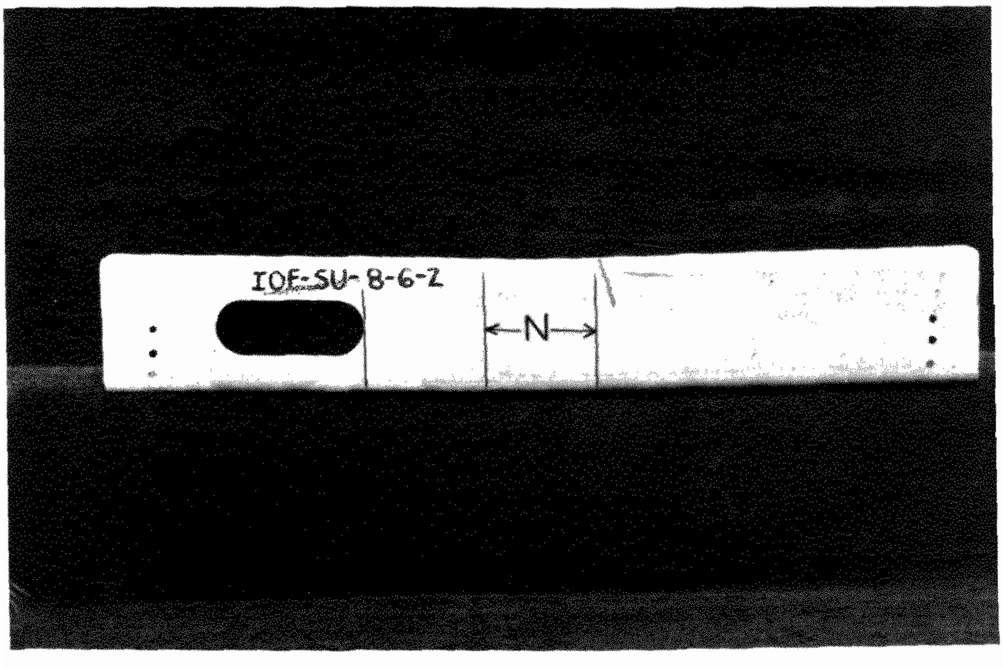


Figure 29: Typical Unreinforced IOF Web Crippling Failure, IOF-SU-8-6-2

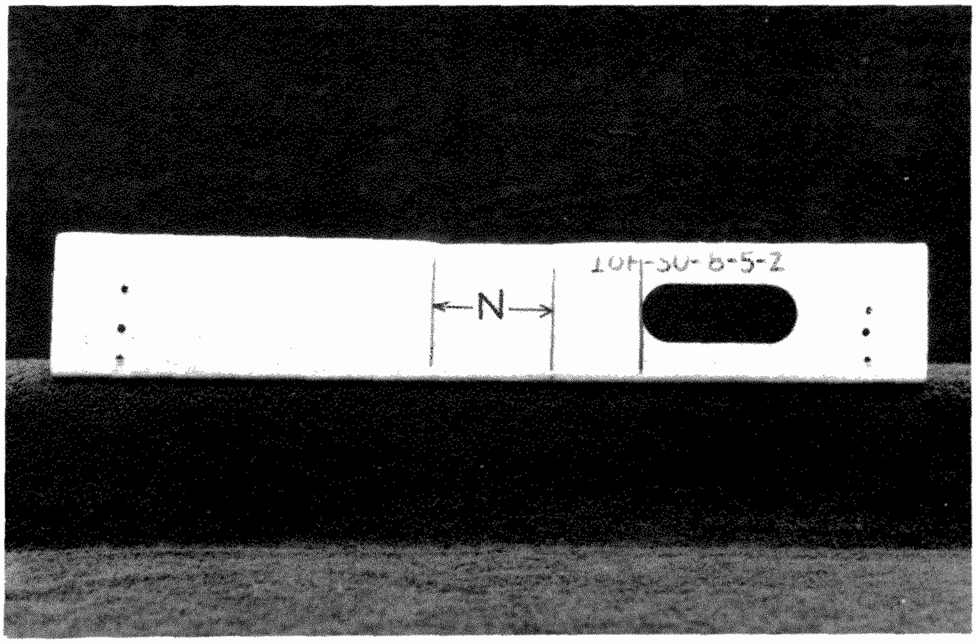


Figure 30: Typical Unreinforced IOF Web Crippling Failure, IOF-SU-8-5-2

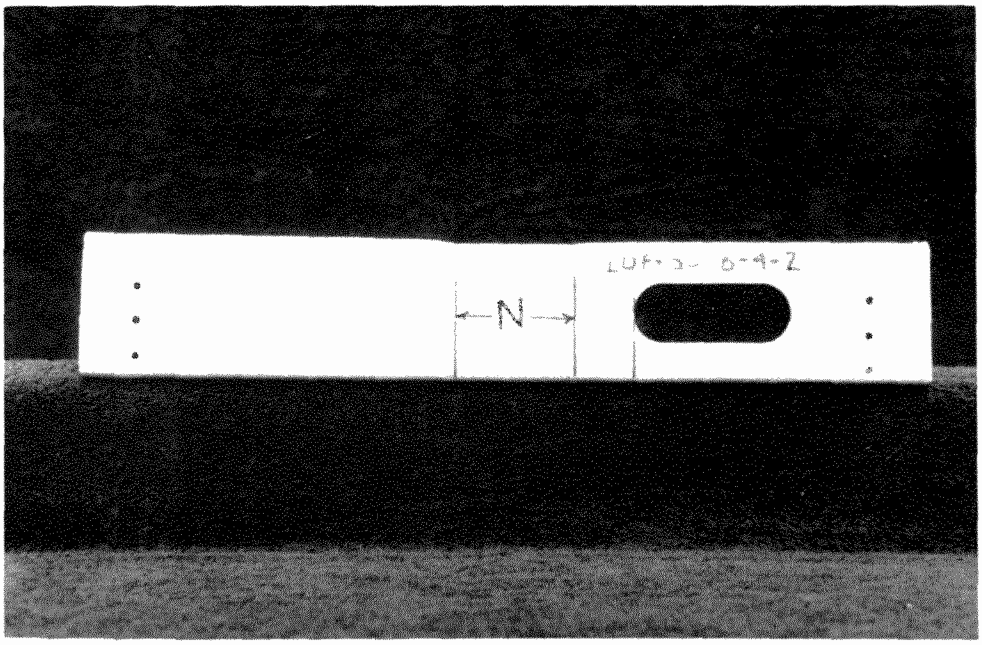


Figure 31: Typical Unreinforced Web Crippling Failure, IOF-SU-8-4-2

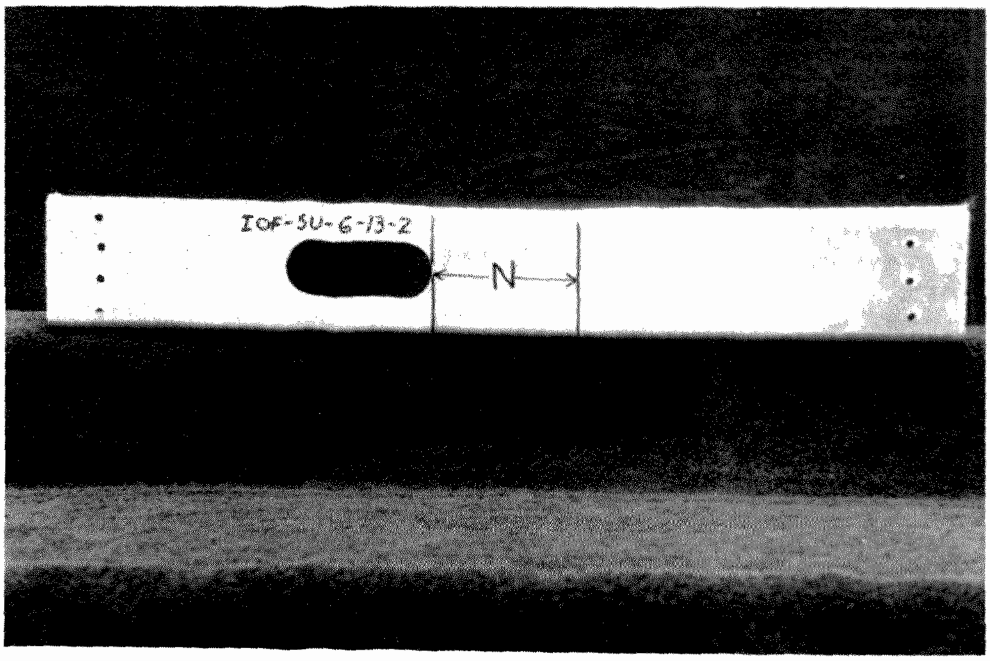


Figure 32: Typical Unreinforced IOF Web Crippling Failure, IOF-SU-6-13-2

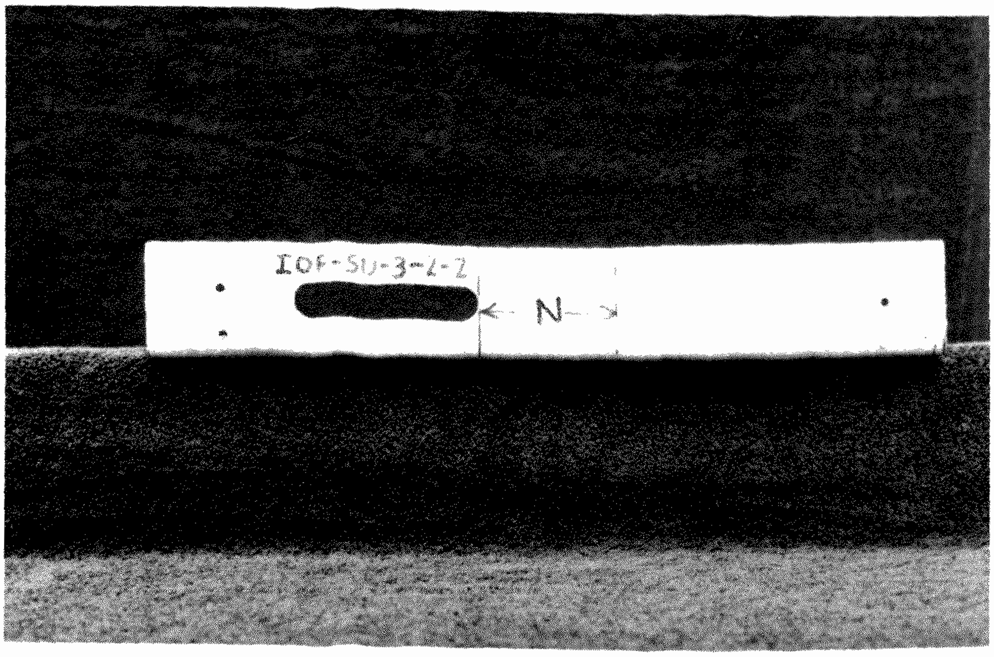


Figure 33: Typical Unreinforced IOF Web Crippling Failure, IOF-SU-3-2-2

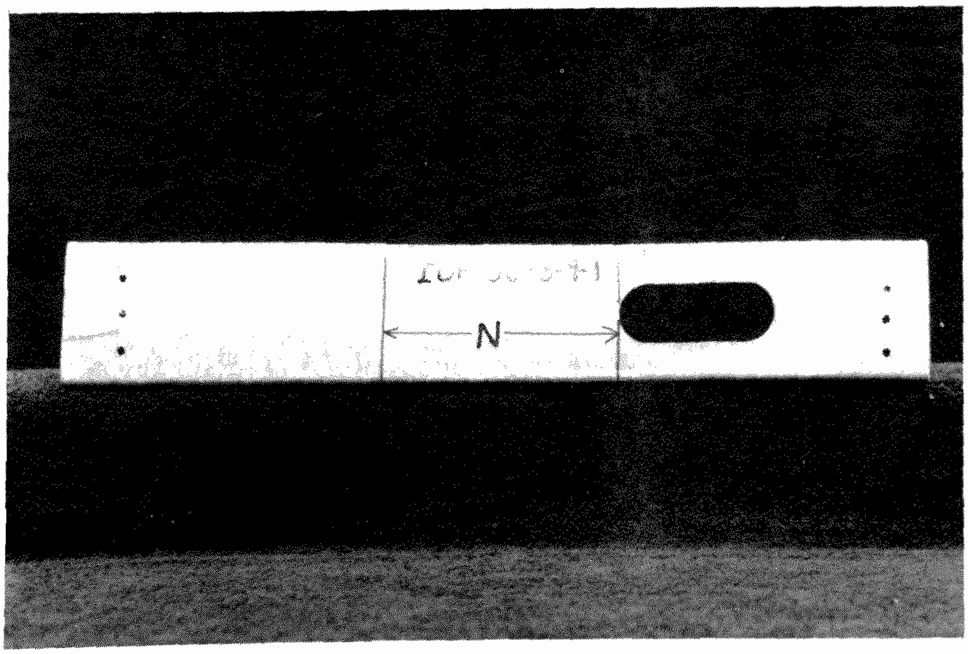


Figure 34: Typical Unreinforced Web Crippling Failure, IOF-SU-8-9-1

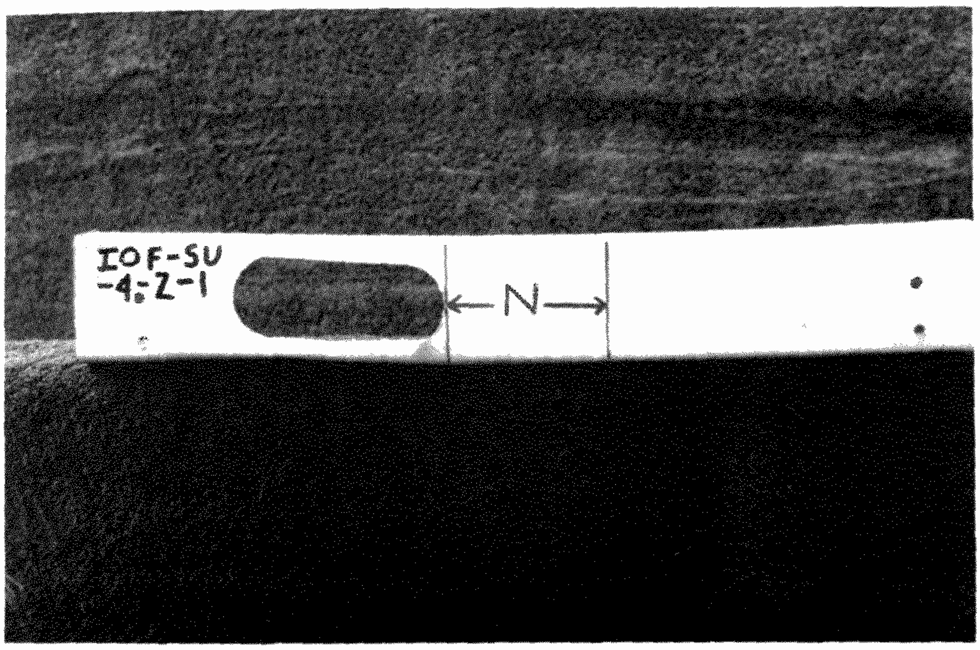
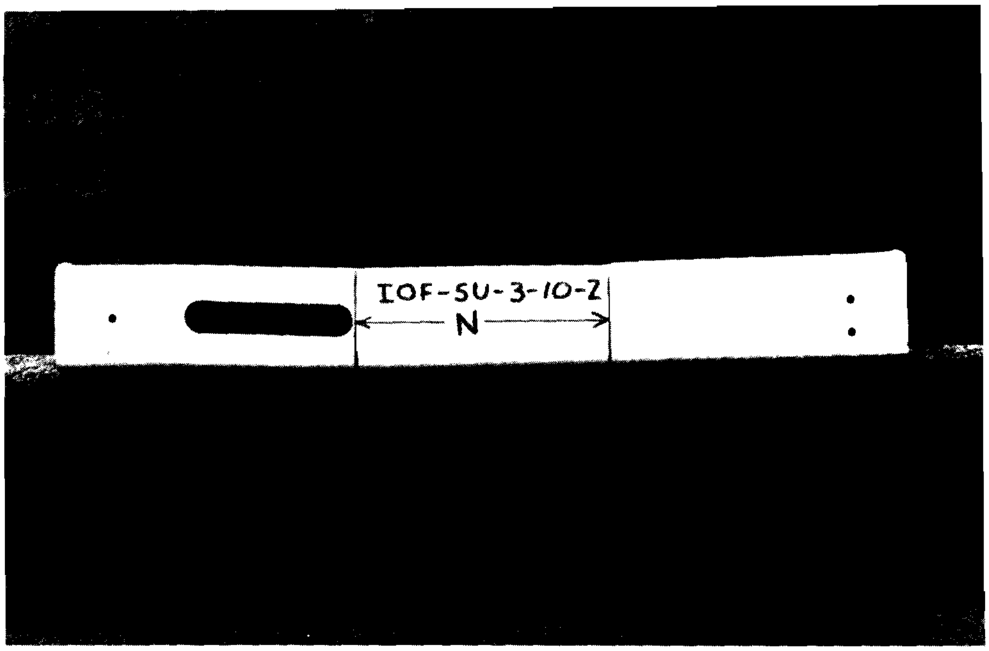
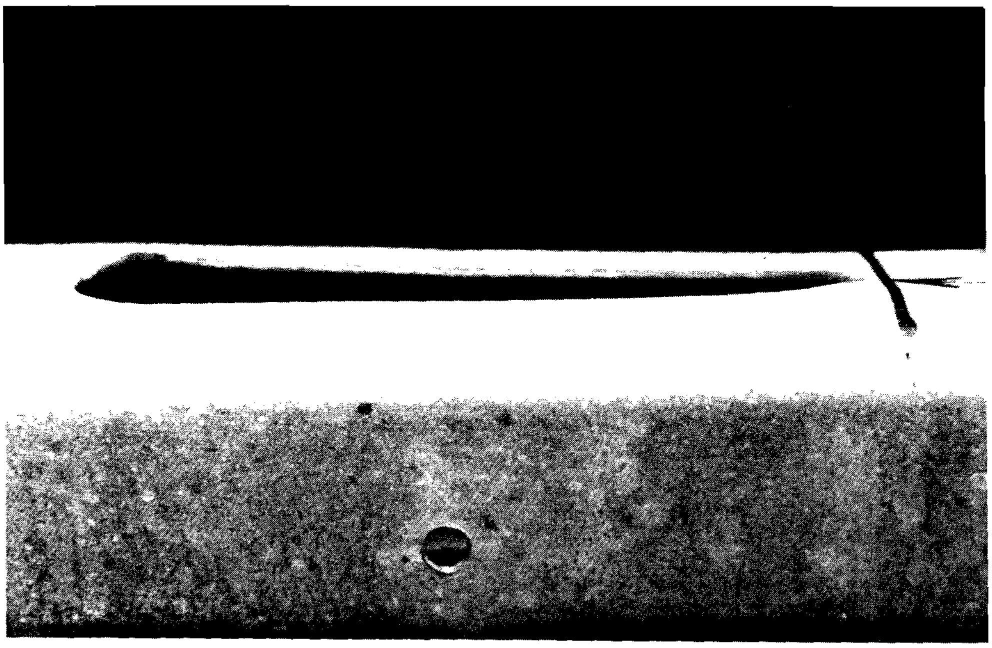


Figure 35: Typical Unreinforced IOF High a/h Value Shear Failure, IOF-SU-4-2-1



(a)



(b)

Figure 36: Typical Unreinforced IOF High N Value Shear Failure, IOF-SU-3-10-2

values of 1.5, 1.0, 0.7, and 0.5, respectively. Figures 32 and 33 show typical web crippling failures of test specimens at α equal to zero for the two different web opening sizes used in this phase of the study. Figures 26 thru 33 had a N value of three inches. Figure 34 shows a typical web crippling failure of a test specimen at α equal to zero, and at a N value of six inches. Figure 35 shows a typical shear failure of a test specimen attributed to a high a/h value. Figure 36 shows a typical shear failure of a test specimen attributed to a high N value.

3. Adjusted Tested Failure Load $(P_n)_{test\ adj}$. The values of the moment-adjusted tested failure load, $(P_n)_{test\ adj}$, as given by Table XI, is determined from the equation:

$$(P_n)_{test,adj} = \left(\frac{1.07}{1.42 - \frac{(M_n)_{test}}{(M_n)_{comp}}} \right) (P_n)_{test} \geq (P_n)_{test} \tag{74}$$

where $(M_n)_{test}$ = the mid-span bending moment at the failure load (Eq. 75), and; $(M_n)_{comp}$ = the nominal bending moment capacity; which is given and defined in Table II. Equation 74 was derived from Equation 43 and therefore is based on the procedure currently used in the AISI Specification provisions for combined bending and web crippling. The derivation of Equation 74 was performed by considering $(P_n)_{test\ adj}$ as the design web crippling strength in the absence of bending moment, $\Phi_w P_n$, and $(P_n)_{test}$ as the required web crippling strength in the presence of bending moment, P_u.

The value of $(M_n)_{comp}$ for each test specimen (Table II) is based on the bending moment capacity of the solid web cross section, and is not reduced for web openings. The rational for using the capacity of the solid web section in provided in Section IV.E.2, Evaluation of Tests Results, Bending and Bending Capacity.

Equation 74 is used to account for the degradation of the web crippling strength of the specimens due to bending interaction, and therefore serves to isolate the IOF web crippling behavior in the absence of bending moment. The equation is assumed to provide the strength of the specimen that would have been realized if the bending interaction was insignificant and therefore caused no degradation of web crippling strength. The use of the inequality is implemented if $(M_n)_{test}/(M_n)_{comp}$ is less than 0.35. This is the range at which bending moment is considered to not degrade web crippling strength.

4. Web Crippling Deformation at Failure. At failure, most specimens were severely deformed and would be considered unserviceable under most applications. Most specimens showed a combination of out-of-plane deformation of the web, and considerable localized vertical displacement of the loaded flange (Figs. 26 thru 34).

This severity of deformation is an important consideration in the selection of the ASD Specification (1986) factor of safety and the AISI LRFD Specification (1991a) resistance factor, because these specifications do not place a serviceability limit on web crippling. The AISI Specifications do not place a serviceability limit on web crippling due to the difficulty in quantifying the deformation and implementing the results in practice. This phenomenon adds further credibility to the use of the AISI ASD web crippling safety factor of 1.85 and the AISI LRFD web crippling resistance factor of 0.75 for single web sections which, as discussed herein, are generally conservative from a strength aspect. Although, Hetrakul and Yu (1978) state that the primary justification for the high ASD factor of safety is caused by the high variance of web crippling test results, and hence is not based on the amount of deformation. The relationships between the variance of the test results, the ASD factor of safety, and the LRFD resistance factor was provided in Section II.J.

The web crippling deformation for tests with low α values extended from the region of the web near the load plate to the corner of the web opening closest to the load plate (Figs. 32 and 33). As α increased, the noticeable deformation eventually ceased to reach the web opening, as shown in Figure 28.

The web crippling deformation at the allowable web crippling load was negligible. Evaluation of the deformation at the allowable web crippling load was accomplished by visual observation of the second test specimen from pairs of two identical specimens. The allowable load was computed from the failure load of the first test specimen of a pair of identical specimens by dividing the failure load of the first specimen by the ASD factor of safety by 1.85. As the second of two identical specimens was loaded, the test specimen was observed as the load reached the allowable capacity.

5. Shear Deformation at Failure. Ten test specimens failed in shear (Table XI). These ten shear failures occurred on five pairs of test specimens, where the test specimens in each pair were identical. The shear failures were very pronounced in the vicinity of the web opening. Shear failures usually occurred with insignificant to moderate IOF web crippling deformation at the load plate (Figs. 35 and 36).

Because of the pronounced shear deformation, shear failures were readily identified, and the data was used by Shan (1994) for studies on flexural members with web openings subjected to shear. An additional observation is that many of the specimens that failed due to web crippling had a slight amount of shear deformation. The location of the shear 'bulges' protruding from the diagonal compression corners of the web opening were the same as distinct shear failures, but the magnitude of the deformation was negligible.

E. EVALUATION OF TEST RESULTS

1. General. The test results were evaluated to determine the factors which influenced the PSW_{adj} values and

therefore influenced the web crippling behavior. After using Equation 74 to account for the degradation caused by bending moment, it was concluded that the web opening parameters a/h and α were the significant influencing factors. These two parameters are ultimately accounted for by their inclusion in the reduction factor equation of the design recommendations (Section IV.F.2).

2. <u>Bending and Bending Capacity.</u> The specimens acted as simply supported spans with a span length equal to the distance between the reaction plate rollers (Figs. 4 and 26a). The bending moment at failure, $(M_n)_{test}$, at mid-span is determined by:

$$(M_n)_{test} = \frac{L_{span}(P_n)_{test}}{4} \tag{75}$$

where $(P_n)_{test}$ = 1/2 of the applied mid-span load, and; L_{span} = L - 3 in.

The nominal or ultimate moment capacity, $(M_n)_{comp}$, of the specimens was determined by using AISI (1986, and 1991a), Section C3.1.1 Nominal Section Strength, Paragraph (a) Procedure I-Based on Initiation of Yielding. The procedure for computing $(M_n)_{comp}$ was provided in the review of the AISI Specification bending moment capacity provisions (Section II.F). The $(M_n)_{comp}$ values for each cross section used in the investigation are given in Table II.

The ratio $(M_n)_{test}/(M_n)_{comp}$ (Table XI), is therefore the bending moment at the failure load, as defined by the value of $(M_n)_{test}$ from Equation 75, divided by the ultimate moment capacity $(M_n)_{comp}$ based on initiation of yielding (Table II).

The value of $(M_n)_{comp}$ was based on the capacity of the solid web section. This resulted from the configuration of the test specimens and their demonstrated bending behavior, and in general is not true for the web crippling of cold-formed steel sections with web openings. Specifically, web openings may reduce the bending capacity in the absence of web crippling, and this reduced capacity must be used as the value of $(M_n)_{comp}$.

Results from a concurrent University of Missouri-Rolla study on the effect of web openings on the bending capacity of sections used in standard practice indicate that the bending capacity reduction may be only as much as ten percent due to the web openings (Shan, 1994). The bending study for sections with web openings used third-point loading geometry, which provided a long span region with constant-maximum moment. Therefore, several web openings were located within the constant-maximum moment region.

For the IOF web crippling study, no reduction in $(M_n)_{comp}$ was used for specimens with web openings because of the following three reasons: First, web openings do not significantly decrease the moment capacity of the sections used in standard practice (Shan, 1994). Second, the point of maximum moment for the IOF web crippling study, at mid-span, does not coincide with the location of the web opening. For this study, an idealized triangular bending moment diagram for simply supported spans was used. As a minimum, the location of the web opening, i.e. at α is equal to zero, is at a distance equal to N/2 from mid-span. Third, there is significant scatter in combined bending and web crippling behavior (Hetrakul and Yu, 1978, and Fig. 7). This scatter is therefore incorporated into the AISI Specification interaction equations (Eqs. 42 and 43) which is used extensively herein to evaluate the test results. This evaluation is accomplished by using Equation 74 to compute $(P_n)_{test,\ adj}$ (Table XI). Hence, any small magnitude of bending moment capacity reduction at mid-span due to the web opening is insignificant in comparison to the scatter associated with the model used in predicting the effect of the moment capacity reduction on the web crippling capacity in the absence of bending moment.

3. Bending Interaction. As exhibited by the test specimens, the length of the specimen, L, was a parameter that affected the $(P_n)_{test}$ value of the specimens because of its effect on bending moment (Eq. 75) and therefore the value of L affected the interaction of bending and IOF web crippling. The specimen had to be of sufficient length to accommodated the various constituent lengths and requirements of: 1. a clear distance between bearing plates of greater than or equal to 1.5h, as required for one-flange-loading (Eq. 72), 2. a value of x′ (Fig. 4) greater than or equal to zero (Eq. 73), and 3. the length N of the

mid-span and two end-of-span bearing plates (Eqs. 72 and 73).

The second requirement increased L by the amount 2(b+x-1.5h), above what is required to satisfy the definition of the one-flange loading condition as given by Equation 72. The second requirement was not a factor in the previous investigations discussed in the literature review. In the current study, this requirement often constituted a significant portion of overall specimen length, and hence influenced the value of $(M_n)_{test}$ (Eq. 75). Therefore, web crippling capacity could not be studied directly without consideration of the combined bending and web crippling behavior.

In practice, significant bending moment may typically exist at locations of IOF loading. A common example is the IOF reaction resulting from a continuous wall stud subjected to a distributed wind load which spans a girt or intermediate support. A discussion of the effect of bending interaction on web crippling behavior and the resulting need for interaction equations was provided by Yu (1991) in the review of the AISI Specification combined bending and web crippling provisions (Section II.F).

The AISI Specification web crippling interaction equation (Eqs. 42 and 43) results from a regression analysis of the highly scattered data associated with the interaction phenomenon (Fig. 7). Therefore, use of Equation 75 to compute $(P_n)_{test,\ adj}$, and therefore to account for the effect of bending interaction on web crippling behavior is not exact. However, it is the best model available, and reflects the current design practice. Furthermore as discussed herein, it succeeds in rectifying the erroneous trend of decreasing web crippling strength as the clear distance, x, between the load and the web opening is increased.

It is assumed that the location of interaction between bending and web crippling was at mid-span of the test specimens, despite the location of the web opening in the test specimens. This is based on the assumption that the web crippling failures occurred at mid-span, such as is exhibited by solid web specimens. The web at the mid-span interaction failure location is influenced by the strength and stiffness characteristics of the adjacent regions of the web, and therefore is influenced by the presence of a web opening.

4. Effect of α and a/h on Web Crippling Behavior.

a. General. Based on the results of the specimens tested in this study, the parameters α and a/h had a distinct effect on web crippling behavior. Distinct relationships exist in that the value of α was directly proportional to the value of PSW_{adj}, and the value of a/h was inversely proportional to the value of PSW_{adj}. For the determination of the PSW_{adj} values, the value of $(P_n)_{test,\ adj}$ (Eq. 74) was used for the capacity of all test specimens, including those with solid webs.

b. <u>Effect of α on Web Crippling Behavior.</u> A notable trend exists within the test results. As α increased, the PSW value did not increase to 100 percent. This is in sharp contract to the results of the EOF unreinforced web opening study, for which the value of PSW was equal to the value of PSW_{adj}, and the values of PSW_{adj} were directly proportional to the α values. This trend of the relationship between PSW and α and between PSW_{adj} and α values is shown in Table XI for the IOF tests. Figure 37 shows α vs. the average PSW value for a typical cross-section, IOF-SU-5 at N is equal to three inches. Figure 37 is in contrast to the results of the EOF tests shown in Figure 19, which showed PSW_{adj} to converge to 100 percent as α increased.

The reason for the decrease in PSW at high α values for the IOF results is due to the moment degradation of the web crippling strength of the specimens as α increased. As shown Table XI, this trend is largely corrected by computing PSW_{adj} for all IOF loading condition tests. The use of PSW_{adj} removes bending interaction from the PSW results, and provides a trend of α vs. PSW_{adj} similar to that demonstrated by the EOF tests.

A useful comparison can be seen by comparing the PSW and PSW_{adj} values for each specimen (Table XI) to see the effect of using Equation 74. Even with the use of Equation 74 to compute the PSW_{adj} values, as can be seen by the results of Table XI, the trend is not as distinct as for the

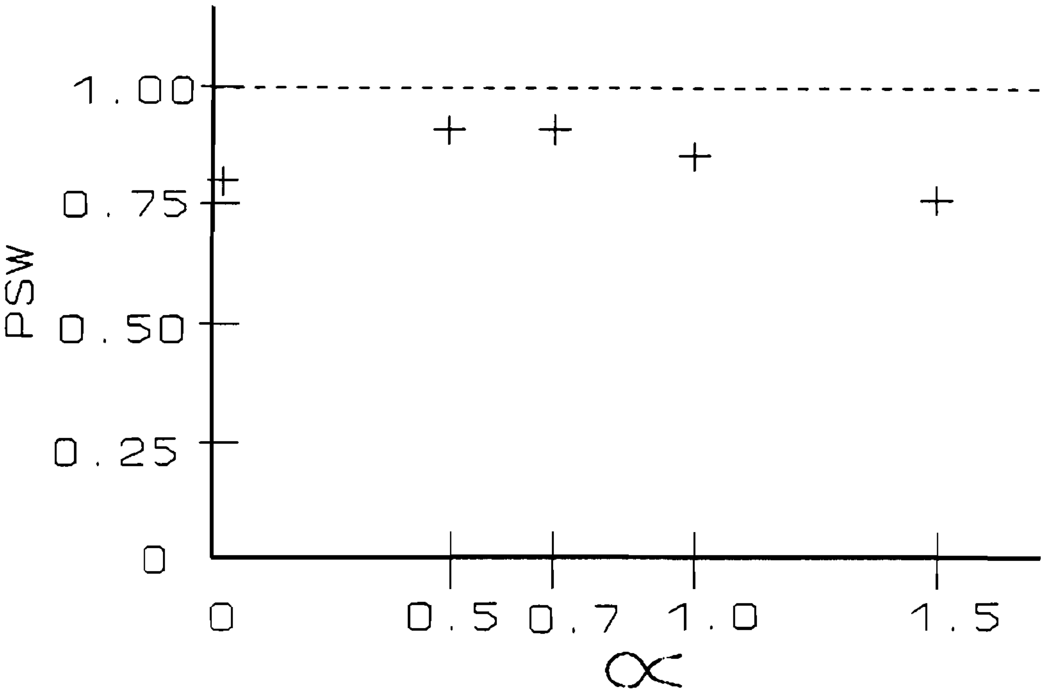
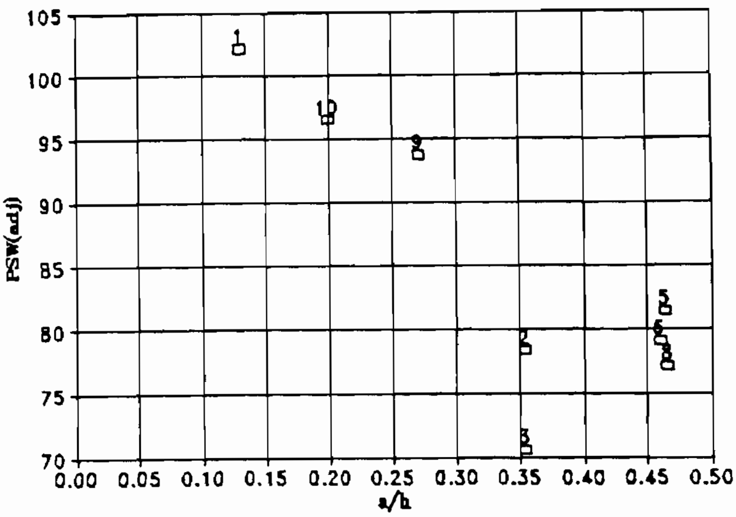


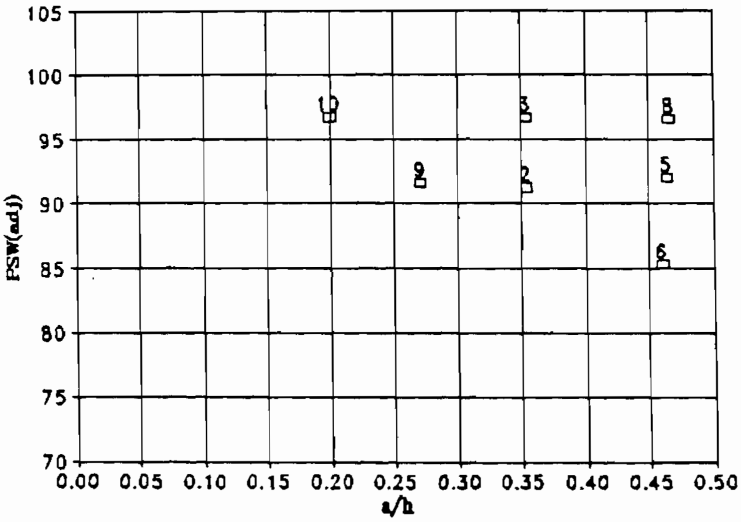
Figure 37: PSW vs. α for Cross-Section IOF-SU-5
at N = 3 inches

EOF results; this is primarily due to the complexity and scatter inherent in the interaction phenomenon.

c. Effect of a/h on Web Crippling Behavior. As existed for the EOF tests of Section III, a trend existed in which the value of PSW_{adj} was inversely proportional to the a/h value. For example, Figure 38 shows the results of a/h versus the average PSW_{adj} values for the eight cross sections which failed in web crippling for which N was equal to 3.00 inches and α was equal to zero and 0.5. Figures 38a and 38b can be compared to Figures 20a and 20b for the unreinforced EOF tests at the same two α values.



(a) $\alpha = 0$



(b) $\alpha = 0.50$

Figure 38: PSW_{adj} vs. a/h for IOF Tests

d. <u>Effect of b on Web Crippling Behavior.</u> The length of the mechanism, or path of severe web deformation exhibited by the test specimens, is independent of b as shown in Figure 39. Therefore, the capacity of the section is assumed to be independent of the b value. This phenomenon is in contrast to the results of Sivakumaran and Zielonka, (1989). However, the failure mechanism is much different for their tests because of the web opening being centered on the load plate, thereby justifying the incorporation of b into their reduction factor equation (Eq. 6). It is recognized that the value of b might affect the capacity of the section if both b and α are very small. For example, this could occur when a narrow vertical slit of height a is located near or adjacent to the load plate, and the entire web opening falls within the region of concentrated load dissipation, which is assumed to occur at approximately a 45 degree angle. However, the web crippling behavior of test specimens with small b values was not studied because of the smallest web opening b value of two inches. In practice, b will typically not be less than two inches for providing passage of services.

e. <u>Summary of the Effect of α and a/h on Web Crippling Behavior.</u> The web opening parameters of α and a/h provided the only conclusive correlation with PSW_{adj}. As a result of the above findings, PSW_{adj} and therefore the reduction factor equation, are dependent only upon the web opening parameters of α and a/h. The reduction factor equation will therefore

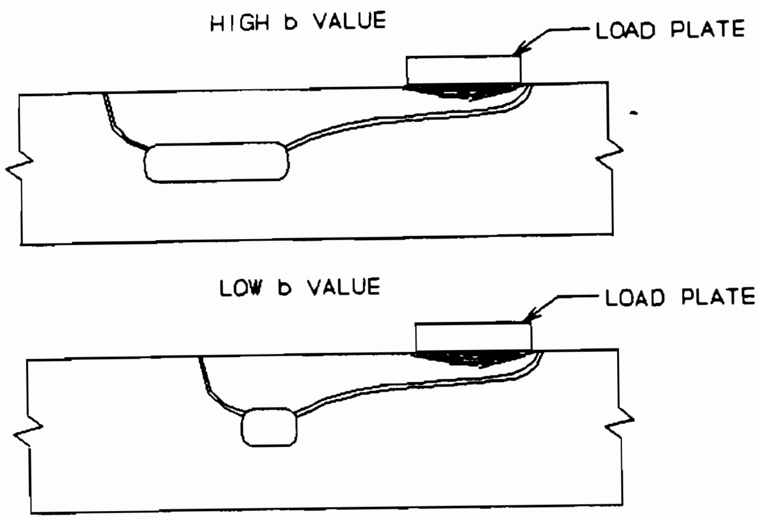


Figure 39: Effect of b Parameter for IOF Tests

not include any parameters intrinsic to the solid web specimens. Many of the parameters associated with solid web sections are included in the existing AISI Specification web crippling provisions, Equations 30 thru 35.

The cross-section parameters shown in Table II, with the exception of the web opening parameters of α, b, a, and therefore a/h, proportionally affected both the $(P_n)_{\text{test adj, solid web}}$ and $(P_n)_{\text{test adj, web opening}}$ values. The values of $(P_n)_{\text{test adj, solid web}}$ and $(P_n)_{\text{test adj, web opening}}$ comprise the denominator and numerator, respectively, of the relationship defining PSW_{adj}. Therefore, the effect of the parameters intrinsic to solid web sections of t, F_y, h/t, N/t and R/t, is nullified by their having the same effect on both the numerator and denominator of the PSW_{adj} relationship. Conversely, the parameters α and a/h influenced PSW_{adj} since these two parameters influenced only the numerator of the PSW_{adj} relationship, $(P_n)_{test,\ web\ opening}$.

The influence of the remaining web opening parameter, b, is addressed by imposing a maximum limit on b according to that which exists in standard practice as provided in Section IV.F.

5. Comparison with Previous Studies for Specimens with Solid Webs. As can be seen from Table XII, the mean $(P_n)_{test\ adj}/(P_n)_{comp}$ value for all 44 solid web tests with F_y less than 70 ksi was equal to 1.001, and therefore corresponds well with the previous solid web investigation performed by Hetrakul and Yu (1978). Hetrakul and Yu (1978) had a mean $(P_n)_{test}/(P_n)_{comp}$ value of 0.997 for the IOF tests.

Hetrakul and Yu (1978) strictly used the value of $(P_n)_{test}$ in their determination of $(P_n)_{test}/(P_n)_{comp}$, because bending moment did not degrade the $(P_n)_{test}$ values, and therefore did not require computation of the $(P_n)_{test\ adj}$ values. The test results used by Hetrakul and Yu (1978) to develop their equation for $(P_n)_{comp}$ (Eqs. 25 and 26) consistently had a $(M_t)_{test}/(M_n)_{comp}$ value below 0.30.

The mean $(P_n)_{test}/(P_n)_{comp}$ value of 0.997 obtained by Hetrakul and Yu (1978) was approximately equal to unity because the equation for determining $(P_n)_{comp}$ was developed based on their test results. Hence, this can be considered as using the resulting equation as an operator for the original data.

Cross-sections IOF-SU-9 and IOF-SU-10 were excluded from the statistical analysis because their yield strengths greatly exceeded those stated in Hetrakul and Yu (1978). Cross-section IOF-SU-9 and IOF-SU-10 had F_y values of 93 and 72 ksi, respectively (Table II). Cross-sections IOF-SU-9 and IOF-SU-10 had $(P_n)_{test\ adj}/(P_n)_{comp}$ values significantly greater than unity, even at the lowest α value tested of zero.

Examination of the parameters of cross-sections IOF-SU-9 and IOF-SU-10 indicate that the high F_y values resulted in the conservatism of the sections. As stated previously, Equation 34, which was adopted from Equations 25 and 26, was developed from tests with F_y values less than 54 ksi. Cross-sections IOF-SU-9 and IOF-SU-10 had average $(P_n)_{test\ adj}/(P_n)_{comp}$ values equal to 1.71 and 1.34, respectively for the solid web test specimens at N is equal to three inches.

Cross-sections IOF-SU-9 and IOF-SU-10 also had h/t ratios significantly greater than those of the other cross sections used in the current study. However, Hetrakul and Yu (1978) reported the results from numerous tests on sections with h/t values as great as 250. Therefore, the results strongly indicate that high h/t values are not the cause of the conservative results. Therefore, it is believed that the high F_y values solely contributed to the conservative results from cross-sections IOF-SU-9 and IOF-SU-10.

It is recommended that sections with high F_y values not be exempted from the reduction equation developed herein to account for the effect of web openings on web crippling behavior. The conservatism of a section should be addressed through the modification of Equations 34 and 35, and not through the modification of the reduction factor equation. It is desirable to use a reduction factor equation which possesses no parameters inherent in the solid web cross section such as F_y and t.

As shown in Table XIII, use of the web crippling equations for solid webs developed by Santaputra, Parks, and Yu (1989) (Section II.G) provided approximately the same value as the current AISI Specification web crippling provisions. The Equations developed by Santaputra, Parks, and Yu (1989) were used for the comparison of the web crippling behavior of these two cross sections, because they are valid for F_y is less than or equal to 190 ksi. Based on the geometry of the current study, Equations 46 and 47 apply, with the smaller value from the two equations providing $(P_n)_{comp}$. For both cross sections, Equation 47 defined $(P_n)_{comp}$.

For the solid web tests from cross-section IOF-SU-9, the average value of $(P_n)_{comp}$ from Santaputra, Parks, and Yu (1989) divided by $(P_n)_{comp}$ from Equations 34 and 35 is 0.997 at N is equal to three inches. For the solid web tests from cross-section IOF-SU-10, the average value of $(P_n)_{comp}$ from

Table XIII: Comparison of IOF Results with Equations from Santaputra, Parks, and Yu (1989)

		Santaputra, Parks, and Yu Equations (lbs.)		$(P_n)_{comp}$ (lbs.)		Average $(P_n)_{test\ adj}$ (lbs.)	$(P_n)_{test}/(P_n)_{comp}$	
	F_y (ksi)	P_{cy} (Eq. 46)	P_{cb} (Eq. 47)	Lesser of P_{cy} and P_{cb}	Eqs. 34 & 35		Lesser of P_{cy} and P_{cb}	Eqs. 34 & 35
IOF-SU-9	93	1490	1033	1033	1036	1769	1.71	1.71
IOF-SU-10	72	2261	2029	2029	1711	2288	1.13	1.34

Notes: 1. All tests performed on solid web sections at N is equal to 3.00 inches.
2. Cross-section designations:
IOF: Interior-One-Flange loading condition, SU: Single Unreinforced web
IOF-SU-cross section number-specimen designation

Santaputra, Parks, and Yu (1989) divided by $(P_n)_{comp}$ from Equations 34 and 35 is 1.19 at N is equal to three inches. Overall for the IOF tests, the use of the equations developed by Santaputra, Parks, and Yu (1989) provided less conservative results. This was the same findings reported for the EOF tests of specimens with high F_y values as given in Section III (Table X).

6. Evaluation of Shear Failures. Shear failures generally occurred for two reasons. First, higher bearing lengths, N, (Fig. 36) increased the likelihood of a shear failure because an increase in N provides an increase in the web crippling strength of the section (Eqs. 34 and 35) but does not affect the shear capacity of the section (Eqs. 48 thru 54). Figure 36 shows a shear failure of a test specimen which is attributed to a high N value. The test specimen had a relatively low a/h value of 0.354.

Secondly, shear failures also occurred at high values of the a/h parameter. This occurred because of the removal of a considerable portion of the shear carrying portion of the cross section. As shown in Figure 35, cross-section IOF-SU-4 demonstrates this phenomenon for an a/h value of 0.73. The specimens IOF-SU-4-2-(1 and 2) were the only test specimens which failed in shear at the lowest N value tested of three inches.

Since a specific web crippling-shear transition is not defined, shear must be checked separately using the design recommendations of Shan (1994).

As provided earlier, many of the specimens that failed due to web crippling had a slight amount of shear deformation. The location of the shear 'bulges' protruding from the diagonal compression corners of the web opening were the same as distinct shear failures, but the magnitude of the deformation was negligible. Failure modes were identified as either web crippling or shear. No attempt has been made to establish the interaction of shear and web crippling, because Hetrakul and Yu (1978), stated "It is expected that shear will not affect the web crippling load even for the beams having high V/V_u ratios."

F. <u>DESIGN RECOMMENDATIONS</u>

1. <u>General.</u> Ninety tests were conducted on specimens with web openings that failed in web crippling. Two multi-variable linear regression analyses were performed on the 90 test results to develop reduction factor equations. The development of the recommended reduction factor equation and an alternative reduction factor equation are given subsequently as follows.

2. <u>Recommended Reduction Factor Equation.</u> A bivariate linear regression was performed on the results for the 90 test specimens with web openings which failed in web crippling. The regression was performed with α and a/h as the independent variables and PSW_{adj} as the dependant variable. The resulting reduction factor equation, with a maximum of 100 percent is:

$$RF = 96.44-(27.20\frac{a}{h})+(6.31\alpha) \leq 100\% \tag{76}$$

or,

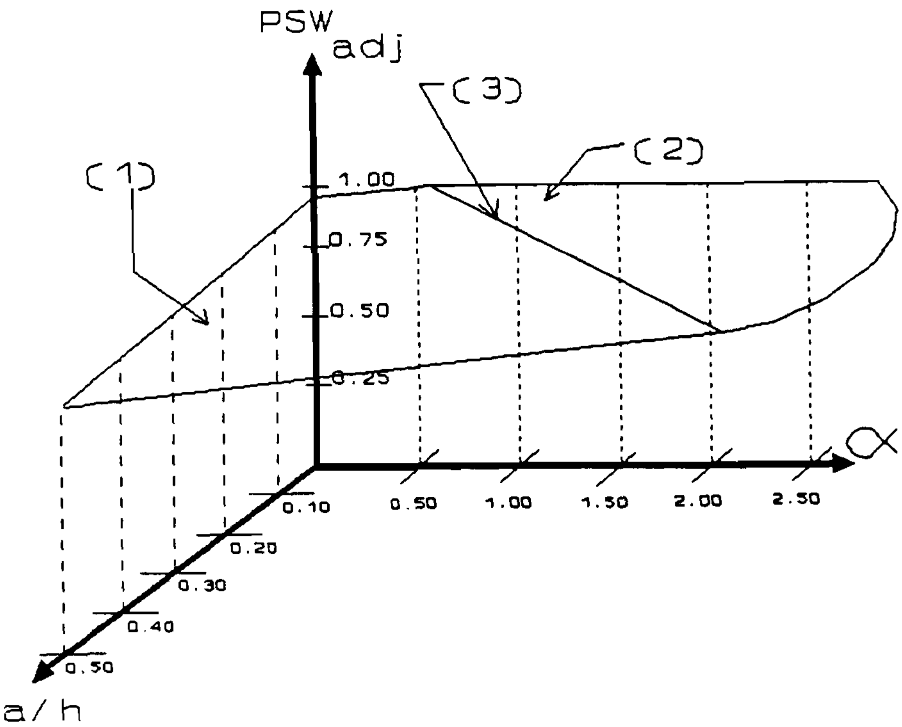
$$RF = 0.964-(0.272\frac{a}{h})+(0.0631\alpha) \leq 1.00 \tag{77}$$

Equation 77 is graphically represented by plane 1 of Figure 40 for the 90 data points. A PSW_{adj} value of 100 percent signifies that no strength reduction is required ((2), Fig. 40). The reduction factor equation indicates that at 100 PSW_{adj} ((3), Fig. 40):

$$\alpha \geq (4.31\frac{a}{h})+0.571 \geq 0 \tag{78}$$

Equation 78 implies that for a web opening of infinitesimal size, α must be greater than or equal to 0.571 for no reduction of the solid web strength. Intuitively, the solid web capacity should not require a reduction for an infinitesimal web opening even at the minimum α value of zero. However, Equation 77 yields a satisfactory value of approximately unity, 0.964, when α is equal to zero and a/h is slightly greater than zero. The joint region of α and a/h, which requires no strength reduction, is shown as (2) in Figure 40 as a horizontal plane with a PSW_{adj} value of 1.00.

The parameters of α and a/h provided the only conclusive correlation with PSW_{adj}. The additional parameters shown in Table II, with the exception of b, proportionally affected both of the $(P_n)_{test\ adj}$ values which



(1) $PSW_{adj} = 0.964 - 0.272(a/h) + 0.0631\alpha$
(2) $PSW_{adj} = 1.00$ (3) $\alpha = 4.31(a/h) + 0.57$

Figure 40: IOF, PSW_{adj} vs. α and a/h

determine PSW_{adj} of $PSW_{test\ adj,\ web\ opening}$ and $PSW_{test\ adj,\ solid\ web}$. However, only α and a/h influenced PSW_{adj} since they are intrinsic only to specimens with web openings, and therefore they affected only the numerator of the PSW_{adj} equation. The influence of b is addressed by imposing an upper limit on b equal to the maximum permitted in standard practice (Section IV.F.4).

The $(M_n)_{test}/(M_n)_{comp}$ value is not included in the bivariate linear regression analysis (Eq. 77) which was determined from PSW_{adj} versus the α and a/h parameters. The alternative regression factor equation discussed subsequently includes $(M_n)_{test}/(M_n)_{comp}$, and therefore is based on a trivariate linear regression of PSW_{adj} versus α, a/h, and $(M_n)_{test}/(M_n)_{comp}$. Equation 77 has the desirable characteristic of using the established practice of employing the current AISI Specification combined bending and web crippling provision equations (Eqs. 42 and 43) to check bending interaction.

The modified web crippling load for specimens with web openings can be obtained by applying the reduction factor given by Equation 77, which is less than or equal to unity, by using Equations 2 and 3.

3. Alternate Reduction Factor Equation. The following reduction factor equation was derived from the ninety tests conducted on specimens with web openings that failed in web crippling. It is based on a trivariate linear regression analysis.

For the statistical analysis, a different form of Percent of Solid Web Strength was used. This form is the Solid Web Bending Moment Adjusted value, $PSW_{s\ adj}$. For the computation of $PSW_{s\ adj}$, bending moment degradation for the tests performed on solid web tests was accounted for by use of Equation 74. However, no bending moment degradation in web crippling capacity for the tests performed on test specimens with web openings was performed. Instead, the bending moment degradation on the test specimens with web openings was considered by the inclusion of $(M_n)_{test}/(M_n)_{comp}$ as an independent variable in the regression analysis.

For the regression analysis, the dependent variable is $PSW_{s\ adj.}$ The independent variables are α, a/h, and $(M_n)_{test}/(M_n)_{comp}$.

$$RF = 1.174-(0.264\frac{a}{h})+(0.0526\alpha)-(0.663\frac{(M_n)_{test}}{(M_n)_{comp}}) \leq 1.00 \qquad (79)$$

Use of this equation would therefore preclude the need for using another interaction equation. Ideally, this equation could replace interaction Equations 42 and 43 for specimens with web openings. However, this is not suggested because of the established practice of using the current interaction equations and the existing data base of the test results, which were used to define the current AISI Specification combined bending and web crippling provisions (Eqs. 42 and 43), greatly exceeds the data base available from the current investigation.

At a $(M_n)_{test}/(M_n)_{comp}$ value of 0.35, i.e. at the minimum value where bending moment degrades web crippling capacity, Equation 79 yields:

$$RF = 0.942-0.264\frac{a}{h}+0.0526\alpha \leq 1.00 \qquad \mathbf{(80)}$$

The three constant coefficients of Equation 80 are approximately the same as for the recommended reduction factor equation, and hence provides approximately the same value as Equation 77 at this value of $(M_n)_{test}/(M_n)_{comp}$.

4. Limitations of Reduction Factor. Equation 77 is applicable to all cross sections and conditions that meet the ranges of applicability as follows. The justification for these ranges of applicability is based on four factors: 1. the limits imposed on the existing AISI Specification web crippling provisions as given in Section II.F. 2. the industry imposed limits on web opening parameters, 3. engineering judgement, and 4. the range of parameters for the test specimens (Table V). The use of engineering judgement was frequently used to extrapolate the limits for the test specimens to correspond with those of the current AISI Specification provisions and those of the industry imposed limits on web opening parameters.

i. Current AISI Web Crippling Provisions (Eqs. 34 and 35): Although the testing was limited to specimens with edge-stiffened flanges, the same percent reduction in strength is expected for sections with unstiffened flanges. If Equation 77 is used to reduce the allowable strength of Equations 34 and 35, the limits on h/t, R/t, N/t, and N/h ratios stated in the AISI Specification web crippling provisions (AISI, 1986, and AISI, 1991a) must be met (Section II.F).

(1) h/t: Although the maximum h/t ratio tested was 168, this h/t ratio be extended to the maximum allowable prescribed for Equations 34 and 35 of 200 for use of Equation 77. No minimum h/t is prescribed although the minimum h/t tested was 39.

(2) N/t: The tested range for N/t was 30.6 to 181.8. However, all N/t values less than or equal to 210 are valid for use of Equation 77 because this is the maximum limit imposed for Equations 34 and 35.

(3) R/t: The tested range for R/t was 1.59 to 4.88. However, all R/t values less than or equal to 6.0 are valid for use of Equation 77, because this is the maximum limit imposed for Equations 34 and 35.

(4) N/h: The tested range for N/h was 0.260 to 2.96. However, all N/h values less than or equal to 3.5 are valid for use of Equation 77 because this is the maximum limit imposed for Equations 34 and 35.

(5) θ: Theta equalled 90° for all tests. However, it is assumed that all θ values within the allowable limits of Equations 34 and 35 of 45° to 90° are valid for use of Equation 77 .

ii. a/h: Although the maximum a/h value tested which failed in web crippling was 0.464, Equation 77 is assumed to be valid for a/h less than or equal to 0.50. This limit corresponds to the maximum a/h employed by industry standard sections. As discussed herein, high a/h values increase the probability of a shear failure. Therefore, shear must be checked separately using results from Shan (1994).

Establishing a maximum value for the a/h value of the web opening has precedence for web crippling reduction factor equations, as discussed in the review of the Yu and

Davis (1973) and Sivakumaran and Zielonka (1989) reduction factor equations, (Section II.C).

iii. α: Alpha ranged from 0 to 1.5 for all tests with web openings. The recommended minimum value for α in Equation 77 is zero. It is standard industry practice to place a web stiffener on all sections that have α values less than zero, i.e. when any portion of the web opening is above or below the IOF load plate.

Although it is presumed that in lieu of placing a stiffener, a reduction factor could be employed by either: 1. Allowing the α value of Equation 77 to be negative. However, this is not recommended, since no upper limit for the magnitude of this negative α value, for which Equation 77 will still be valid, can rationally be determined without sufficient experimental data. Also, as the centerline of the web opening approaches the centerline of the load, the failure mode will change to those reported by Sivakumaran and Zielonka (1989), or 2. Using the Sivakumaran and Zielonka reduction factor equation (Eq. 6). If used, it is recommended that no increase in allowable web crippling capacity be made for web openings not centered on the load. Sivakumaran and Zielonka (1989) stated, "The web openings were directly under the load, thus the above equation establishes the influence of an opening under the worst possible scenario [for web opening location]."

However, based on unreinforced web tests performed during the EOF and IOF web reinforcement study, and reported herein in Section V, the following recommendations are given for unreinforced web sections subject to IOF loading:

1. Use Equation 6 for the IOF loading condition when any portion of a symmetric web opening is above or below the load plate, and the web opening and loading plate have coincident centerlines.

2. Use the lesser of Equation 6 and Equation 77, with α equal to zero, for the IOF loading condition when any portion of a web opening is above or below the load plate, and the web opening and loading plate do not have coincident centerlines, or the web opening in not symmetric.

For 1 and 2, non-symmetric web openings pertain to those with an offset distance from the load centerline or those which have an opening shape that is not symmetric about a line parallel to the loading.

3. For the IOF loading condition when no portion of a web opening is above or below the load plate, use Equation 77, with the applicable α value.

No maximum limit is placed on α, because at high α values, Equation 77 will yield a value of unity. Furthermore, with the standard practice of using sections with openings separated by 24 inches on-center, the maximum value of α will be constrained by the α value of the web opening on the opposite side of the load.

iv. Bearing Length, N: Although Equation 77 is based primarily on tests at N equal to three inches, with limited tests at N equal to four, five, and six inches, Equation 77 is applicable to all N values greater than or equal to three inches. A N value of three inches is the minimum limit of N for the IOF loading conditions in most situations. As provided in the review of the investigations performed by Yu and Davis (1973) and Sivakumaran and Zielonka (1989) (Section II.C), the reduction factor equations are not limited to the N values used in the investigation. However, N will be limited by the maximum allowable value of N/t and N/h of 210 and 3.5, respectively, as applies to Equations 34 and 35.

As provided in Section IV.E.6, a cross section may change from web crippling to shear failure at a particular N value inherent to the cross-section properties. Therefore, shear must be checked separately using the results of Shan (1994).

v. Height of the Flat Portion of the Web, h: The tested range of specimens that exhibited web crippling failures was 2.12 to 11.54 inches. However, all h values are valid for use of Equation 77 if the h/t maximum limit of 200 is not exceeded.

vi. Base metal thickness, t: The tested range of base metal thickness was 0.032 to 0.098 inches. However, all t values are valid for use of Equation 77 if the h/t maximum limit of 200 is not exceeded.

vii. Yield Strength, F_y: The tested range of yield strength was 36 to 93 ksi. However, all F_y are valid for use of Equation 77. For cross sections with F_y greater than

91.5 ksi, 91.5 ksi may be used in Equations 34 and 35. However, for Grade E materials, the F_y and F_u values must be in accordance with Section A3.2.2 of the Specification.

viii. Maximum Web Opening Size:

(1) Web Opening Height, a: No maximum limit is prescribed for a. However, the maximum allowable a/h value used in standard practice of 0.50 must be adhered to.

(2) Web Opening Length, b: Although the maximum b value tested was four inches, it is recommended that the maximum limit for b be extended to the industry standard maximum of 4.5 inches. The parameter b is not included in the reduction factor equation, hence no variation in allowable load for b values between zero and 4.5 inches is recommended.

Establishing a maximum value for the length of the web opening has precedence for web crippling reduction factor equations, as discussed in the review of the Yu and Davis (1973) and Sivakumaran and Zielonka (1989) reduction factor equations (Section II.C). Although Yu and Davis (1973) did not explicitly state a maximum web opening length for use of Equations 4 and 5, a limit for this parameter does indirectly exist. Their study was limited to square or circular openings, and they gave maximum limits on the ratio of the height of the web opening to the depth of the section.

Conservative consideration for irregularly shaped or eccentric web openings is given herein as Figures 5 and 6.

G. EVALUATION OF DESIGN RECOMMENDATIONS

The results of applying the Equation 77 to the test results is shown in Table XII under the column titled "Interaction Equation Value". The interaction equation value was computed using Equation 28. For use of Equation 28: $(P_n)_{test}$ is given in Table XI, the value of $(P_n)_{comp}$ was equal to the web opening adjusted design web crippling capacity (Table XII):

$$(P_n)_{comp} = RF \times (P_n)_{comp,\,solid\,web} \tag{81}$$

where RF is from Equation 77 and $(P_n)_{comp,\ solid\ web}$ was from Equations 34 and 35, and the value of $(M_n)_{test}/(M_n)_{comp}$ is given in Table XI. Because of the use of Equation 28, the current design practice is recognized (Eq. 43).

The mean of all interaction equation values is 1.373, which is approximately equal to the maximum permissible value of 1.42 (Table XII). This indicates that the use of Equation 77 essentially maintains the present design practice as compared to the results from Figure 7 on which the existing AISI combined bending and web crippling provisions are based (Hetrakul and Yu, 1978). The coefficient of variation for the interaction equation values was equal to 0.197.

Table XI shows the reduction values from the Sivakumaran and Zielonka study (Eq. 6) and the current study (Eq. 77) for each test specimen which had a web crippling failure. Table XII shows three $(P_n)_{comp}$ values. These three values correspond to the results from Equations 34 and 35 and the reduced values from the reduction factor equations (Eqs. 6 and 77). The computation of $(P_n)_{comp,\ web\ opening}$ using the reduction factor equations is shown in Equation 2. Table XII also shows the $(P_n)_{test\ adj}/(P_n)_{comp}$ values using the three $(P_n)_{comp}$ values for all tests that failed in web crippling.

The value of Φ (Eq. 55) and the value of $(F.S)_{LRFD}$ (Eq. 56) are also shown in Table XII. Comparison of the results from Table XII shows that the use of the reduction factor equation from Sivakumaran and Zielonka (Eq. 6) and the current study (Eq. 77) provide nearly identical results in increasing the mean $(P_n)_{test\ adj}/(P_n)_{comp}$ value to account for web openings.

The mean $(P_n)_{test\ adj}/(P_n)_{comp}$ using the reduction factor from Sivakumaran and Zielonka (Eq. 6) and the current study (Eq. 77) were 0.972 and 0.976, respectively. However, this effect is the aggregate for the full range of α values tested. Because Equation 6 does not consider the effect of the web opening in relation to the load plate, it is less conservative at low α values, and more conservative for high α values, than those based on Equation 77 from the current study. Furthermore, Equation 6 has no provision for allowing $(P_n)_{comp,\ web\ opening}$ to be equal to $(P_n)_{comp,\ solid\ web}$ at high α values, where the test results show that the web opening at high α values does not degrade web crippling strength.

Table XII shows that the mean factor of safety for the solid web tests was 2.07. The computation for this mean value excluded the results from the cross sections with high F_y values, which were cross-sections IOF-SU-9 and IOF-SU-10. This mean is 12 percent higher than the factor of safety of 1.85 which is incorporated into Equations 34 and 35. The difference between the factors of safety is due to the effect of the coefficient of variation for the $(P_n)_{test\ adj}/(P_n)_{comp}$ values, which was 0.210 for this phase of the investigation. The coefficient of variation is greater than the coefficient of variation of 0.163 from the previous IOF web crippling tests used in the development of the current AISI Specification IOF web crippling provisions (Hetrakul and Yu, 1978). However, the coefficient of variation from Hetrakul and Yu (1978) is based on tests which had $(M_n)_{test}/(M_n)_{comp}$ values less than 0.30. The average $(M_n)_{test}/(M_n)_{comp}$ value for the 44 solid web tests from the current study, excluding cross-sections IOF-SU-9 and IOF-SU-10, was 0.448. Therefore, the increase in the coefficient of variation was partially caused by the scatter associated with the bending and web crippling interaction phenomenon in the current study.

The Φ value for all tests with F_y values less than 70 ksi was 0.598 prior to use of Equation 77, and was 0.696 with use of Equation 77 (Table XII). Hence, the use of Equation 77 significantly reduced the variance attributed to the web opening parameters. Although the Φ value of 0.696

is less than the Φ_w value from the AISI LRFD Specification (AISI, 1991a) for single web sections of 0.75, no modification to Φ_w is needed because of the approximate equality of the two resistance factors.

H. SUMMARY OF THE IOF UNREINFORCED WEB OPENING STUDY

A total of 148 specimens were tested for the IOF loading condition. Analysis of IOF test data provides a simple and practical reduction factor (Eq. 77) to be applied to AISI Equation C3.4-4 (Eqs. 34 and 35). Use of the reduction factor equation can readily be implemented in practice to ensure that the design for the limit states of web crippling and combined bending and web crippling can be accomplished with adequate strength, stability, and serviceability. The reduction factor equation is a function of the α and a/h values of the design situation. A joint region of α and a/h was identified that requires no strength reduction. The reduction factor is valid for bearing lengths, N, greater than three inches, and for all sections that satisfy the ranges of applicability stated herein. Additionally, bending interaction using AISI Eq.3.5-1 (Eqs. 42 and 43) must be checked. Other failure modes, i.e. shear, flexure, and combinations thereof, must be checked separately.

SECTION V. END-ONE-FLANGE AND INTERIOR-ONE-FLANGE REINFORCED WEB OPENING STUDY

A. INTRODUCTION

1. General. This section comprises the complete findings of the UMR study on the web crippling behavior of single reinforced webs for cold-formed steel flexural members with web openings subjected to the end-one-flange, EOF, or interior-one-flange, IOF, loading conditions (Fig. 1). This is the first known study of the effect for reinforced members with web openings subjected to the EOF or IOF loading conditions. The experimental investigation, test procedure, evaluation of test results, and design recommendations provided in this section are independent of those in Section III, EOF Unreinforced Web Opening Study, and Section IV, IOF Unreinforced Web Opening Study.

Sections III and IV dealt only with unreinforced webs. With the exception of the addition of the web reinforcement, the configuration of the test specimens, test setup, and testing procedure used in this phase of the study for sections with reinforced webs, remained the same as stated in Sections III and IV. Both web reinforced EOF and IOF tests were performed during this phase of the study and are discussed herein.

The primary results of the study are design recommendations which are in the form of web reinforcement configurations and the limits of applicability of the web reinforcement configurations.

In the following discussion, the term 'base' specimen or section is the original specimen or section prior to the attachment of web reinforcement, and therefore applies to a web reinforced test specimen or section with web openings, but includes all portions of the specimen or section except the web reinforcement and self-drilling screw connectors.

2. Reasons for Providing Web Reinforcement for Web Crippling. For situations when web crippling is the controlling limit state for a section with web openings, web reinforcement of a section can possibly be an economical alternative as compared to increasing the allowable web crippling capacity of the unreinforced member. The practicality of the web reinforcement can be enhanced when the web reinforcement material is obtained from excess portions of the same cross section. The nominal and allowable capacities of an unreinforced member with web openings, $(P_n)_{comp,\ web\ opening}$ and $(P_a)_{comp,\ web\ opening}$, can be determined from Equations 2 and 3, respectively.

As seen from the parameters of Equations 30 thru 35, there are many options available for increasing the web crippling strength of a section. Specifically, this can be accomplished by either of two means: First, selecting a section with appropriate cross-section properties or by increasing the value of N as required to increase the value of $(P_a)_{comp,\ solid\ web}$ or $(P_n)_{comp,\ solid\ web}$, or, second, selecting α

and a/h values to increase the value from the reduction factor equations (Eqs. 6, 68, and 77).

However, in many situations it may not be economical or practical to change the value of the parameters influencing $(P_a)_{comp,\ solid\ web}$ or $(P_n)_{comp,\ solid\ web}$ by procuring a section with the required cross-section properties or by increasing the bearing length. Likewise, it may not be practical to change the parameters of the applicable reduction factor equation by selecting a cross section with a smaller height of web opening or by relocating the web opening. As given in Section I.A, General Remarks, typically, web openings are located every two feet, center-to-center, and procurement of a section with a modified web opening spacing may be uneconomical and difficult. Also, efforts to increase α by relocating the web opening may be impractical due to the interrelation between other web openings and their nearby concentrated loads. Furthermore, efforts to increase the value of the applicable reduction factor equation may be ineffectual because of the maximum reduction factor limit of unity for Equations 6, 68, and 77.

Therefore, when the value of $(P_n)_{comp,\ web\ opening}$ (Eq. 2) or $(P_a)_{comp,\ web\ opening}$ (Eq. 3) cannot be increased because of expense or impracticality, it is possible that the placement of web reinforcement may be the most viable alternative for increasing the web crippling capacity of a member. Furthermore, unlike many failures such as those caused by flexure, axial loading, shear, and lateral instability, web crippling is a localized condition. It may be wasteful to limit the load capacity of a structural member due to the inadequacy of the member over a short portion of its length or, conversely, by selecting a section with a greater overall capacity simply because of localized conditions at a few concentrated loads.

Increasing the web crippling capacity of sections without web openings by providing web reinforcement may also be performed under similar circumstances. This can be accomplished in accordance with the AISI Specification, Section B6, Stiffeners (AISI, 1986, and AISI, 1991a). However, this subject was not included as part of the investigation, because, the results of the current study do not claim any web crippling strength which exceeds that of the solid web-unreinforced section. Therefore, if achieving the solid web strength by adding web reinforcement is insufficient, a more substantial cross section or greater bearing length must be used to increase the value of $(P_n)_{comp,\ web\ opening}$ or $(P_a)_{comp,\ web\ opening}$. The web reinforcement configurations given herein do not necessarily satisfy the requirements of Section B6 of the Specification.

B. PURPOSE

The purpose of this phase of the research was to investigate the web crippling behavior of single reinforced webs with web openings subjected to the EOF and IOF loading conditions.

The primary goals of this study were to examine the EOF and IOF web crippling behavior under several simple and practical web reinforcement configurations. The purpose was to determine if web reinforcement of specimens with web openings would achieve web crippling strengths of the solid web-unreinforced sections for the same cross section at the same bearing length, N, and same loading condition, i.e. either the EOF or IOF loading condition. Additional information on this topic is provided in Section V.D.2, Generalization of Results.

Web reinforcement configurations which achieve the web crippling strength of the solid web-unreinforced section at the same value of N are compared and contrasted, resulting in recommendations for the optimal design. Consideration is given to economy and accessibility of the web opening for services, i.e. some web reinforcement configurations are tested which partially or fully cover the web opening. The web reinforcement configuration that provided the greatest capacity was not necessarily selected as the optimal web reinforcement configuration.

C. EXPERIMENTAL INVESTIGATION

1. Test Specimens.

a. General. The test specimens were fabricated from industry standard C-sections with web openings centered at the mid-height of the web. Tests were limited to C-shaped sections with edge-stiffened flanges. Therefore, the flanges are classified as partially-stiffened in accordance with the AISI Specification (1986, and 1991a). The configuration of the test specimens was the same as discussed in Section III and Section IV with the exception of the attachment of web reinforcement. For the web reinforced specimens, each of the two C-sections comprising each specimen had one section of web reinforcement attached, such that symmetry was maintained between the two sections comprising the test specimen.

Three cross sections were selected for the study. The properties of the cross sections used in the web reinforcement study are given in Table III, and are shown in Figures 2 thru 4. Figures 2 and 3 apply to the EOF loading condition, and Figures 2 and 4 apply to the IOF loading condition. The web openings were rectangular with fillet corners.

The selection of the cross sections was based primarily on having a/h ratios and b values approaching the maximum limits permitted in standard practice. The maximum limits permitted in standard practice for b and a/h are 4.5 inches and 0.50, respectively. From Table III, the three cross sections had a/h ratios equal to approximately 93 percent of the maximum permissible value of 0.50. For all three cross sections, the b value was four inches, which is approximately 90 percent of the maximum permissible value of 4.5 inches. A secondary consideration for the selection of the cross sections was a range of h/t ratios; the h/t ratios varied from 48 to 98.

All N values for the EOF and IOF tests were equal to one inch and three inches, respectively. These values correspond to the minimum values used in previous phases of the current investigation and the minimum allowable values for application of the previously provided EOF and IOF reduction factor equations, Equations 68 and 77.

b. Web Reinforcement Configurations. The web reinforcement material was taken from the same cross section as the base specimen, and was attached web-to-web to the base specimen with the flanges of the web reinforcement oriented in the same direction and in the same plane as the flanges of the base specimen (Figs. 41 thru 50). The full height of the web reinforcement was used, and the web reinforcement's flanges and flange edge-stiffeners were retained. The horizontal length of the web reinforcement is designated as L_s (Fig. 51). The vertical distance between the centerline of the top and bottom horizontal rows of connections to the top and bottom of the web reinforcement is designated S_V (Fig. 51). The horizontal distance from the centerline of a connection to the nearest vertical edge of the web reinforcement is designated S_H (Fig. 51).

Two general classifications of web reinforcement configurations for both the EOF and IOF loading conditions were investigated. These two classifications, Type 1 and

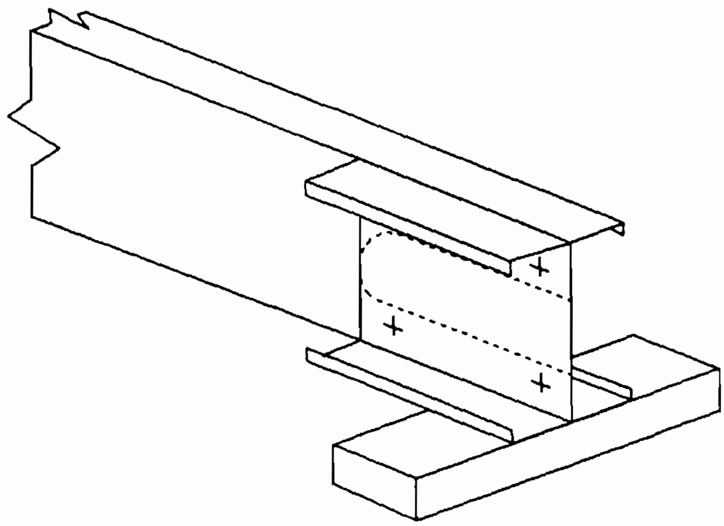


Figure 41: EOF Type 1a Web Reinforcement Configuration

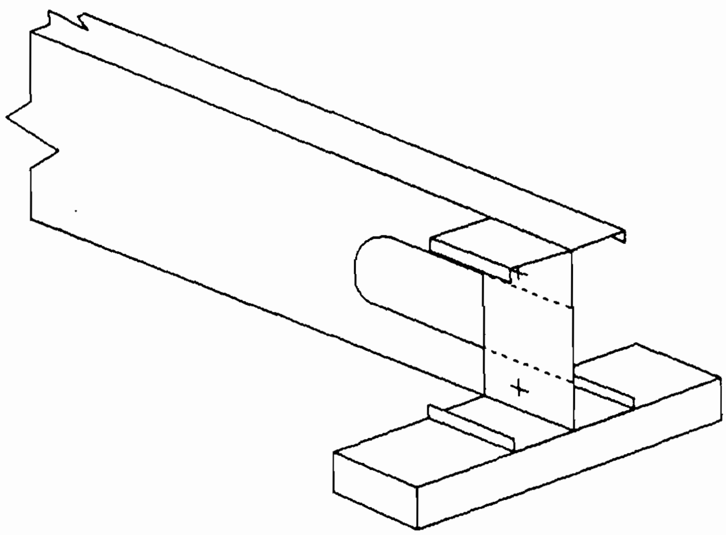


Figure 42: EOF Type 1b Web Reinforcement Configuration

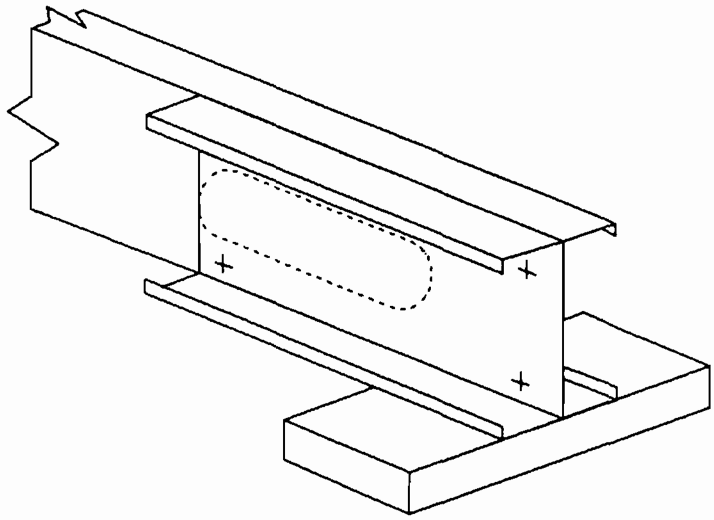


Figure 43: EOF Type 2a Web Reinforcement Configuration

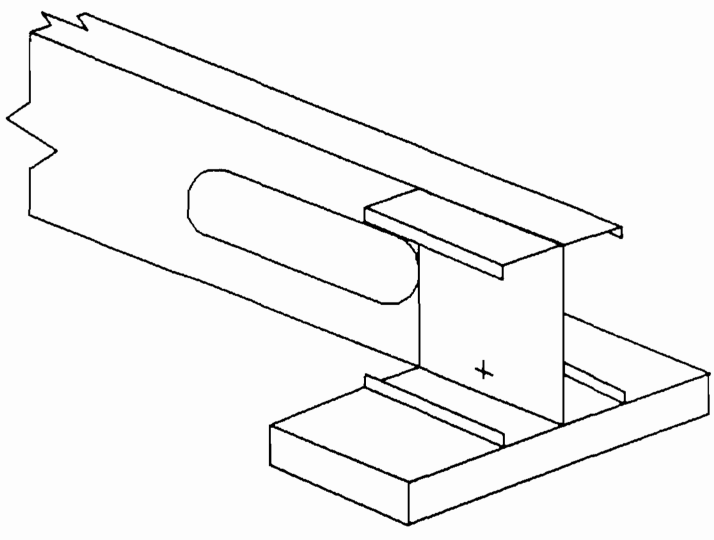


Figure 44: EOF Type 2b Web Reinforcement Configuration

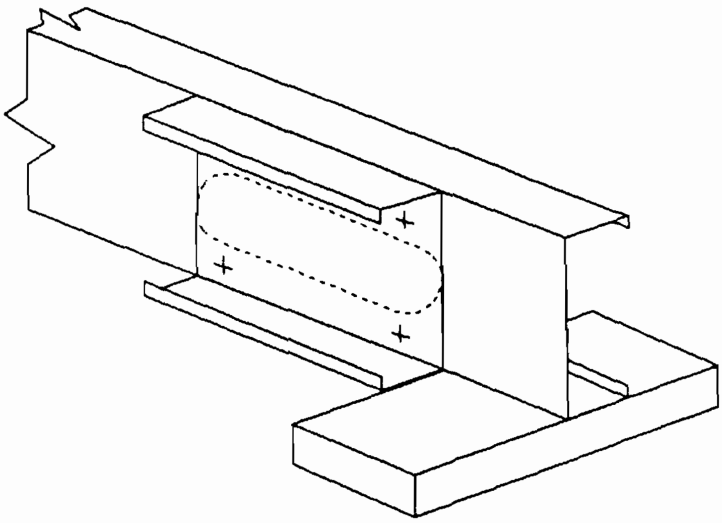


Figure 45: EOF Type 2c Web Reinforcement Configuration

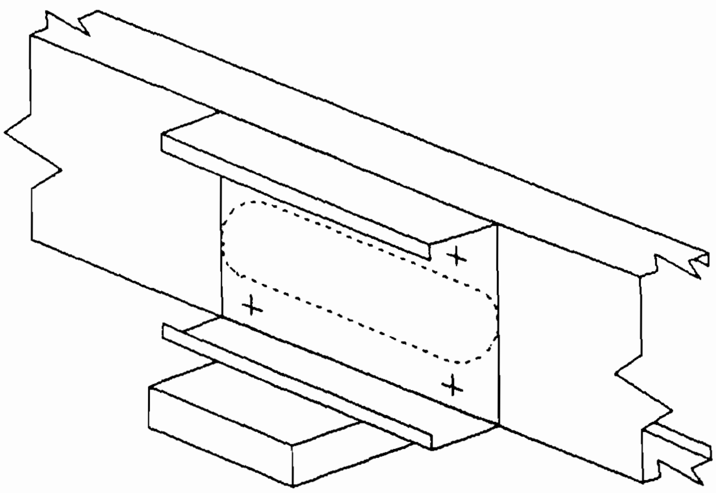


Figure 46: IOF Type 1a Web Reinforcement Configuration

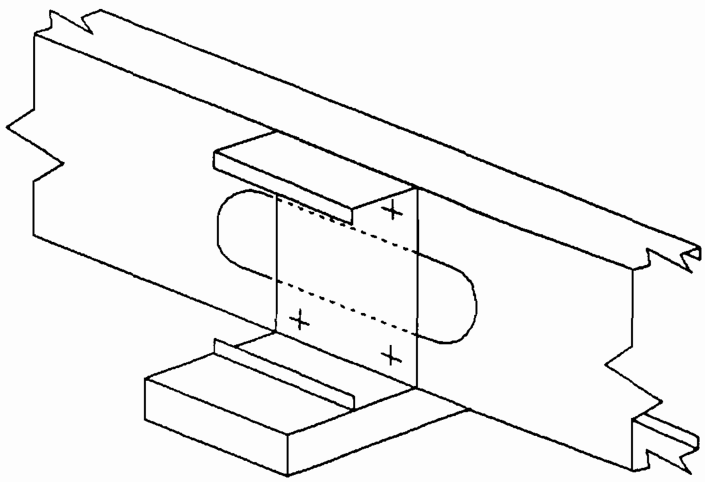


Figure 47: IOF Type 1b Web Reinforcement Configuration

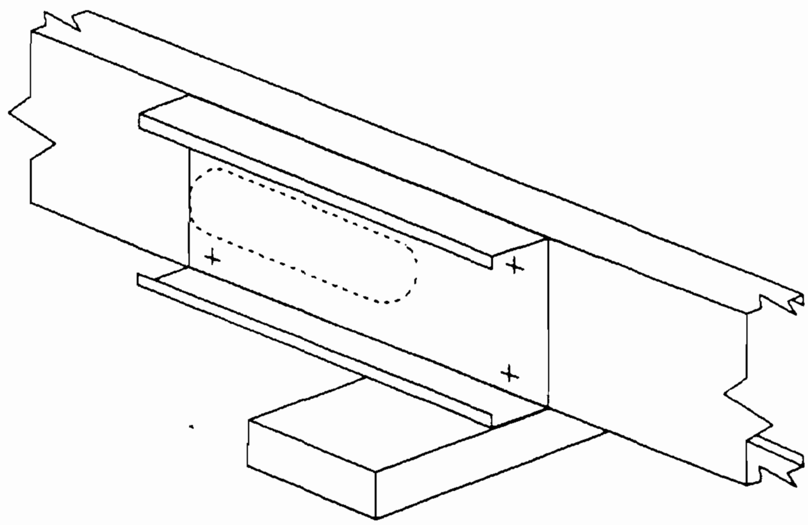


Figure 48: IOF Type 2a Web Reinforcement Configuration

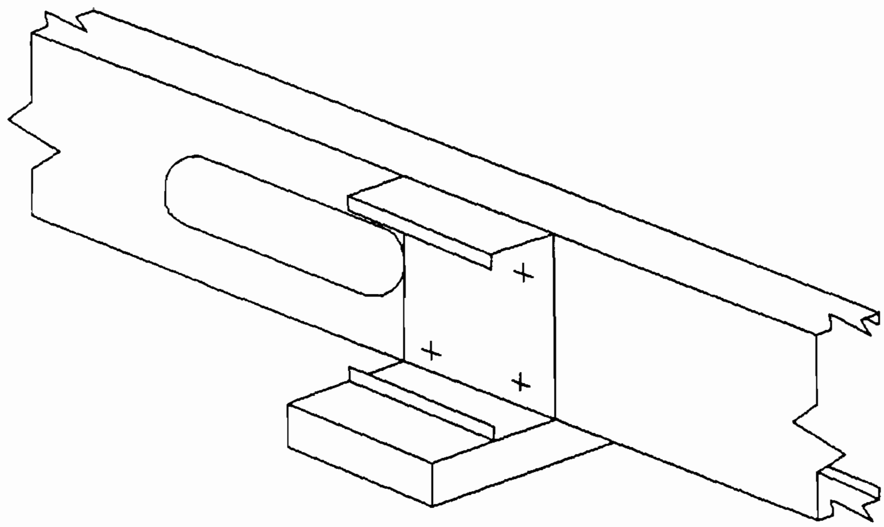


Figure 49: IOF Type 2b Web Reinforcement Configuration

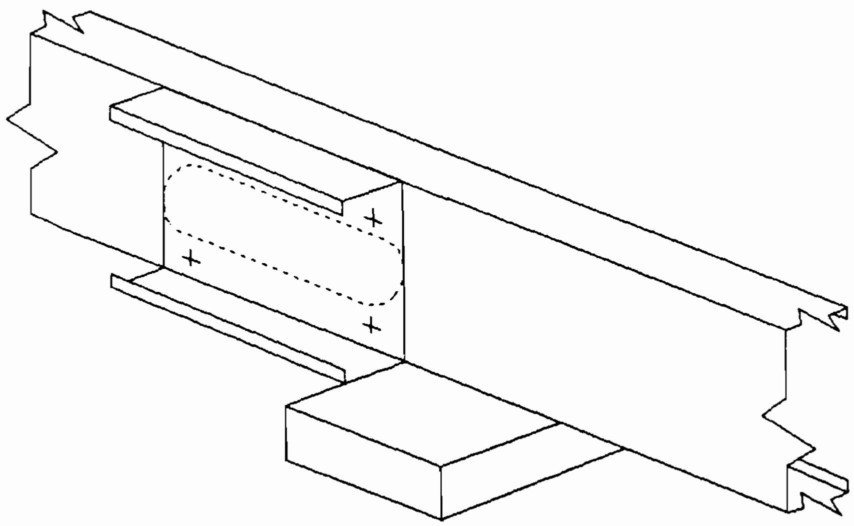


Figure 50: IOF Type 2c Web Reinforcement Configuration

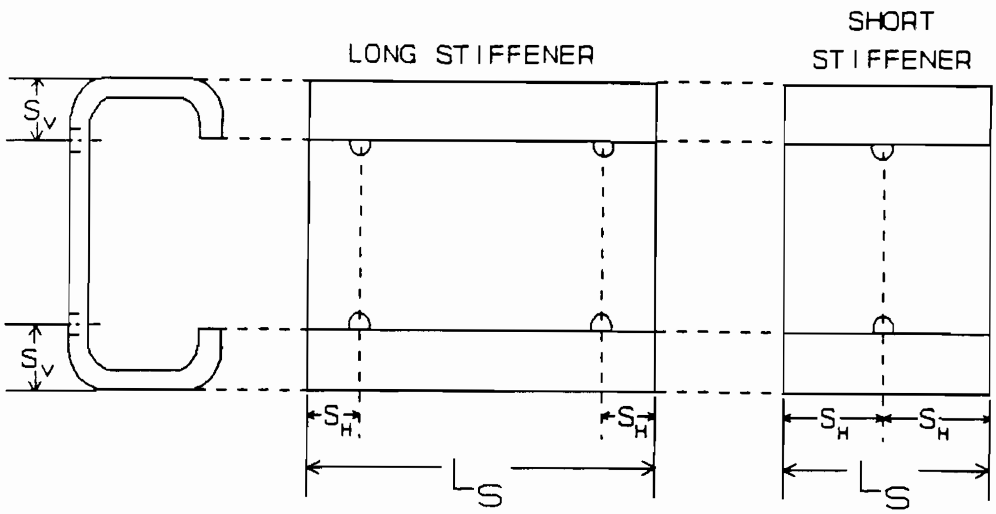


Figure 51: Locations of Web Reinforcement Connections

Type 2, are distinguished by the relative longitudinal positions of the load plate with respect to the web opening. Type 1 corresponds to the condition when any portion of the web opening is located below or above the longitudinal location of the load plate. Type 2 corresponds to the condition of no portion of the web opening being located above or below the longitudinal location of the load plate. The Type 2 web opening condition was used for the unreinforced web EOF and IOF investigations reported herein. Specifically, for all previous tests with web openings, α (Figs. 3 and 4) was greater than or equal to zero. The EOF Type 2 (Figs. 43 thru 45) and IOF Type 2 (Figs. 48 thru 50) web reinforcement configurations are depicted with an arbitrary α value of zero.

Tests were conducted for the four combinations of EOF or IOF loading and Type 1 or Type 2 web opening location. The combinations are designated EOF Type 1, EOF Type 2, IOF Type 1, and IOF Type 2. Within each of these four groups, different web reinforcement configurations are denoted by the addition of a letter designator of a, b, or c (Figs. 41 thru 50). Each of the four different situations were considered separately, and the results, discussion, and recommendations for the four situations are provided separately herein.

i. <u>End-One-Flange Web Reinforcement Configurations.</u> For the EOF tests, five types of web reinforcement configurations were tested in addition to the solid web-unreinforced configuration. Two web reinforcement configurations for the EOF Type 1 condition were studied, and are designated as EOF Type 1a (Fig. 41) and EOF Type 1b (Fig. 42). Three web reinforcement configurations for the EOF Type 2 condition were studied, and are designated as EOF Type 2a (Fig. 43), EOF Type 2b (Fig. 44), and EOF Type 2c (Fig. 45).

Figures 41 thru 45 show the end of the section coincident with the outside edge of the EOF load plate. In general, this is not required because, by the AISI definition of end loading, the section may extend a maximum distance of 1.5h beyond the load plate (Fig. 1). For all EOF tests performed during this phase of the investigation and as given in Section III, the end of the specimen coincided with the outside end of the EOF bearing plate. The AISI Specification (1986, and 1991a) disregards the additional strength provided by the extension of a member beyond the load plate until the extension exceeds a distance of 1.5h, where the condition changes immediately to an interior loading condition. Hence, the adopted test procedure used the worst case EOF scenario for this particular issue by ending the section at the outside edge of the end bearing.

(a) EOF Type 1 Web Reinforcement Configurations. For this study, a special circumstance of the EOF Type 1 condition was used: specifically, when the maximum height of the web opening, a, was continued to the end of the section. For typical ranges of N and the remaining portion of b, this situation is assumed to provide the greatest possible strength reduction for EOF loading for a section with an unreinforced web opening.

The web reinforcement for the EOF Type 1a tests extended from the outside edge of the load plate to the interior end of the web opening as shown in Figure 41. Because the fillet radius of the web openings for all cross sections was 0.75 inches, the remaining length of the web opening and therefore L_s was equal to b less the web opening fillet radius. Hence, L_s was equal to 3.25 inches. The reinforcement for the EOF Type 1b tests extended the length of the bearing as shown in Figure 42. Therefore, L_s was equal to N = 1 inch.

(b) EOF Type 2 Web Reinforcement Configurations. For the study, a special circumstance of the EOF Type 2 condition was used: specifically, the situation where α (Fig. 3) equals zero was used. As determined from the previous EOF tests on unreinforced specimens (Section III) this situation results in the greatest strength reduction for EOF loading when no portion of the web opening is located above the EOF reaction bearing.

For EOF Type 2a tests, the reinforcement extended from the end of the specimen to the interior end of the web opening as shown in Figure 43. Therefore, L_s was equal to the sum of b, x, and N (Fig. 3), which equals five inches. For the EOF Type 2b tests, the reinforcement extended along the length of the EOF reaction bearing as shown by Figure 44. Therefore, L_s was equal to N = 1 inch. For the EOF Type 2c tests, the reinforcement extended from the exterior to interior locations of the web opening as shown in Figure 45. Therefore, L_s was equal to b = 4 inches.

ii. Interior-One-Flange Web Reinforcement Configurations. For the IOF tests, five types of web reinforcement configurations were tested in addition to the solid web-unreinforced specimens. Two web reinforcement configurations for the IOF Type 1 condition were studied, and are designated as IOF Type 1a (Fig. 46) and IOF Type 1b (Fig. 47). Three web reinforcement configurations for the IOF Type 2 condition were studied, and are designated as IOF Type 2a (Fig. 48), IOF Type 2b (Fig. 49), and IOF Type 2c

(Fig. 50). Figures 46 thru 50 show the IOF load bearing below the specimen although the tests were conducted with the IOF mid-span loading plate above the specimen. The web opening location type designations, Type 1 and Type 2, and subsequent web reinforcement configuration letter designations for the IOF tests closely parallel those for the EOF tests. The relationship between the EOF and IOF web reinforcement configurations can readily be seen by comparing Figures 41 and 46, 42 and 47,..., and 45 and 50.

(a) IOF Type 1 Web Reinforcement Configurations. For the study, a special circumstance of the IOF Type 1 condition was used: specifically, the situation when the web opening was longitudinally centered on the IOF load plate. This situation corresponds to the tests performed by Sivakumaran and Zielonka (1989). This condition generally is assumed to provide the greatest possible strength reduction for IOF loading under the Type 1 situation. Discussion of the relationship between the web crippling behavior of this situation as compared to the Type 2 condition is provided in Section V.D.6, Comparison of IOF Type 1 and Type 2 Results, which discusses the different failure mechanisms and tested capacities of the two situations.

The unreinforced web tests using this condition are designated as IOF Type 1 with no subsequent letter designation. The web reinforcement for IOF Type 1a was located between the ends of the web opening as shown in

Figure 46. The length of the web opening and therefore L_s was equal to b = 4 inches. The reinforcement for IOF Type 1b was located along the longitudinal length of the bearing plate as shown in Figure 47. Therefore, L_s was equal to N = 3 inches.

(b) <u>IOF Type 2 Web Reinforcement Configurations.</u> For this study, a special circumstance of the IOF Type 2 condition was used: specifically, the situation where α (Fig. 4) equals zero. As determined in the previous IOF tests on unreinforced web specimens (Section IV) this situation results in the greatest strength reduction for IOF loading under the IOF Type 2 situation. For the IOF Type 2a tests, the reinforcement extended along the length of the load plate and web opening as shown in Figure 48. Therefore, L_s was equal to the sum of b, x, and N (Fig. 4), which equals seven inches. For the IOF Type 2b tests, the reinforcement extended along the length of the IOF load plate as shown in Figure 49. Therefore, L_s was equal to N = 3 inches. For the IOF Type 2c tests, the reinforcement extended along the length of the web opening as shown in Figure 50. Therefore, L_s was equal to b = 4 inches.

c. <u>Attachment of Web Reinforcement.</u> The web reinforcement was attached to the base specimens using four number 12 self-drilling screws, with the exception of the EOF Type 1b (Fig. 42) and EOF Type 2b (Fig. 44) configurations, which had two number 12 self-drilling screw connectors. Two screws were used for these two configurations because of the small L_s value of one inch. All web reinforcement configurations had S_V values (Fig. 51) of 1/2 inch.

Because the three cross sections had h values approximately equal to 3.25 inches, only two horizontal rows of connectors were used. It was desired to have the maximum practical vertical distance between the top and bottom horizontal rows of connectors. The access to the inside face of the web of the base specimen and web reinforcement available for the placement of the screws was limited by the vertical projection of the edge-stiffener of the flanges.

The distance of S_V equal to 1/2 inch provided the minimum necessary clearance, and therefore dictated the maximum vertical distance between the top and bottom rows of connectors. In general, for sections with no flange edge-reinforcements, or with a small value of d_f (Fig. 2), the S_V value (Fig. 51) should equal the sum of t, R, and one-half of the fastener diameter. This would provide a vertical distance between the top and bottom horizontal rows of connectors equal to h minus the diameter of the fastener. However, the centers of the screw fasteners cannot be closer than three times the nominal screw diameter (CCFSS, 1993).

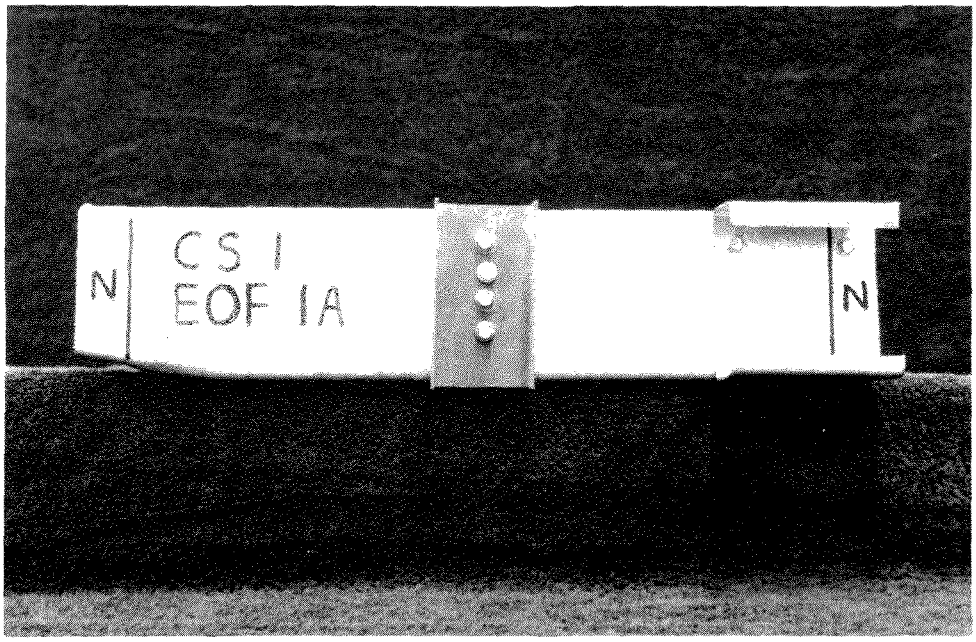
The S_H (Fig. 51) values for all configurations was 1/2 inch. This S_H value resulted for the EOF Type 1b and EOF Type 2b configurations because this was half of the L_S value of one inch.

2. <u>Test Procedure.</u> The test procedure used for the EOF and IOF web reinforced test specimens was the same as that reported in Section III and Section IV. This includes the procedure for the application of the load and the criteria defining failure of the test specimens.

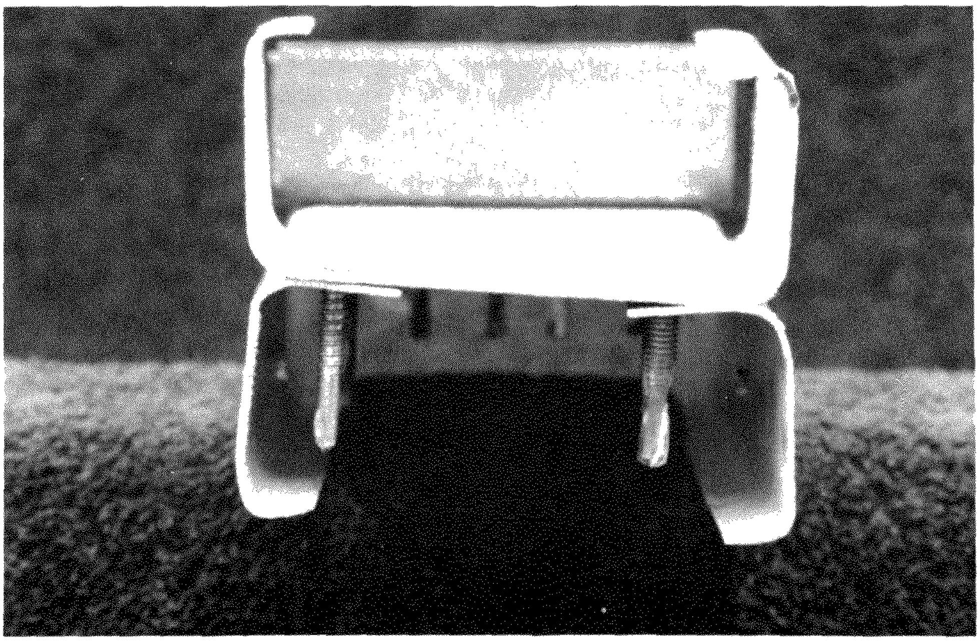
D. <u>EVALUATION OF TEST RESULTS</u>

1. <u>General.</u> The performance of the web reinforcement configurations is provided in this paragraph. Although the connections are an integral part of the web reinforcement configurations, the performance of the connections is evaluated separately in Section V.F, Connections. This was necessitated because the design recommendations given in Section V.E were used extensively in evaluating the performance of the connections of the recommended web reinforcement configurations. Failures exhibited by the test specimens are shown in Figures 52 thru 62.

For this study, 78 tests were conducted, with 26 tests performed on each of the three cross sections. Two identical specimens were tested for each configuration for each cross section. For each cross section, 12 EOF tests were conducted: two solid web tests and two tests using each of the five EOF types of web reinforcement configurations, 1a, 1b, 2a, 2b, and 2c. For each cross section, 14 IOF tests were conducted: two solid web tests, two unreinforced tests using the configuration reported by Sivakumaran and Zielonka (1989), Type 1, and two tests using each of the

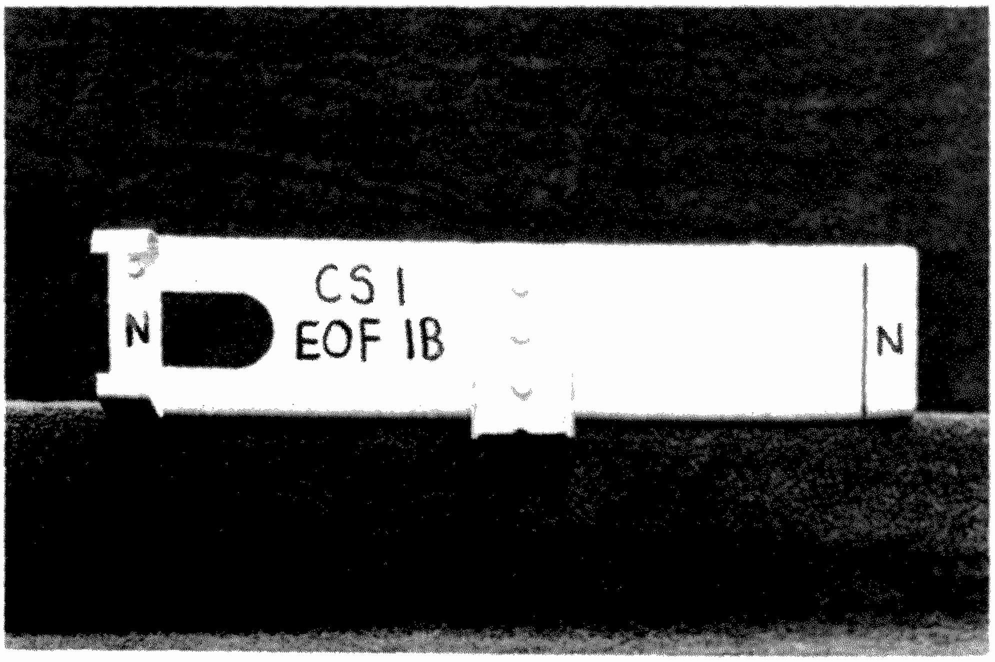


(a)

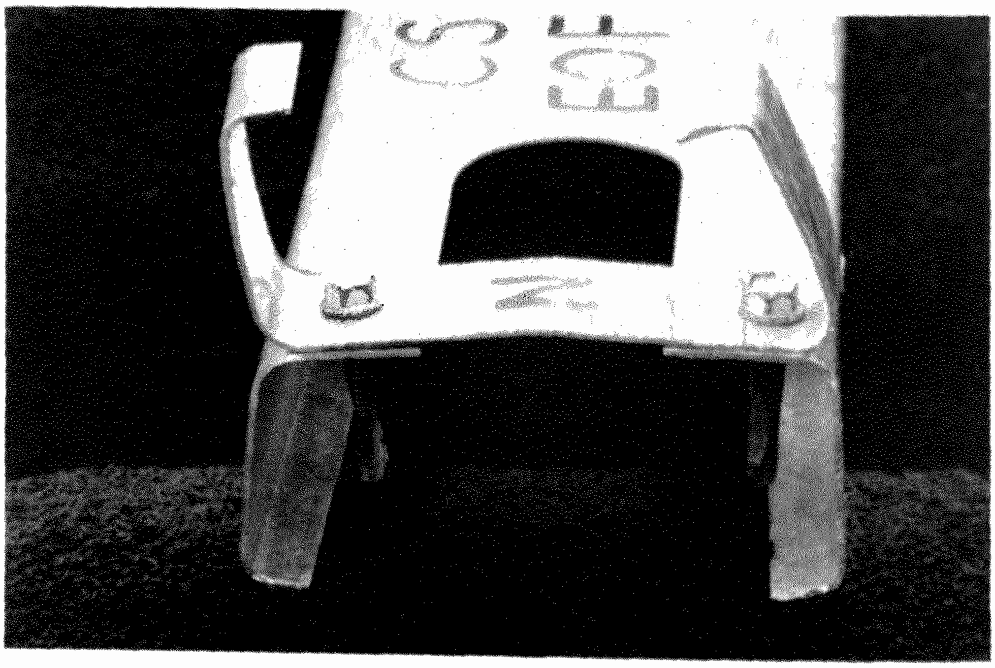


(b)

Figure 52: Typical EOF Type 1a Failure



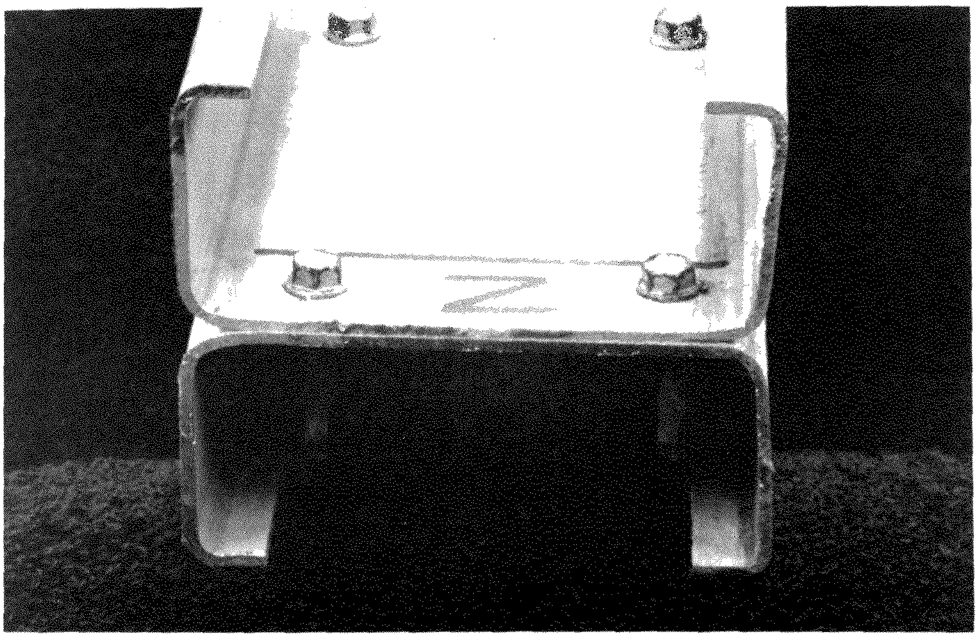
(a)



(b)

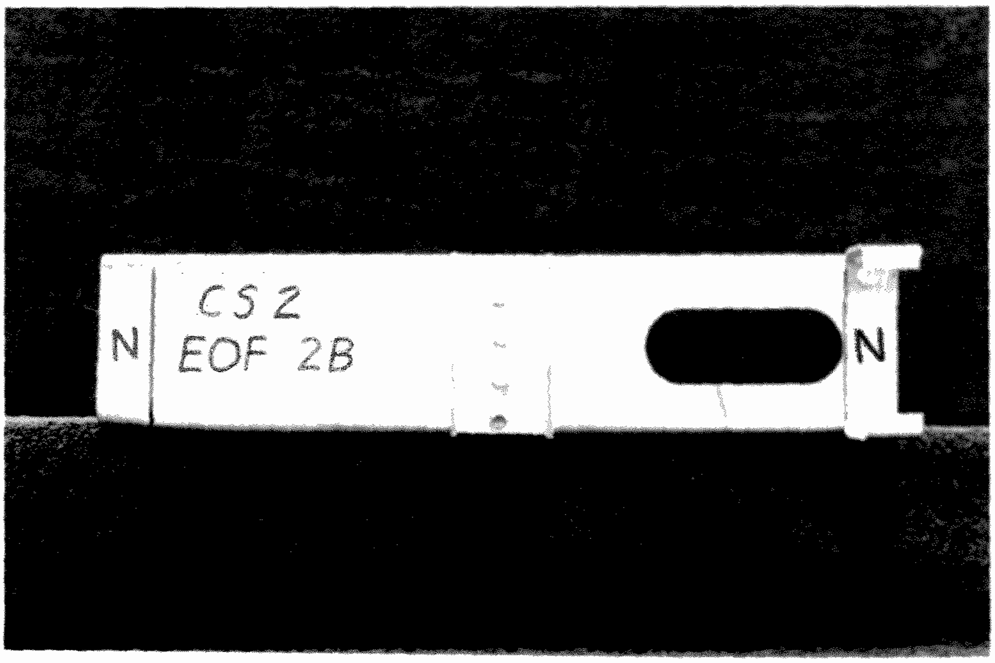
Figure 53: Typical EOF Type 1b Failure

(a)

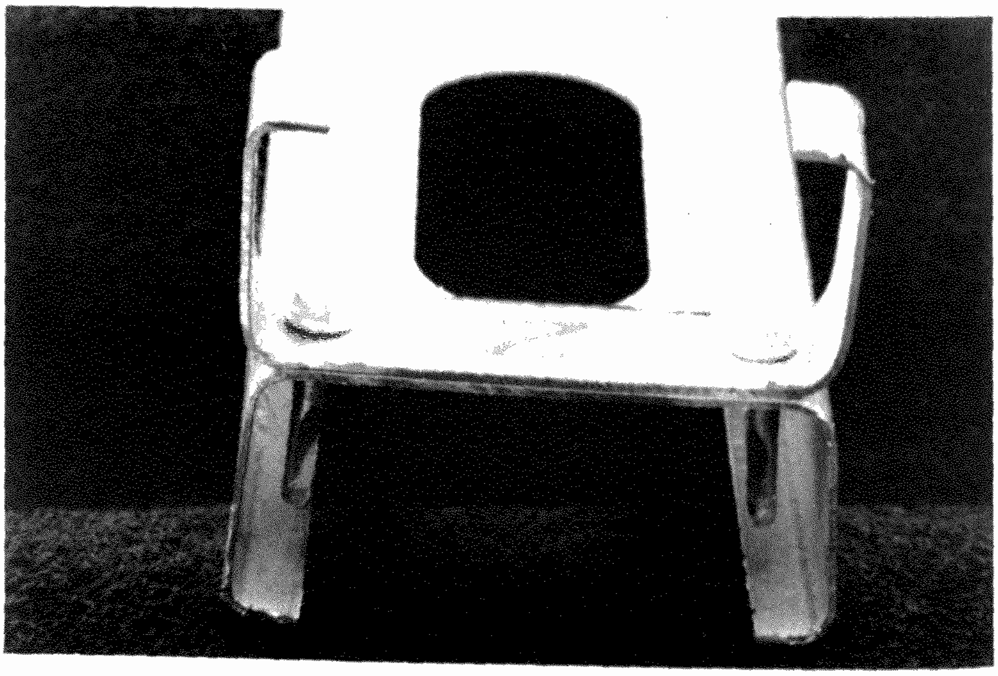


(b)

Figure 54: Typical EOF Type 2a Failure



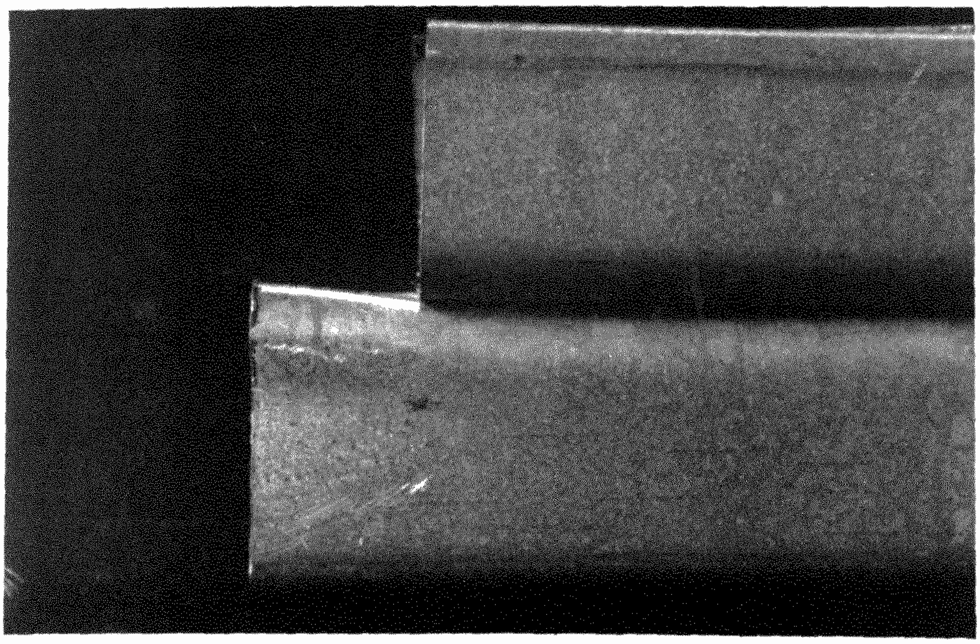
(a)



(b)

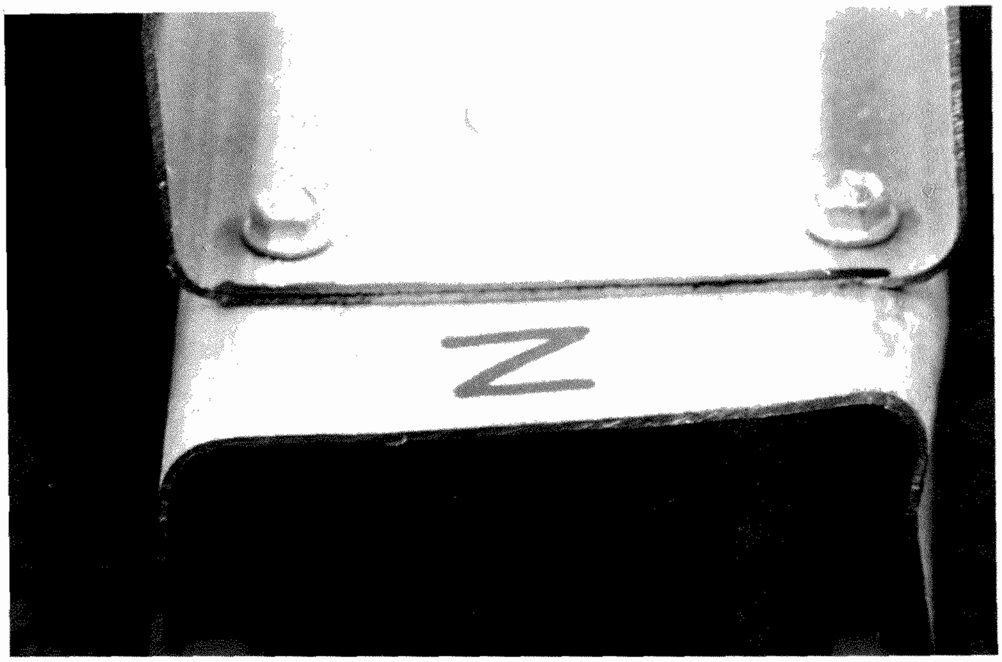
Figure 55: Typical EOF Type 2b Failure

(a)



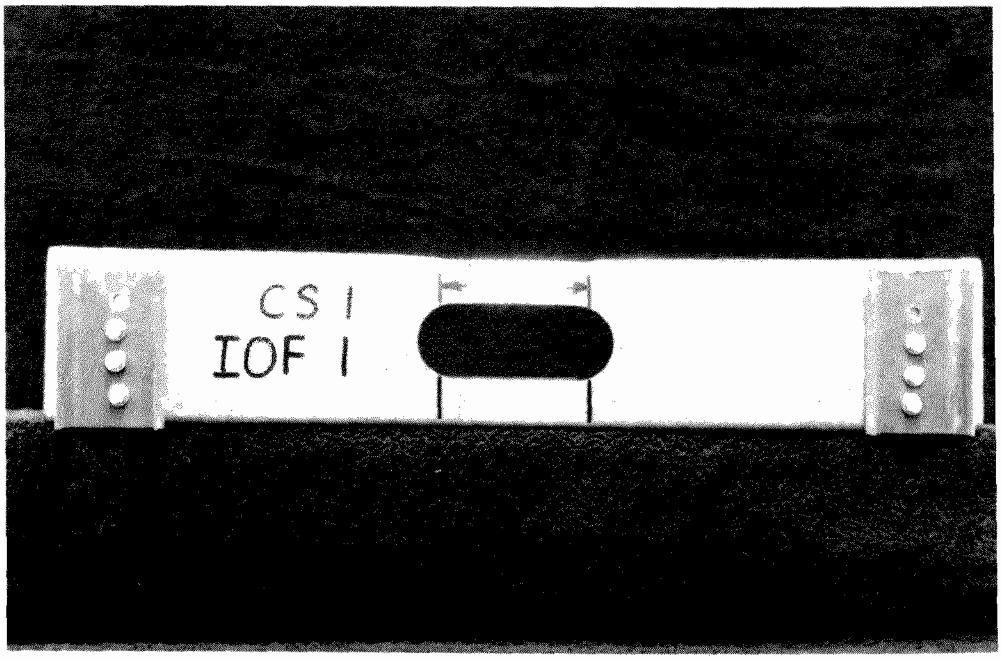
(b)

Figure 56: Typical EOF Type 2c Failure



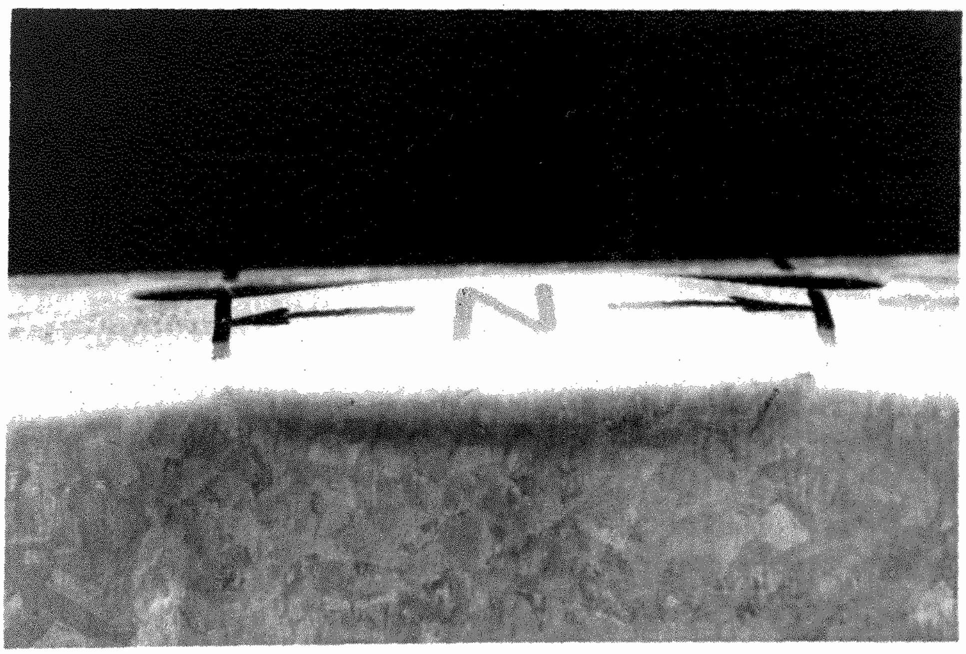
(c)

Figure 56: Typical EOF Type 2c Failure (cont.)

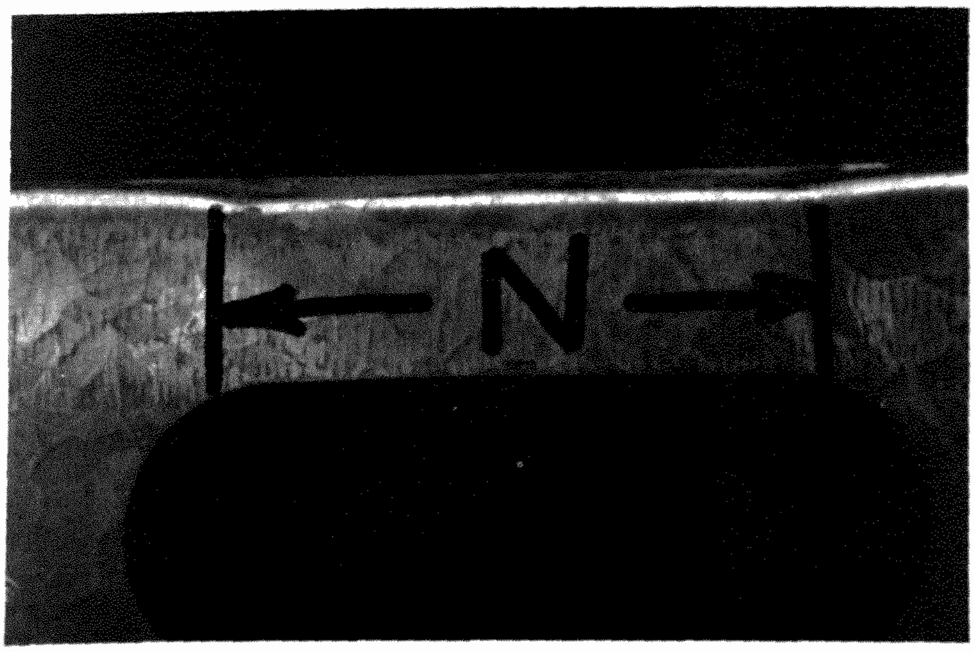


(a)

Figure 57: Typical IOF Type 1 Failure



(b)



(c)

Figure 57: Typical IOF Type 1 Failure (cont.)

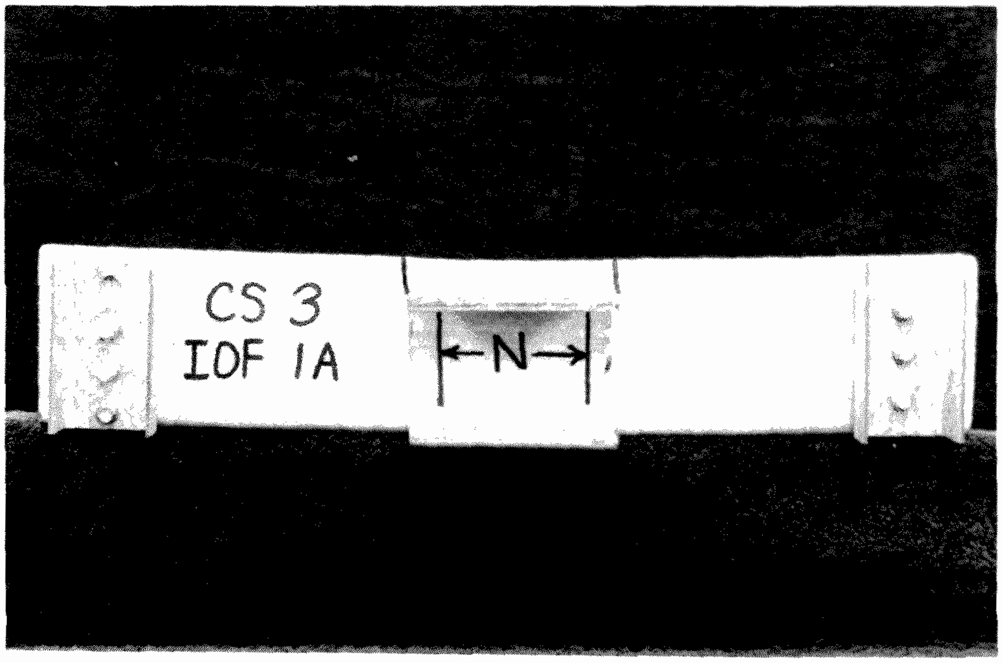
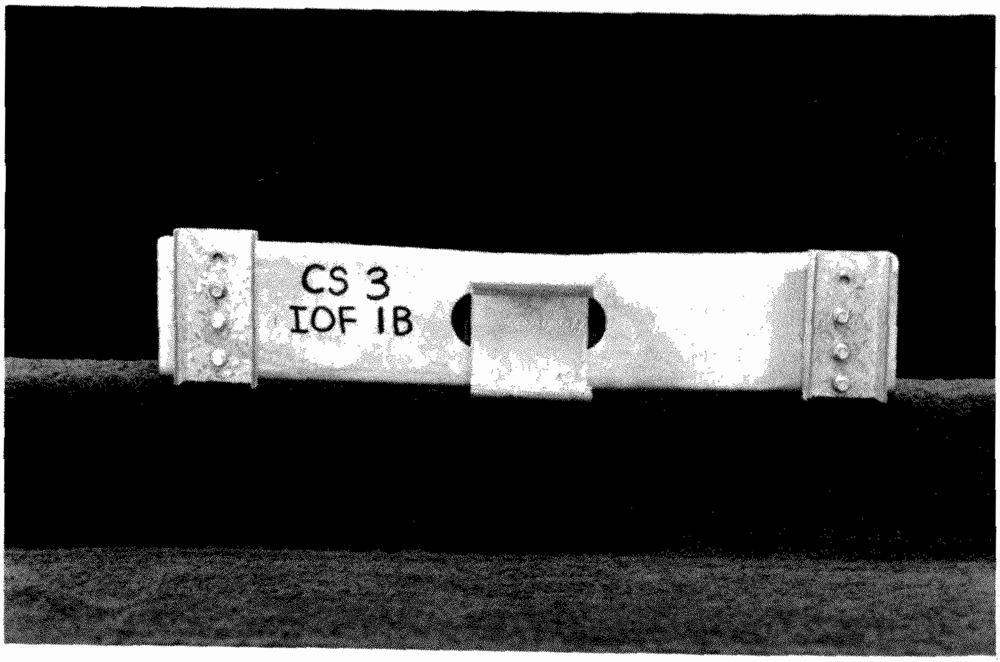
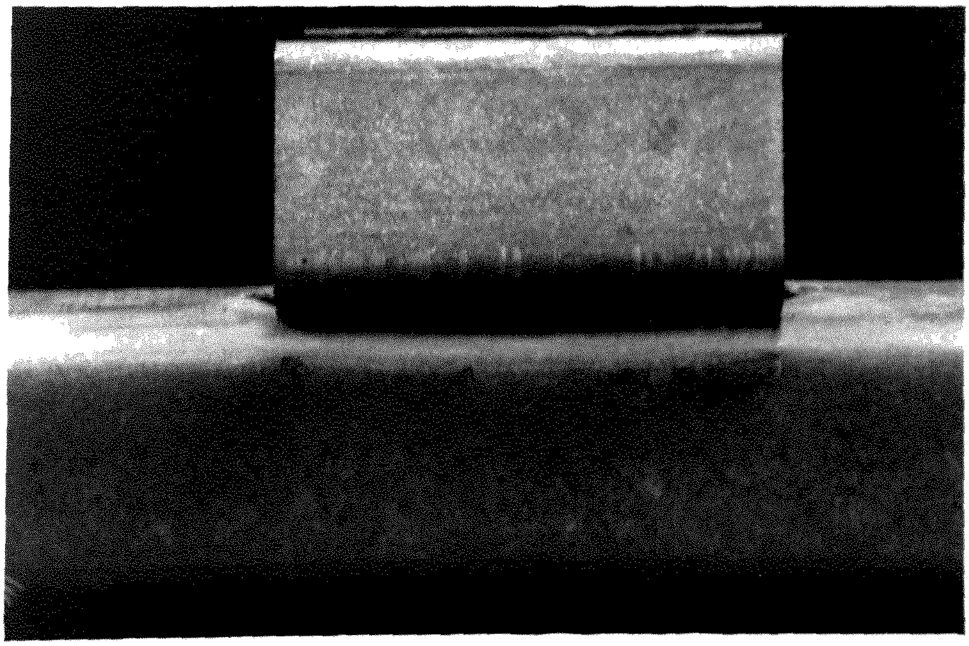


Figure 58: Typical IOF Type 1a Failure



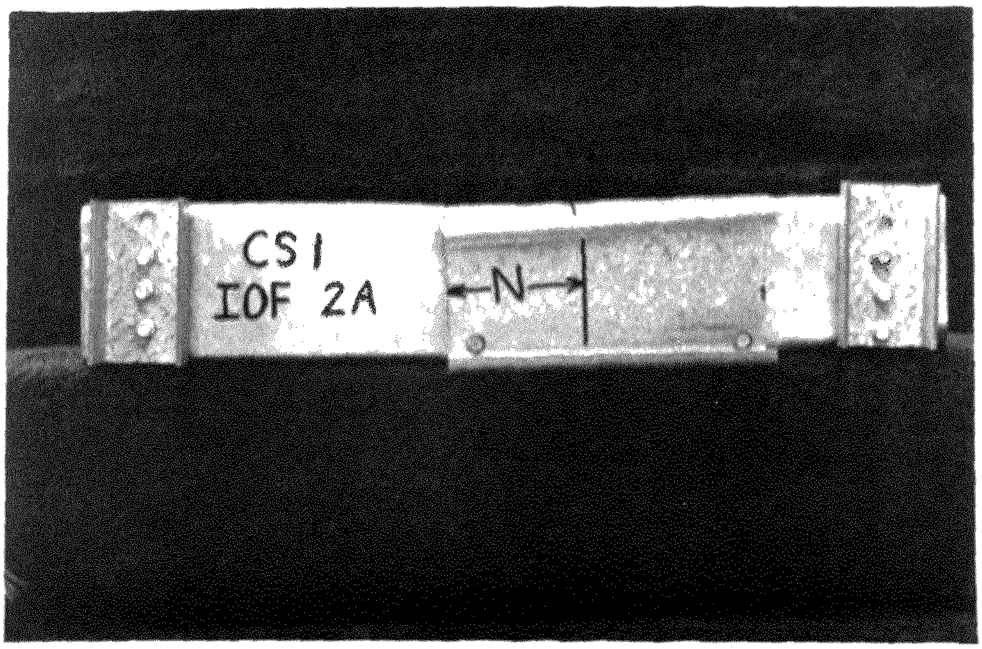
(a)

Figure 59: Typical IOF Type 1b Failure



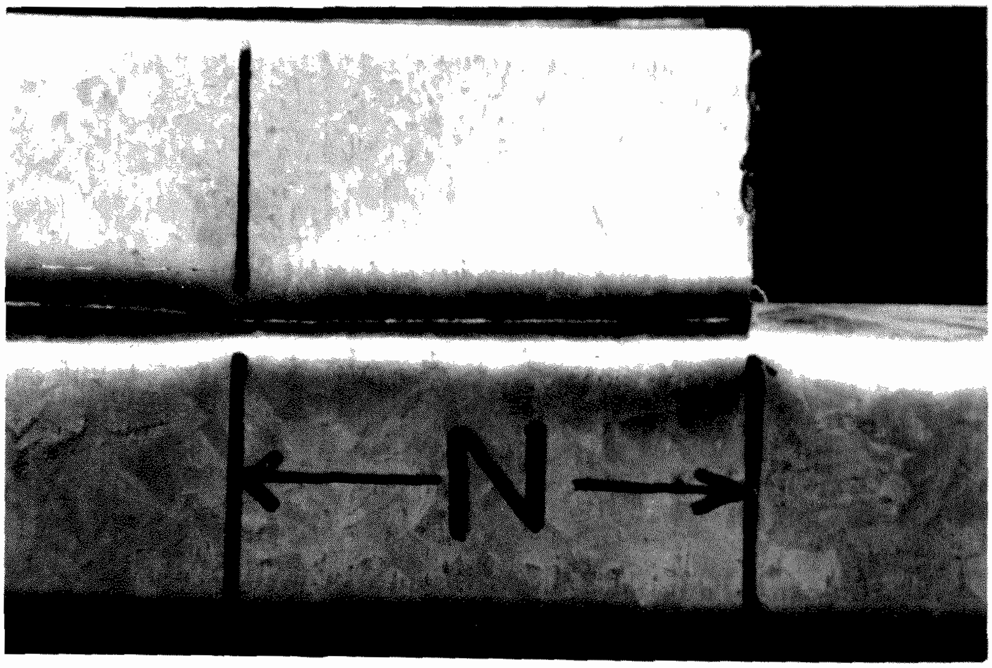
(b)

Figure 59: Typical IOF Type 1b Failure (cont.)

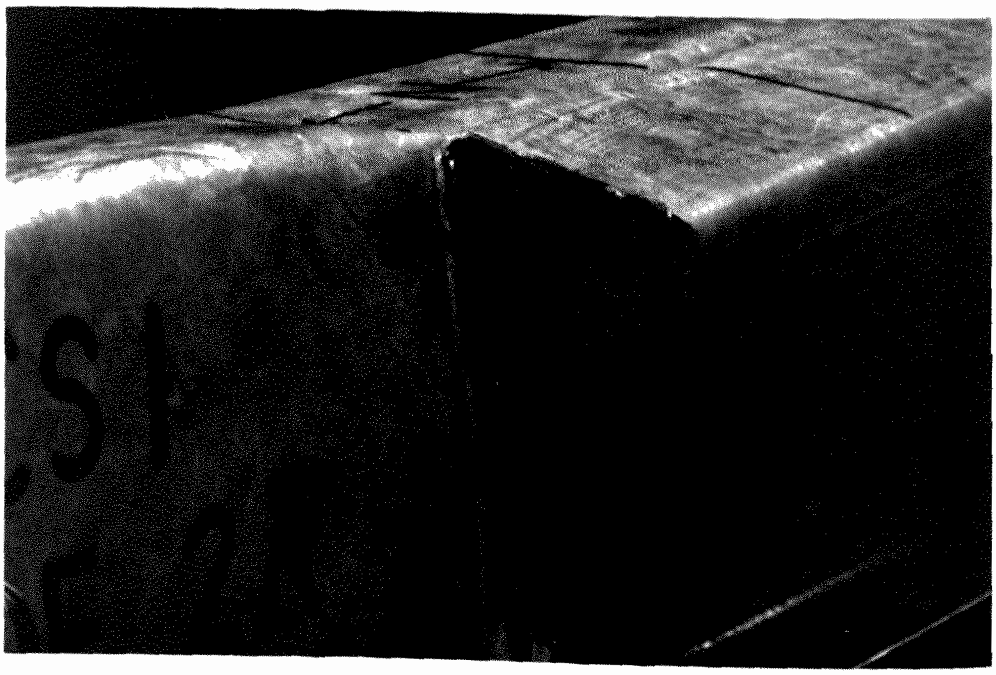


(a)

Figure 60 Typical IOF Type 2a Failure

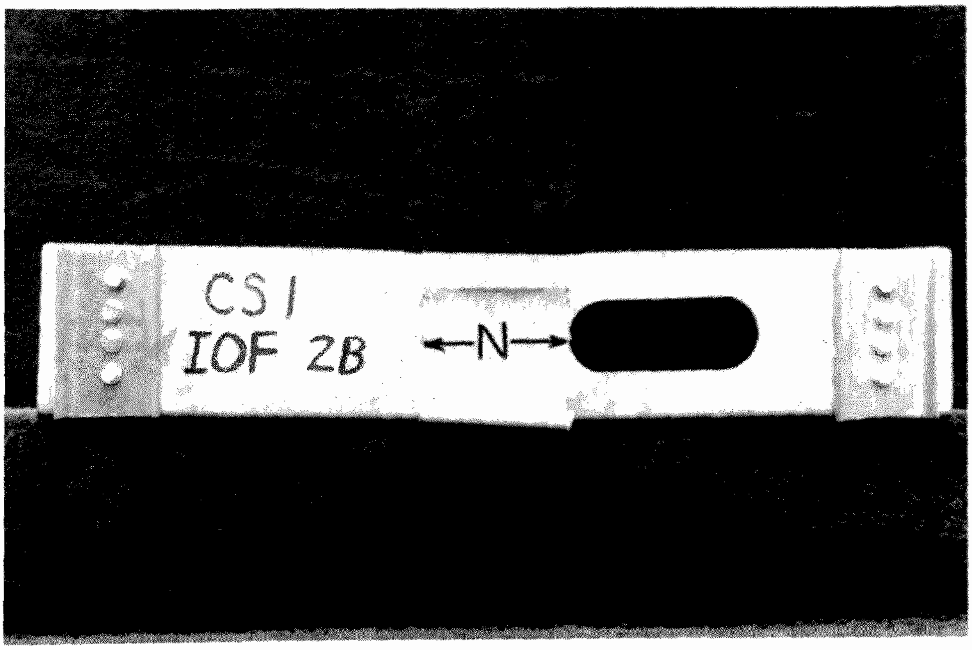


(b)

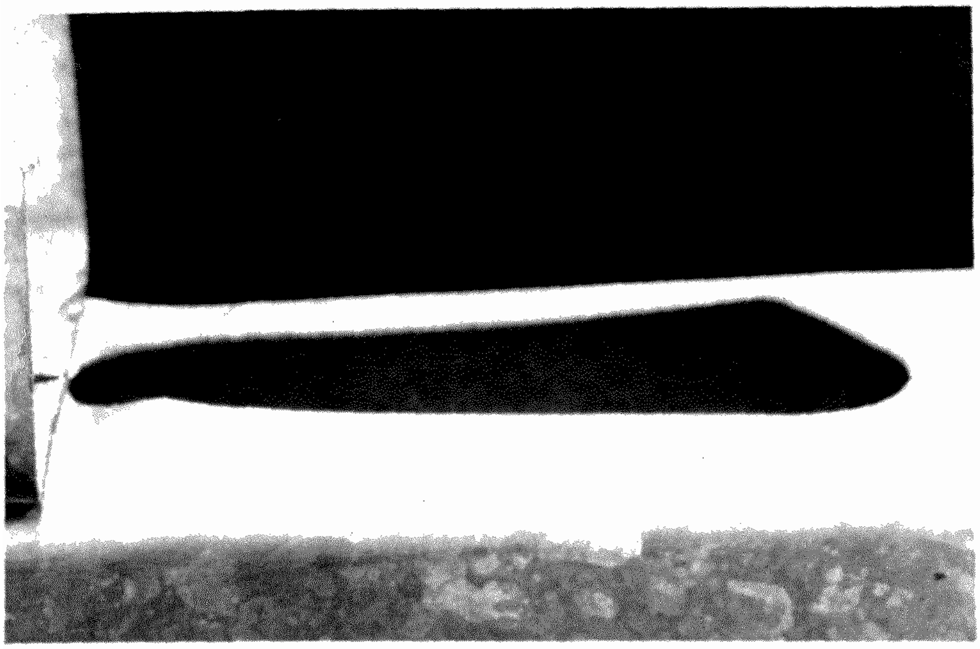


(c)

Figure 60: Typical IOF Type 2a Failure (cont.)

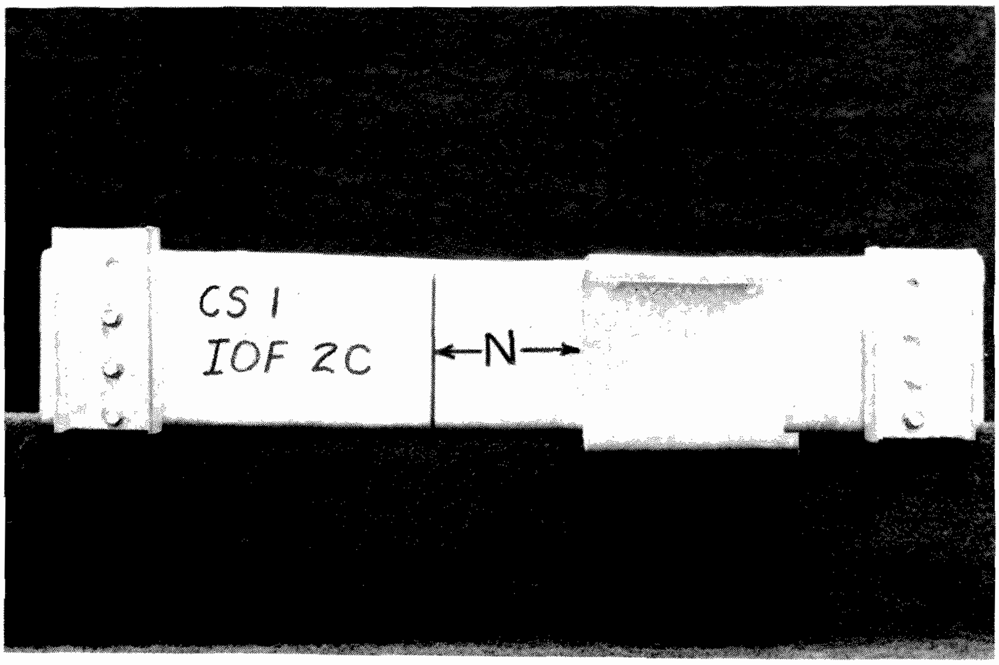


(a)

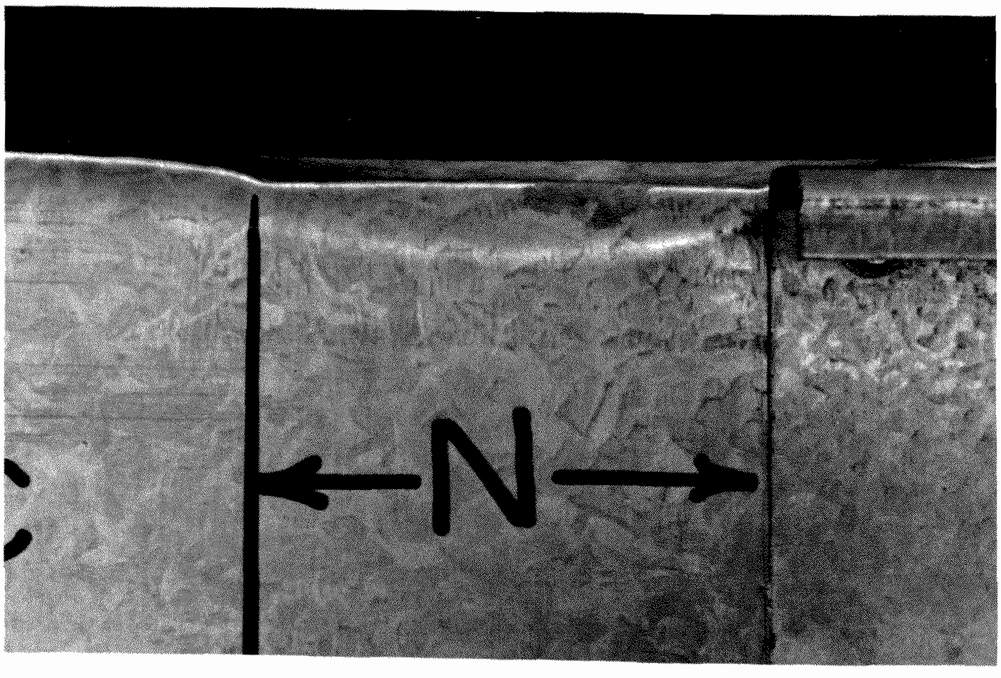


(b)

Figure 61: Typical IOF Type 2b Failure



(a)



(b)

Figure 62: Typical IOF Type 2c Failure

five IOF types of web reinforcement configurations, 1a, 1b,2a, 2b, and 2c.

The EOF and IOF test results for the 78 tests are shown in Table XIV or XV, respectively. Each of the six tests of the same configuration, two per cross section, exhibited the same failure mode. A description of the failure for each configuration is discussed herein. Some specimens exhibited severe flexure or shear deformation due to the presence of web reinforcement. Based on knowledge gained during the previous phases of the investigation, these deformations would have been negligible without the increase in web crippling strength provided by the web reinforcement.

The tested failure loads, $(P_n)_{test}$, per web, for all tests are given in Tables XIV or XV. Many specimens were not symmetric about the mid-span load due to the addition of the EOF web reinforcement at one end of the specimen or due to the addition of a non-symmetric IOF web reinforcement at mid-span. However, from determinate static analysis of the resulting systems, which were assumed to act as simply supported sections, the reported tested failure load per web was taken as 1/4 of the applied mid-span load at failure for EOF tests (Table XIV) and 1/2 of the applied mid-span failure load for IOF tests (Table XV). The results in Tables XIV and XV understate the strength of the web reinforced configurations for EOF tests that failed in web crippling at the unreinforced solid web end of the specimen and for any EOF or IOF tests that failed in a mode other

Table XIV: Reinforced Web EOF Test Results

	SOLID WEB UNREINFORCED		TYPE 1				TYPE 2: $\alpha = 0$					
			1a		1b		2a		2b		2c	
	$(P_n)_{test}$ (lbs.)	PSW	$(P_n)_{test}$ (lbs.)	PSW	$(P_n)_{test}$ (lbs.)	PSW	$(P_n)_{test}$ (lbs.)	PSW	$(P_n)_{test}$ (lbs.)	PSW	$(P_n)_{test}$ (lbs.)	PSW
CROSS-SECTION 1												
test 1	369	100.8	450	123.0	369	100.8	463	126.5	388	106.0	369	100.8
test 2	363	99.2	463	126.5	356	97.3	463	126.5	394	107.7	363	99.2
AVERAGE	366	100.0	457	124.7	363	99.0	463	126.5	391	106.8	366	100.0
CROSS-SECTION 2												
test 1	613	99.0	719	116.2	619	100.0	706	114.1	619	100.0	569	91.9
test 2	625	101.0	719	116.2	600	96.9	719	116.2	638	103.1	569	91.9
AVERAGE	619	100.0	719	116.2	610	98.5	713	115.1	629	101.5	569	91.9
CROSS-SECTION 3												
test 1	1294	98.8	1475	112.6	1319	100.7	1369	104.5	1363	104.1	1344	102.6
test 2	1325	101.2	1431	109.3	1325	101.2	1356	103.6	1325	101.2	1319	100.7
AVERAGE	1310	100.0	1453	111.0	1322	101.0	1363	104.0	1344	102.6	1332	101.7
OVERALL AVERAGE	---	100.0	---	117.3	---	99.5	---	115.2	---	103.7	---	97.9

Table XIV: Reinforced Web EOF Test Results (cont.)

Notes:
1. The mid-span loading plate length of all test specimens was 3.00 inches (Fig. 3).
2. For all tests with web openings, one end of the specimen, with respect to mid-span was unreinforced. Hence, the unreinforced end of the specimen had a solid web configuration. Therefore, $(P_n)_{test}$ understates the true EOF web crippling strength of the reinforcement configuration.
3. All tests performed at N = 1.0 inch.
4. Length of reinforcement:
   Type 1a: 3.25 inches over remaining length of the web opening.
   Type 1b: 1.0 inch over the length of bearing.
   Type 2a: 5.0 inches over the length of bearing and the web opening.
   Type 2b: 1.0 inch over the length of bearing.
   Type 2c: 4.0 inches over the length of the web opening.

Table XV: Reinforced Web IOF Test Results

	SOLID WEB UNREINFORCED		TYPE 1						TYPE 2: $\alpha = 0$					
			1		1a		1b		2a		2b		2c	
	$(P_n)_{test}$ (lbs.)	PSW	$(P_n)_{test}$ (lbs.)	PSW	$(P_n)_{test}$ (lbs.)	PSW	$(P_n)_{test}$ (lbs.)	PSW	$(P_n)_{test}$ (lbs.)	PSW	$(P_n)_{test}$ (lbs.)	PSW	$(P_n)_{test}$ (lbs.)	PSW
CROSS-SECTION 1: Sivakumaran and Zielonka reduction factor (Eq. 6) = 0.871														
test 1	925	100.0	738	79.8	1413	152.8	1375	148.6	2050	221.6	1163	125.7	938	101.4
test 2	925	100.0	763	82.5	1413	152.8	1325	143.2	1983	214.4	1188	128.4	950	102.7
AVERAGE	925	100.0	751	81.1	1413	152.8	1350	145.9	2017	218.0	1176	127.1	944	102.1
CROSS-SECTION 2: Sivakumaran and Zielonka reduction factor (Eq. 6) = 0.872														
test 1	1438	102.7	1375	98.2	2788	199.1	1837	131.2	2500	178.5	1925	137.5	1713	122.3
test 2	1363	97.3	1350	96.4	2588	184.8	1763	125.9	2538	181.2	1925	137.5	1738	124.1
AVERAGE	1401	100.0	1363	97.3	2688	191.9	1800	128.5	2519	179.9	1925	137.5	1726	123.2
CROSS-SECTION 3: Sivakumaran and Zielonka reduction factor (Eq. 6) = 0.870														
test 1	2950	98.7	2563	85.8	5013	167.8	4413	147.7	5913	197.9	4050	135.6	3400	113.8
test 2	3025	101.3	2513	84.1	4513	151.1	4463	149.4	6100	204.2	4050	135.6	3450	115.5
AVERAGE	2988	100.0	2538	85.0	4763	159.4	4438	148.6	6007	201.1	4050	135.6	3425	114.6
OVERALL AVERAGE	---	100.0	---	87.8	---	168.0	---	141.0	---	199.6	---	133.4	---	113.3

Table XV: Reinforced Web IOF Test Results (cont.)

Notes: 1. The end-of-span bearing lengths of all test specimens was 3.00 inches (Fig 4).
2. All tests performed at N = 3.0 inches.
3. Length of reinforcement:
Type 1: unreinforced
Type 1a: 4.0 inches over the length of the web opening.
Type 1b: 3.0 inches over the length of bearing.
Type 2a: 7.0 inches over the length of bearing and the web opening.
Type 2b: 3.0 inches over the length of bearing.
Type 2c: 4.0 inches over the length of the web opening.

than web crippling. However, conservatively, no strength above that reported in the tables are claimed for the web reinforced configurations. Furthermore, no quantitative method is provided herein to infer any additional strength of the web reinforcement configurations which exceeds those reported in Tables XIV and XV.

Web reinforced EOF tests which failed in web crippling at the unreinforced solid web end of the specimen exhibited web crippling capacities which are greater than their counterpart solid web unreinforced specimens. For example, cross-section 1 had an average $(P_n)_{test}$ value of 366 lbs. for the EOF solid web tests, and an average $(P_n)_{test}$ of 457 lbs. for the EOF Type 1a web reinforcement configuration (Table XIV). However, this does not imply that it is suggested that additional capacity be allowed for any web crippling reaction due to the existence of web reinforcement provided at another location along the member's length.

The average value of the Percent of Solid Web strength, PSW, is also reported in the Tables XIV and XV. The value of PSW is the strength of a specimen divided by the average strength from the solid web test specimens from the same cross section for tests performed at the same value of N (Section I.D, Terminology). Therefore, all PSW values stated in Tables XIV and XV apply strictly to N equal to one and three inches, respectively.

2. <u>Generalization of Results.</u> As stated previously, the intent of the experimental study was to determine what

practical web reinforcement configurations would achieve the strength of the solid web-unreinforced section from the same cross section. The purpose was not to develop either reduction factor equation(s) or augmentation factor equation(s) for the web reinforcement effect of the configurations as compared to either the solid web-unreinforced section or web opening-unreinforced section.

Three principal factors were used in the design of the test specimens: 1. large web openings, specifically high a/h and b values approaching the maximum permitted in practice; 2. minimum attachment of web reinforcement to the base specimen, specifically the fewest reasonable number of connectors of either two or four self-drilling screws, based on the value of L_s (Fig. 51) and h (Fig. 2); and 3. most critical location of the web opening, as given in Section V.C.1.b, Web Reinforcement Configurations.

The intent was to test web reinforced specimens under conditions which had the worst case scenario for strength of the base specimen, i.e. the least possible web crippling strength as compared to their solid web-unreinforced counterparts for the value of N used. The underlying concept is that if the full strength of the solid web-unreinforced section could be obtained under these worst case conditions, then the results could be generalized to all possible conditions for single web opened specimens subjected to the EOF and IOF loading conditions.

3. <u>End-One-Flange Results.</u>

a. <u>General Observations.</u> The EOF test specimens were designed such that one support required reinforcing, due to the proximity of the web opening, while at the other support, the section remained solid web-unreinforced. Figures 52 thru 56 show typical failures of specimens for each of the five EOF configurations. For all configurations, the solid web-unreinforced end of the specimen exhibited severe web crippling deformation. For all EOF configurations, with the exception of EOF Type 2c (Fig. 56), the severe web crippling deformation at the solid web-unreinforced half of the specimen defined failure of the specimen. The web crippling failures at the solid web-unreinforced ends of the specimens exhibited failure deformation shapes identical to those of the solid web EOF tests reported in Section III.

The EOF Type 1a configuration (Fig. 52) showed very slight separation of the web of the base specimen from the web reinforcement and upward rotation of the unloaded flange of the base specimen. The separation occurred near the web opening at the end of the section. The EOF Type 1b configuration (Fig. 53) showed severe deformation at the web opening-reinforced half of the specimen. Although the failure mechanisms of the two ends of the EOF Type 1b specimens were of different types, the effects of the overall severity of the deformation of the two ends were of the same extent. The EOF Type 1b configuration had a complex mechanism at the web opening-reinforced end of the specimen. This included the slight deformation described for EOF Type 1a, and bifurcation of the one inch long web reinforcement at its mid-height, and rotation of the loaded flange of the web reinforcement.

The EOF Type 2a (Fig. 54) and EOF Type 2b (Fig. 55) configurations showed no significant deformation at the web opening-reinforced half of the specimen, because of the great strength and rigidity of the web reinforced end as compared to the solid web-unreinforced end of the specimen. The EOF Type 2c configuration (Fig. 56) showed moderate to severe web crippling deformation over the unreinforced bearing length of the web opening-reinforced end of the specimen. The web reinforcement for the EOF Type 2c configuration prevented the deformation from extending longitudinally along the section beyond the bearing length; however it did not provide adequate support to appreciably reduce the web crippling deformation over the unreinforced bearing length. The EOF Type 2c configuration showed no significant deformation in the web reinforcement or in the base specimen in the vicinity of the covered web opening.

Because most failures were defined by the performance of the solid web-unreinforced EOF supported end of the specimen, the PSW values reported in Table XIV do not represent the full strength of the EOF web reinforcement configurations. However, the actual strength of the configurations is not the primary item of interest.

Therefore, the specific magnitude of the PSW values is not critical; as stated previously, the intent was to determine if the PSW values were greater than 100 percent.

b. <u>End-One-Flange Type 1 Configuration Results.</u> The description of the failure deformations was provided previously (Figs. 52 and 53). The PSW values for the six EOF Type 1a tests had an average value of 117.3 percent with a minimum value of 109.3 percent, and therefore, attained the goal of 100 percent (Table XIV). The results for the EOF Type 1b web reinforcement configuration are not as unequivocally definite. The PSW values for the six EOF Type 1b tests had an average value of 99.5 percent with a minimum value of 96.9 percent. Four of the six PSW values were equal to 100 percent or greater, and each of the three cross sections had at least one of its EOF Type 1b tests with a PSW value greater than or equal to 100 percent. Furthermore, cross-section 2 had the minimum PSW value of 96.9 percent. However, this value was only 2.1 percent lower than the lesser of the two solid web tests from cross-section 2, which was 99.0 percent of the average solid web strength. Therefore, although the average PSW value for the EOF Type 1b web reinforcement configuration was less than 100 percent, the results are considered to have essentially reached the goal of 100 percent.

Since both EOF Type 1a (Figs. 41 and 52) and EOF Type 1b (Figs. 42 and 53) configurations achieved or essentially attained 100 percent PSW values, both are adequate web reinforcement configurations. However, EOF Type 1b is more economical than EOF Type 1a in terms of the required reinforcement material, as judged by the lower L_s value (Fig. 51), and the number of connectors. Furthermore, the EOF Type 1b configuration will usually provide the advantage of keeping at least a small part of the web opening accessible for services for most values of N and the remaining length of b. For each of the EOF Type 1b specimens, 2.25 inches of the remaining web opening was not covered with a reinforcement. This approaches the maximum distance that will exist in practice for a rectangular web opening.

c. <u>End-One-Flange Type 2 Configuration Results.</u> The description of the failure deformations was provided previously (Figs. 54 thru 56). The average PSW values for EOF Type 2a and EOF Type 2b were 115.2 and 103.7 percent respectively with minimum values of 103.6 and 100.0 percent respectively. Therefore, both of these configurations attained the goal of 100 percent of the solid web strength. Type 2c exhibited an average PSW value of 97.9 percent with a minimum value of 91.9 percent. Therefore, EOF type 2c did not reach or essentially attain the goal of 100 percent.

A notable observation is that the EOF Type 2 web reinforcement configuration which required the least reinforcement material, and only two screw connectors, EOF Type 2b (Figs. 44 and 55), achieved better results than EOF Type 2c (Figs. 45 and 56) which used a significantly longer web reinforcement and more screw connectors. Specifically, for the tests performed, with a N value of one inch, and b value of four inches, EOF Type 2b required 25 percent of the web reinforcement material required for EOF Type 2c, and half as many connections. Furthermore, use of web reinforcement configuration EOF Type 2c would preclude use of the web opening for services.

The reasons for the deficiency in strength of EOF Type 2c is attributed to two factors. First, of the EOF Type 2 web reinforcement configurations, only EOF Type 2c did not have web reinforcement material in contact with the EOF bearing plate. Therefore, it is evident that having full bearing length contact between the web reinforcement and the bearing plate, assuming adequate connection, ensures attainment of an 100 percent PSW value. Secondly, simply covering the web opening length of the base specimen with the web reinforcement, as existed for EOF Type 2c, does not ensure the strength will reach 100 percent of the solid web strength. This is because the configuration is not a true composite. The forces can be transmitted to the web reinforcement only at the screw connector locations, and the web reinforcement exhibited no noticeable deformation. Therefore, the web reinforcement for the IOF Type 2c configuration essentially acted as a rigid body while absorbing no strain energy. Additional screws should rectify this situation. However, because the simpler configuration of EOF Type 2b consistently achieved the desired goal of 100 percent of the solid web strength, investigation into the issue of connectivity was not undertaken.

Because both EOF Type 2a and EOF Type 2b consistently exhibited PSW values above 100 percent, they both satisfactorily met the goals of the study. However, EOF Type 2b always requires a lower L_s value than EOF Type 2a. The difference in L_s values is equal to the sum of x and b. This difference will become very significant as the x distance (Fig. 3), or αh, is increased. Furthermore, the EOF Type 2b configuration provides the advantage of keeping the web opening accessible for services, while the EOF Type 2a does not.

4. <u>Interior-One-Flange Results</u>.

a. <u>General Observations.</u> Figures 57 thru 62 show typical failures of specimens for each of the six IOF configurations. As existed for the EOF configurations, the actual strength of the web reinforcement configurations is not the primary item of interest: the comparison of the results with 100 percent of the solid web strength is the principal consideration. However, unlike for the EOF results, the PSW values reported in Table XV better represent the full strength of the IOF web reinforcement configurations because of improved or complete symmetry of the specimens about the mid-span IOF loading and single web crippling failure location at mid-span of the specimens. Similar to the web reinforced EOF tests, the web crippling strength of the configurations is most likely greater than those stated in Table XV for tests that failed in a mode other than web crippling.

For the IOF tests, the web reinforcement enhanced the flexural characteristics of the specimens, however, the effect of bending interaction on the IOF web crippling strength was not considered. The three reasons for this are: 1. The additional flexural strength provided by the web reinforcement is difficult to determine because it was limited by the few number of connectors and the short length of the reinforcement. This restricted the diffusion of the flexural forces into the web reinforcement. 2. The recommended IOF web reinforcement configurations for both IOF Type 1 and 2 conditions, to be stated later, exhibited PSW values which significantly exceeded 100 percent. Any plausible method to adjust the tested PSW values to account for bending moment will increase the web crippling PSW values. Extensive use of adjusting PSW values to account for bending interaction on the web crippling strength was performed during the analysis of previous IOF results given in Section IV. 3. The length of the idealized simply supported span of the specimens was less than five percent longer than the minimum length required to satisfy the AISI requirements for one-flange loading. Hence, the value of $(M_n)_{test}/(M_n)_{comp}$, which is the primary factor in the interaction effect of bending on web crippling, was restricted to approximately the lowest value possible. The idealized simply supported span length, between centers of end bearings, was a major consideration for the previous IOF research conducted during the investigation. The primary factor which attributed to greater span lengths, and hence significant $(M_n)_{test}/(M_n)_{comp}$ values, for the previous IOF tests was high α values. These high α values often necessitated making the length of the specimens much greater than that required to satisfy the one-flange loading condition. However, the α values (Fig. 4) for this phase of the study never exceeded zero.

b. Interior-One-Flange Type 1 Configuration Results. The IOF Type 1 unreinforced (Fig. 57), Type 1a (Figs. 46 and 58), and Type 1b (Figs. 47 and 59) configurations failed due to IOF web crippling. The IOF Type 1a (Fig. 58) and Type 1b (Fig. 59) configurations exhibited significant deformation of the loaded flange of the web reinforcement and flexural deformation at mid-span.

The average PSW value for the six IOF Type 1a tests was 168.0 percent with a minimum PSW value of 151.1 percent, and therefore consistently exceeded 100 percent of the average solid web strength. The six IOF Type 1b tests had an average value of 141.0 percent with a minimum value of 125.9 percent, and therefore consistently exceeded 100 percent of the average solid web strength. Therefore, both IOF Type 1a and IOF Type 1b web reinforcement configurations met the goals of the study. However, IOF Type 1b is more economical than IOF Type 1a in terms of the required web reinforcement material. The L_s value for IOF Type 1a is equal to the sum of N and b less the length of the web opening which is below the IOF load plate. The L_s value for IOF Type 1b is equal to N. Therefore, IOF Type 1a will always require a L_s value greater than or equal to that required for IOF Type 1b.

Furthermore, the EOF Type 1b configuration (Figs. 47 and 59) provides the advantage of keeping at least a minimal amount of the web opening accessible for services for typical values of N and b. For the IOF Type 1b web reinforcement configuration used in the tests, the area of the uncovered web opening was very small. For each of the EOF Type 1b specimens, one inch of the web opening was not covered with a reinforcement. Since the web opening was centered on the IOF load plate, 1/2 inch of uncovered web opening existed on each side of the web reinforcement. In practice, for N values greater than or equal three inches, and b values less than or equal to 4.5 inches, the maximum continuous length of uncovered web opening will be less than 1.5 inches. This exceeds the maximum continuous length of 1/2 inch for the tests specimens. However, the conservative IOF Type 1b test results ensure that the solid web-unreinforced strength will be obtained by using the IOF Type 1b web reinforcement configuration when the maximum uncovered length of 1.5 inches exists.

c. Interior-One-Flange Type 2 Configuration Results. The failure for the IOF Type 2a configuration (Fig. 60) is difficult to characterize. It was a complex superposition of flexure, web crippling, and rotation of the loaded portion of the flange of the web reinforcement. The IOF Type 2b configuration (Fig. 61) failed primarily due to shear, though there was significant web crippling deformation and rotation of the loaded flange of the web reinforcement. The IOF Type 2c configuration (Fig. 62) failed in web crippling over the unreinforced load area; the web reinforcement showed no deformation.

The region of the shear failures for the IOF Type 2b configuration (Fig. 61) was identical to shear failures reported and discussed in previous phases of the study (Sections III and IV). Based on knowledge gained from the previous phases of the study, none of the three cross sections used in this phase of the study would have failed in shear if web reinforcement was not provided. This is because the N values and a/h values used in this phase of the study were below that which result in the web crippling strength exceeding the shear strength.

The IOF Type 2a, 2b, and 2c web reinforcement configurations had average PSW values of 199.6, 133.4, and 113.3 percent respectively, and minimum values of 178.5, 125.7, and 101.4 percent, respectively. Therefore, each of these configurations met the goals of the study.

The results for IOF Type 2a tests were extremely conservative and require a greater L_s value (Fig. 51) than for the IOF Type 2b and IOF Type 2c web reinforcement configurations. Furthermore, similar to the previous discussion of the L_s value for the EOF Type 2a web reinforcement configuration, the L_s value for the IOF Type 2a configuration becomes very large for high α values. Hence, IOF Type 2a is not the most favorable web reinforcement configuration, although it met the primary goal of the investigation.

The IOF Type 2b web reinforcement configuration had an average PSW value 20 percent greater than for IOF Type 2c. Type 2b accomplished this with an one inch lower L_s value. Furthermore, of the three IOF Type 2 web reinforcement configurations, IOF Type 2b will usually be the most economical for most b and N values. The reasons for the lower strength of IOF Type 2c, as compared to the other IOF Type 2 configurations, are the same as the two factors stated previously that limited the strength of the EOF Type 2c tests. Interior-One-Flange Type 2b is the only IOF Type 2 web reinforcement configuration which provides the advantage of keeping the web opening accessible for services. The length of the uncovered web opening is equal to the b value.

5. Comparison with Sivakumaran and Zielonka Results. Although not directly associated with the goals of the current phase of the research, unreinforced specimens using the Sivakumaran and Zielonka specimen configuration, IOF Type 1 (Fig. 57), were tested and the results compared to the reduction factor equation, Equation 6, developed by Sivakumaran and Zielonka (1989).

The resulting values for Equation 6 are shown in Table XV for the three cross sections. The average PSW value for the six tests IOF Type 1 tests was 87.8 (Table XV). The average of the values from Equation 6 was 87.1 percent.

For the six IOF Type 1 unreinforced tests, the ratio of predicted strength to solid web strength, using Equation 6, divided by the ratio of tested strength to solid web strength is equal to 0.992, (0.871/0.878). Since this is approximately unity, good correlation exists between the overall average of the predicted (Eq. 6) to tested results.

Cross-section 2 had an average predicted to tested strength ratio of 0.896, {0.872/[(0.982+0.964)/2]}, which is 10.4 percent below unity. Sivakumaran and Zielonka (1989) state, "only 4% of [the predicted to tested] values lying outside of 0.9 and 1.1". Therefore, the results from cross-section 2 are within the greatest limits of dispersion found by Sivakumaran and Zielonka. Cross-section 1 had a predicted to tested ratio of 1.08, {0.871/[(0.798 + 0.825)/2]}. Cross-section 3 had a predicted to tested ratio of 1.02, {0.870/[(0.858+0.841)/2]}.

6. <u>Comparison of IOF Type 1 and Type 2 Results.</u> Intuitively, the greatest reduction in IOF web crippling strength occurs at the special case of the IOF Type 1 situation used during the testing, specifically, when the web opening is centered directly on the IOF load. Any offset distance between the centerline of the load and the centerline of the web opening would intuitively increase the

web crippling capacity of the section, for the same value of N and effect of bending moment. Analysis of the results show that this concept is not always correct for all cross sections due to possible existence of different failure mechanisms for the IOF Type 1 and Type 2 conditions.

The results for the cross-section 2, IOF Type 1 unreinforced configuration indicate that failures from the Type 1 condition and Type 2 are caused by different mechanisms. Cross-section 2 had PSW values of 98.2 and 96.4 percent for the IOF Type 1 configuration. For the IOF Type 2 condition, Equation 77 yields a value of 83.9 percent for cross-section 2 at α equal to zero. Furthermore, cross-section 2 was tested as specimens IOF-SU-6-2-1 and IOF-SU-6-2-2 for L equal to 18.78 inches, N equal to three inches, and α equal to zero. The PSW_{adj} values were 84.8 and 85.7 percent, respectively (Section IV and Table XI). Therefore, the difference in PSW_{adj} values between the Type 1 condition with the web opening centered on the load and the Type 2 condition with α equal to zero was 97.3, [(98.2+96.4)/2] compared to 85.3, [(84.8+85.7)/2], yields a decrease of 12.0 percent.

These results strongly indicate that the situation when the web opening is centered on the IOF load plate does not necessarily result in the least web crippling capacity for the IOF loading condition. It is possible that an increase in web crippling capacity exists for some offset distance between the centerline of the web opening and centerline of the load for the IOF Type 1 condition. This would be similar to the situation of the demonstrated increase in capacity as α increases from zero for the IOF Type 2 condition. However, as the offset for the Type 1 condition is increased, a transformation to the Type 2 failure mechanism will eventually occur, and this could occur while a portion of the web opening is located below the IOF load, i.e. when the IOF Type 1 condition exists. As indicated by the results for cross-section 2, the mechanism for the IOF Type 2 condition could be more critical than for the IOF Type 1 condition. Accordingly, Sivakumaran and Zielonka did not incorporate any increase in Equation 6 to account for any offset.

Cross-sections 1 and 3 performed according to the previously stated intuitive concept. Cross-section 1 had PSW values of 79.8 and 82.5 percent for the IOF Type 1 configuration. For the IOF Type 2 condition, Equation 77 yields a value of 83.9 percent for cross-section 1 at α equal to zero. Cross-section 1 was tested as specimens IOF-SU-5-2-1 and IOF-SU-5-2-2 for L equal to 18.69 inches, N equal to three inches, and α equal to zero. The PSW_{adj} values for these two test specimens were 90.6 and 89.2 percent (Section IV and Table XI). Therefore, the difference in PSW values between the Type 1 condition with the web opening centered on the load and the Type 2 condition with α equal to zero was 81.2, [(79.8+82.5)/2] compared to 89.9, [(90.6+89.2)/2], yields an increase of 8.7 percent.

Cross-section 3 had PSW values of 85.8 and 84.1 percent for the IOF Type 1 configuration. For the IOF Type 2 condition, Equation 77 yields a value of 83.9 percent for cross-section 3 at α equal to zero. Cross-section 3 was tested as specimens IOF-SU-8-2-1 and IOF-SU-8-2-2 for L equal to 18.66 inches, N equal to three inches, and α equal to zero. The PSW_{adj} values for these two test specimens were 85.8 and 86.4 percent (Section IV and Table XI). Therefore, the difference in PSW values between the Type 1 condition with the web opening centered on the load and the Type 2 condition with α is equal to zero was 85.0, [(85.8+84.1)/2] compared to 86.1, [(85.8+86.4)/2], yields an increase of 1.1 percent.

As a result of these findings, recommendations for unreinforced single web sections subjected to the IOF loading condition were given in Section V.F.4 under the limitations for the α parameter.

Equating Equations 6 and 77 produces notable results. There are realistic circumstances when the IOF Type 1, no offset condition (Eq. 6), and the IOF Type 2, α equal to zero condition (Eq. 77), produce the same reduction factor value. For example, this can be observed by starting with a baseline set of typical values for N, b, a, and h of 3, 4, 1.5, and 3.25 inches, respectively. If one of the values is allowed to change, while the others are maintained at the baseline value, specifically, if either N, b, a, or h is allowed to change to 2.28, 4.71, 0.26, or 2.29 inches respectively, then the two equation yield the same reduction factor value. The N, b, and a/h values required for the equality are outside the ranges of standard practice. However, web crippling analysis has a relatively large variation, and therefore conditions for the parameters at the limits of standard practice could frequently result in the IOF Type 1 no offset and the EOF Type 2 α is equal to zero conditions providing the same degradation in web crippling strength of the solid web section. Furthermore, as exhibited by cross-section 2, the latter condition could provide more strength degradation.

7. Evaluation of Connection Performance. For evaluation of the screw connections, see Section V.F.3.

E. DESIGN RECOMMENDATIONS

1. End-One-Flange Recommendations. The following recommendations for both EOF Type 1 and EOF Type 2 conditions are applicable to N values greater than or equal to one inch. For both of these recommended EOF web reinforcement configurations, it is recommended that full bearing length contact between the web reinforcement and EOF load plate be provided. Therefore, the L_s value is equal to N.

a. End-One-Flange Type 1. For the condition of any portion of the web opening being located above the bearing, the EOF Type 1b web reinforcement configuration (Figs. 42 and 53) is satisfactory and will essentially provide a PSW value of 100 percent. Full bearing length contact between the web reinforcement and load plate should be maintained even if the web opening does not continue to the exterior or interior end of the EOF load plate.

b. End-One-Flange Type 2. For the condition of no portion of the web opening being located above the bearing plate, the EOF Type 2b web reinforcement configuration (Figs. 44 and 55) consistently exhibited PSW values above 100 percent and therefore is satisfactory.

2. Interior-One-Flange Recommendations. The following recommendations for both IOF Type 1 and IOF Type 2 conditions are applicable to N values greater than or equal to three inches. For both of these IOF web reinforcement configurations, it is recommended that full bearing length contact be maintained between the reinforcement and the IOF loading plate. Therefore, the L_s value is equal to N.

a. Interior-One-Flange Type 1. For the condition of any portion of the web opening being located below the IOF load, the IOF Type 1b reinforcement configuration (Figs. 47 and 59) is satisfactory and will ensure a PSW value of 100 percent.

b. Interior-One-Flange Type 2. For the condition of no portion of the web opening being located below the IOF load plate, the IOF Type 2b configuration (Figs. 49 and 61), is satisfactory and will ensure a PSW value of 100 percent.

3. <u>Discussion of the Configuration Design Recommendations.</u> The four recommended web reinforcement configurations are EOF Type 1b (Figs. 42 and 53), EOF Type 2b (Figs. 44 and 55), IOF Type 1b (Figs. 47 and 59), and IOF Type 2b (49 and 61). The four configurations met the goals of the study as stated in Section V.B. Furthermore, they usually require a lower L_s value than their counterparts, and usually provide at least minimal accessibility of the web opening for typical ranges of N and b. They have the common characteristic of having the web reinforcement coincident with the load bearing or reaction plate. Each of these configurations must have L_s values equal to N and must be reinforced along the full length of the bearing.

The web reinforcement configurations are applicable to N values greater than or equal to one inch and three inches for the EOF and IOF loading conditions, respectively. The maximum permissible b and a/h values for application of the web reinforcement configurations are 4.5 inches and 0.50, respectively. In accordance with the AISI provisions for the computation of the solid web strength (Section II.F), the maximum permissible R/t, N/t, N/h, and h/t values are 6, 210, 3.5, and 200, respectively. These limits therefore apply to the recommended web reinforcement configurations.

Although the maximum h/t ratio tested was 98 (Table III), the results are valid for all h/t values. The h/t limit of 200 for use with the web reinforcement configurations is adopted from the limits stated for the current AISI web crippling provisions for unreinforced sections. Tables XIV and XV show no conclusive relationship between h/t and PSW values for the four recommend web reinforcement configurations. It is therefore concluded that the web reinforcement configurations will attain the web crippling capacity of the solid web section for all h/t values at the same N value. Furthermore, the use of the results for h/t values which exceed the maximum tested h/t value of 98 is an extrapolation of the demonstrated phenomenon and not a quantitative extrapolation of any specific derived mathematical relationship.

No allowance for additional capacity is recommended for decreasing the size of the web openings, or for increasing the horizontal distance between the web opening and the load, i.e. for incorporating and increasing a web opening offset distance for the Type 1 condition or for increasing the α value for the Type 2 condition. Specifically, no provision is recommended for any strength which exceeds the allowable capacity of the solid web-unreinforced section as determined from the current AISI Specification web crippling provisions.

No significant material or labor savings will be realized by not reinforcing the full length of the load, and therefore, investigation into this subject was not conducted. Furthermore, to develop a relationship between lesser required L_s values and the resulting PSW values would require extensive testing of numerous cross sections under various arrangements. In addition to testing reduced L_s values, numerous combinations of other complex factors would have to be considered. These factors include the location of the reinforcement, i.e. which region of the bearing length must be reinforced; various arrangements and numbers of connections; web opening sizes and locations; and a range of N values. The effort required in using the resulting equations and inspection of fabrication would offset the simplicity of the aforementioned requirements.

Use of a web reinforcement configuration having the web reinforcement flanges oriented perpendicular to the flanges of the base section, using excess material from the same cross section as the web reinforcement, was not investigated because the configuration will rarely provide a L_s value approximately equal to N. Specifically, if the D value (Figs. 2, 3, and 4) of the section is greater than N, then one or both of the flanges of the web reinforcement will not be in contact with the load plate, and the flange(s) of the web reinforcement will not be efficiently utilized. Likewise, if the D value of the section is less than N, then the section will not be reinforced over the entire bearing length.

Because of the previously stated reasons for the PSW values not representing the actual strength of the configurations, investigation into the relationship between the cross-section parameters, namely h/t and F_y, and the PSW values was not undertaken.

4. Web Reinforcement and Base Section Connection Recommendations. The following recommendations apply only to self-drilling screw connections. Other types of connections must be designed in accordance with the AISI Specification (1986, and 1991a) Section E, Connections. However, for other types of connectors, the following provides relationships for determining the forces between the connected parts. For screw connections, the AISI provisions published by the Center for Cold-Formed Steel Structures, CCFSS, (CCFSS, 1993) apply; these provisions and their commentary were approved for inclusion in a future edition of the AISI Specification, as Section E4, Screw Connections. These provisions were reviewed in Section II.I with the applicable provisions given in Appendix B.

The four recommended web reinforcement configurations will achieve their counterpart solid web-unreinforced strength only if the web reinforcement is adequately attached to the base section. Therefore, the attachment design must possess integrity of both the individual connections and the overall configuration. Both of these aspects must be examined.

First, the adequacy of the individual screw connections is provided for by CCFSS (1993), which will ensure adequate strength of the components of each connection. These components include the screw connectors and the connected parts of the web reinforcement and base section. Because both the web reinforcement and base section are from the same cross section, the provisions are greatly simplified.

Second, the overall adequacy of the connection arrangement is generalized from the arrangements used in the four recommended web reinforcement configurations. This discussion is greatly facilitated by the common characteristics of the four recommended web reinforcement configurations, most notably, coincident longitudinal positions of the web reinforcement and the load plate.

The AISI provisions (CCFSS, 1993) are simplified by the characteristics of the recommended web reinforcement configurations. Because of these characteristics, many provision equations (Appendix B) do not apply or are redundant. Specifically, many of the equations allow for different properties for the two connected parts. The connected parts are differentiated in the AISI provisions by their relative position to the screw head; they are designated as being either in contact or not in contact with the screw head. Therefore, the direction of screw insertion is immaterial in the assembly of the web reinforcement configurations. This could often expedite work site fabrication, especially if the precise final locations of web openings are not known until the sections are placed.

As stated previously, the requirements for ensuring overall performance of the connection design are generalized from the connection arrangements used during the tests for the recommended web reinforcement configurations. These requirements will consist of prescribing minimum values for the number of vertical rows of connections, N_{vr}; the number of horizontal rows of connections, N_{hr}; minimum edge distances for the outer vertical rows of connections; and minimum edge distances for any connections that are in proximity to the web opening.

It is recommended that screw connections be placed in N_{vr}, number of vertical rows, and N_{hr}, number of horizontal rows as given in (a) and (b) herein. The total number of screws is the product of N_{vr} and N_{hr}. The screw connections will be located at the intersection of the horizontal and vertical locations given by Parts (a) and (b) of this paragraph. Part (a) gives the requirements in the horizontal direction along the length of the web reinforcement and length of bearing, i.e. the requirements of N_{vr} and S_H (Fig. 51). Part (b) gives the requirements in the vertical direction, i.e. the requirements of N_{hr} and S_V (Fig. 51).

(a) The values of N_{vr} and S_H (Fig. 51) depend upon the value of N as given in Table XVI and as discussed herein.

Table XVI: Values of N_{vr} and S_H

Bearing length, N (in.)	Minimum N_{vr}	S_H value of each vertical row
$\leq$ 2	1	N/2
> 2 to $\leq$ 6	2	both rows: 1/2 inch
> 6 to $\leq$ 9	3	both exterior rows: 1/2 in.
		interior row: N/2
> 9	----	----

The value of N is equal to the length of the web reinforcement, L_s (Fig. 51), based on the four recommended web reinforcement configurations.

The value of N_{vr} must be increased, above that given in Table XVI, as necessary to ensure that the shear and tension forces in the connection are in compliance with Section E4.3, Shear, and E4.4, Tension, of CCFSS (1993). As given subsequently herein, an increase in N_{vr} results in a decrease in the shear and tension forces in the individual connections.

Because the shear force in each screw is in one direction only, and this direction is parallel to the longitudinal edge of the web reinforcement, in accordance with CCFSS (1993), Section E4.2, Minimum Edge and End Distance, the minimum allowable edge distance is 1.5d. For the largest allowable screw diameter size, d, of 1/4 inch, 1.5d is equal to 0.375 inches. Therefore, the S_H value of

1/2 inch based on overall adequacy of the configuration will govern. Hence, under no circumstances will the edge distance requirements be violated for d values less than or equal to 1/4 inch.

For N values greater than nine inches, tests must be conducted in accordance with Section F1 of the AISI Specification (1986, and 1991a).

(b) The values of N_{hr} and S_v (Fig. 51) depend upon the depth of the section, D, (Table XVII), and as given herein.

Table XVII: Values of N_{hr} and S_v

Depth of section, D (in.)	Minimum N_{hr}	S_v value of each horizontal row
≤ 6	2	1/2 in.
> 6 to ≤ 9	3	both top and bottom row: 1/2 in.
		interior row: D/2
> 9	----	----

The S_v value should not exceed 1/2 inch for the upper and lower horizontal rows of connections. This requirement will rarely pose a problem in practice because the value of d_f or the sum of R, t, (Fig. 2) and d/2 infrequently exceed 1/2 inch.

The value of N_{hr} must be increased, above that given in Table XVII, as necessary to ensure that the shear force in the connections are in compliance with Section E4.3, Shear, of CCFSS (1993). As given subsequently herein, an increase in N_{hr} results in a decrease in the shear force in the individual connections. However, it is conservatively assumed that an increase in N_{hr} does not affect the tension force in the connections.

For sections with a total depth, D (Figs. 2, 3, and 4), between six and nine inches, an additional horizontal row of connectors is recommended. The location of the additional horizontal row of connectors should be at mid-height of the web.

However, the minimum edge distance from the edge of a web opening must comply with the AISI provisions (CCFSS, 1993), Section E4.2, Minimum Edge and End Distance. Noting that the shear force will be perpendicular to the edge of a web opening that may be covered by the web reinforcement, the minimum edge distance of 3d will apply. If any mid-height connections must be relocated vertically due to the proximity of a web opening, the adjusted location should be towards the load plate.

For D (Figs. 2 thru 4) values greater than nine inches, tests must be conducted in accordance with Section F1 of the AISI Specification (1986, and 1991a). The limit of nine inches, based on engineering judgement, is recommended to prevent local buckling between the horizontal rows of connections. This limit is not directly related to the h/t limit recommendation. Based on typical values of the height of web opening, a (Figs. 2 thru 4), sections with D values greater than nine inches will typically not have a significant web crippling strength reduction due to the presence of web openings. For deep sections, web reinforcement will typically provide only a small increase in the allowable capacity of the configuration, because the reduction factor value approaches unity.

For example, for a section with a D value of nine inches, and corresponding h value equal to 8.6 inches, and a height of web opening of 1.5 inches, Equation 68 yields a value of 0.97, and Equation 77 yields a value of 0.92 at α is equal to zero. Furthermore, with a N value of 3 inches and b value of 4 inches, Equation 6 yields a value of 0.97.

F. CONNECTIONS

1. General. This paragraph contains relationships which provide the forces in the connections for the web reinforcement configurations. These forces are compared to the AISI Specification provisions for screw connections (CCFSS, 1993) as given in Appendix B. Additionally, the performance of the connections of the test specimens for the four recommended web reinforcement configurations is evaluated.

2. Forces in Connections. In order to use the AISI provisions stated in CCFSS (1993), as given in Section II.F.

and Appendix B, for checking the adequacy of the individual screw connections, the forces of the connection must be known. Therefore, relationships are given herein to determine the forces. This is accomplished by relating the connection forces to the total concentrated force applied to the section, which is equal to the allowable web crippling capacity of the web reinforced section. In accordance with the primary goal of this phase of the investigation (Section V.B), this total applied force is therefore assumed equal to the allowable capacity of the solid web-unreinforced section, $(P_a)_{comp,\ solid\ web}$.

The allowable capacity was used for evaluation of the connections, because the AISI provisions (CCFSS, 1993) are based on the design load and hence incorporate a safety factor for connectors of 3. Therefore, use of the value of $(P_n)_{comp,\ solid\ web}$ is unnecessarily conservative. The provisions consider components of the connection forces to either cause shear or tension in the connection. Hence, the shear and tension forces in each connection are expressed separately as a function of $(P_a)_{comp,\ solid\ web}$.

The greatest shear and tension will exist in the connections when the load plate is in direct contact only with the web reinforcement, and no contact exists between the load plate and the base section. In this situation, the load must be fully transferred to the base section within the longitudinal limits of the web reinforcement and load plate. Hence, the full applied load is transferred through the screws. It is assumed that the base section will receive load only after the required deformation has occurred in the web reinforcement, primarily due to deflection of the flange of the web reinforcement and the radius of the web reinforcement at the flange to web juncture. This situation can occur in practice, because it is often difficult to ensure that the flanges of the web reinforcement and base section are flush. Frequently, it is difficult to assess the evenness of the configuration because the webs and flanges of many cross sections are not perpendicular; often the interior angle between the flange and the web, although within manufacturer tolerance, is somewhat greater than ninety degrees. Furthermore, shifting of the configuration during the placement of the first few screws is difficult to eliminate, and this will make the flanges of the web reinforcement and base section uneven.

Conversely, if the full load is applied directly to the base section, then the web reinforcement will be subjected only to minor contact forces caused by deformation of the base section and changes in relative position of the connections. For practical purposes, the web reinforcement will be unstressed and subjected to a rigid body motion as the base section deflects. In this case, the web reinforcement will receive direct load from the load plate only when the flange of the base section is deformed to the required amount.

Neither of these two extreme conditions are cause for distinct concern if a reasonable effort is taken to prevent significant unevenness of the flanges of the configuration. The deformation of the system will ensure that neither connected part carries a critically disproportionate share of the load. However, for the purposes of the connection design, the former case will be used, i.e. when the web reinforcement initially receives the full load, and the full load must be transferred to the base section through the connections.

Figure 63 is a free body diagram of the web reinforcement. In accordance with the standard practice of connection design for thin-walled members, it is assumed that no moment reaction exists at the connection locations. This is because the moment reaction is insignificant as compared to the other reactions present.

Figure 63 shows one of the vertical rows of connections. Equilibrium equations were developed based on the forces shown in Figure 63, and then generalized to the situation when additional vertical rows of connections are provided. The equilibrium of the system is based on first order analysis of the undeformed geometry of the system. As the system deforms the base section will receive a portion of the applied load, thereby reducing the forces in the screws. Furthermore, during any excessive deformation, the centroid of the applied load will move closer to the web of the web reinforcement as the corner in the cross section

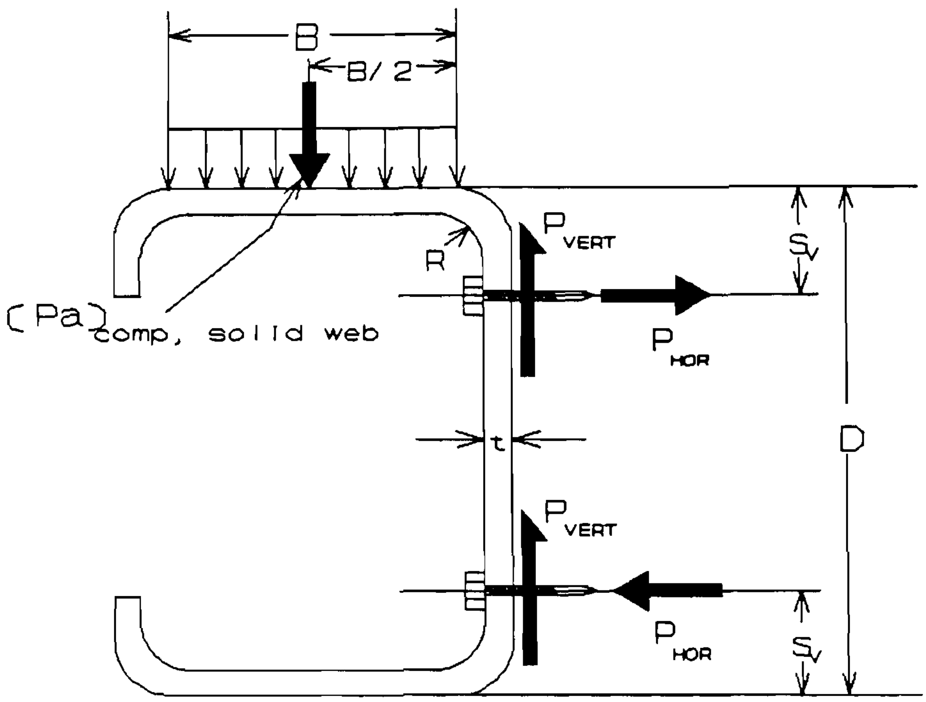


Figure 63: Forces in Screw Connections of Web Reinforcement Configurations

nearest the load flange flattens. This will reduce the lever arm, and hence the moment, which causes tension in the connectors closest to the load. The web crippling deformation was observed to be minor or insignificant until the allowable load is exceeded. This occurs at 1/1.85 or approximately 54 percent of the nominal web crippling capacity. Therefore, the undeformed geometry is the worst case condition for forces in the screws, because the undeformed geometry will exist at the design load of $(P_a)_{comp, solid\ web}$.

The system shown in Figure 63 is statically indeterminate for equilibrium in the vertical direction, i.e. for the shear forces, P_{VERT}. Therefore, the P_{VERT} forces can be found only by knowledge of the internal state of stiffness. However, based on the following two reasons, the P_{VERT} in each screw connector of the configuration is assumed equal. First, the total shear force carried by each vertical row of screw connectors is assumed equal. Second, the P_{VERT} forces among all connectors in each vertical row is assumed equal, because any deviations between equal distribution of shear forces among screw connectors will be largely rectified by redistribution of forces during loading. This will occur through distortions of the overall system, primarily due to elastic and plastic deformations in the bearing areas of the screw connections. In accordance with the standard practice of connection design in ductile metal components, yielding in the bearing area is acceptable and required for efficient design. Hence, the relationship between the applied load and P_{VERT} is:

$$P_{VERT} = \frac{(P_a)_{comp,\ solid\ web}}{N_{hr}} \tag{82}$$

Equilibrium in the horizontal direction is straightforward for configurations with two horizontal rows of connections. Contact pressure between the web reinforcement and base section will exist in the region opposite from the applied load, and the portion of the compression contact force carried by the screws in this region will be slight. However, for convenience, a resultant force for the contact pressure can be assumed at the connection location in this region. Hence, for a configuration with two screws in each vertical row, equilibrium dictates that the forces are equal and opposite. These forces are denoted as P_{HOR} (Fig. 63) and provide tension in the horizontal row of connections closest to the load plate. Furthermore, as stated later, the maximum N_{hr} value is three. For this situation, the additional horizontal row will be in the vicinity of mid-height of the section. This additional row is conservatively considered to not relieve the tension force in the horizontal row of screws closest to the load plate.

Finally, moment equilibrium about any arbitrary point in the plane of the cross section dictates, based on the forces shown in Figure 63, that:

$$P_{HOR} = (P_a)_{comp,\,solid\ web} \left(\frac{\frac{B}{2}+R+t}{D-2S_V} \right) \tag{83}$$

Generalizing the previous development of equilibrium for Figure 63, the shear force per screw, P_{shear}, and tension force per screw, $P_{tension}$, which will be used to compare with the AISI provisions (CCFSS, 1993) are:

$$P_{shear} = (P_a)_{comp,\,solid\ web} \ / \ (N_{hr} \times N_{vr}) \tag{84}$$

$$P_{tension} = \frac{(P_a)_{comp,\,solid\ web}}{N_{vr}} \left(\frac{\frac{B}{2}+R+t}{D-2S_V} \right) \tag{85}$$

Equation 84 for P_{shear} was derived for the expression for P_{VERT} (Eq. 82) by dividing P_{VERT} by N_{vr} to consider equal contribution of each vertical row of connections. The value of $P_{tension}$ (Eq. 85) was derived from the expression for P_{HOR} (Eq. 83) by dividing P_{HOR} by N_{vr} to consider equal contribution of each vertical row of connections. The $P_{tension}$ value (Eq. 85) allows for the same design in all screws of the configuration, including those not subjected to tension. Note that the value of $P_{tension}$ from Equation 85 is not reduced by an increase in the value of N_{hr}, and therefore is based strictly on a N_{hr} value of two. For Equations 84 and 85, $(P_a)_{comp,\ solid\ web}$ is from the current AISI Specification web crippling provisions (Eqs. 30 thru 35).

3. Performance of Connections. None of the test specimens exhibited failure attributable to the inadequacy of the connections. This includes failure of the reinforcement and base specimen material in the region of the connection, or of the number 12 self-drilling screws due to the shear and tension forces of the attachment.

Analysis of the connectors used during the testing of the four recommended web reinforcement configurations given Section V.F, Design Recommendations is shown in Tables XVIII and XIX. The design load was taken as $(P_n)_{test}$ (Tables XIV or XV) divided by the ASD web crippling factor of safety of 1.85. This value corresponds to the tested counterpart of $(P_a)_{comp,\ solid\ web}$ incorporated into Equations 84 and 85.

Table XVIII: Connection Analysis of Recommended EOF Web Reinforcement Configurations

	N_{vr}	N_{hr}	$(P_n)_{test}$ avg. (kips) Table XIV	$(P_a)_{test}$ (kips)	Applied Force per Screw at $(P_a)_{test}$ (kips)		Shear Forces and Capacities (kips)						Tension Forces and Capacities (kips)					
					P_{shear} Eq.84	$P_{tension}$ Eq.85	P_{ns} Eq.94	P_{ns} Eq.95	P_{ns} lesser	$P_{as} = P_{ns}/3.00$ Eq.93	see legend item (1)	see legend item (2)	P_{not} Eq.97	P_{nov} Eq.98	P_{nt} lesser	$P_{at} = P_{nt}/3.00$ Eq.96	see legend item (3)	see legend item (4)
EOF Type 1b and 2b																		
CS1	1	2	0.366	0.198	0.099	0.075	0.866	1.424	0.866	0.289	1.082	3.026	0.446	1.520	0.448	0.149	0.560	4.000
CS2	1	2	0.619	0.335	0.167	0.127	1.304	1.837	1.304	0.435	1.630	3.026	0.578	1.961	0.578	0.193	0.723	4.000
CS3	1	2	1.310	0.708	0.354	0.273	1.997	2.305	1.997	0.666	2.497	3.026	0.726	2.461	0.726	0.242	0.907	4.000
CS3 with 1/4" screws	1	2	1.310	0.708	0.354	0.273	2.149	2.668	2.149	0.716	2.686	3.454	0.840	2.461	0.840	0.280	1.050	5.033

Legend:
(1) Required Screw Shear Strength = 1.25 P_{ns}
(2) Provided Screw Shear Strength
(3) Required Screw Tension Strength = 1.25 P_{nt}
(4) Provided Screw Tension Strength

Table XVIII: Connection Analysis of Recommended EOF Web Reinforcement Configurations (cont.)

Notes:
1. CS__ is the cross-section number
2. N_{vr} and N_{hr} are the number of vertical and horizontal rows, respectively, of screw connections.
3. $(P_a)_{test} = (P_n)_{test}/1.85$. These are the tested counterparts of $(P_a)_{comp,\ solid\ web}$ and are based on performance of the solid web tests. The $(P_n)_{test}$ values for the solid web tests are from Table XIV.
4. Items which are underlined did not meet the provisions due to the factor of safety of 3.00. Subsequent rows show improved and acceptable design.
5. Screw information for screw washer diameter, d_w, and provided screw shear and tension strengths are from manufacturer information (Buildex, 1979).
   a. #12 screws were used unless stated otherwise: d = 0.2160 in., d_w = 0.415 in.
   b. 1/4" screws: d = 0.2500 in., d_w = 0.415 in.
   c. Shear and tension strengths of screws are not provided explicitly in Buildex (1979). Strengths are based on test results reported for the applicable screw diameter.
6. See Table III for cross-section information used to compute the shear and tension loads and shear and tension capacities.

Table XIX: Connection Analysis of Recommended IOF Web Reinforcement Configurations

	N_{vr}	N_{hr}	$(P_n)_{test}$ avg. (kips) Table XV	$(P_a)_{test}$ (kips)	Applied Force per Screw at $(P_a)_{test}$ (kips)		Shear Forces and Capacities (kips)						Tension Forces and Capacities (kips)					
					P_{shear} Eq.84	$P_{tension}$ Eq.85	P_{ns} Eq.94	P_{ns} Eq.95	P_{ns} lesser	$P_{as} = P_{ns}/3.00$ Eq.93	see legend item (1)	see legend item (2)	P_{not} Eq.97	P_{nov} Eq.98	P_{nt} lesser	$P_{at} = P_{nt}/3.00$ Eq.96	see legend item (3)	see legend item (4)
IOF Type 1b and 2b																		
CS1	1	2	0.925	0.500	0.125	0.095	0.866	1.424	0.866	0.289	1.082	3.026	0.448	1.520	0.448	0.149	0.580	4.000
CS2	2	2	1.401	0.757	0.189	0.144	1.304	1.837	1.304	0.435	1.630	3.026	0.578	1.961	0.578	0.193	0.723	4.000
CS3	2	2	2.988	1.615	0.404	0.312	1.997	2.305	1.997	0.666	2.497	2.036	0.726	2.461	0.726	0.242	0.907	4.000
CS3 with 1/4" screws	2	2	2.988	1.615	0.404	0.312	2.149	2.668	2.149	0.716	2.686	3.454	0.840	2.461	0.840	0.280	1.050	5.033
CS3 with increased N_{vr} and #12 screws	3	2	2.988	1.615	0.269	0.208	1.997	2.305	1.997	0.666	2.497	3.026	0.726	2.461	0.726	0.242	0.907	4.000

Legend:

(1) Required Screw Shear Strength = 1.25 P_{ns}
(2) Provided Screw Shear Strength
(3) Required Screw Tension Strength = 1.25 P_{nt}
(4) Provided Screw Tension Strength

Table XIX: Connection Analysis of Recommended IOF Web Reinforcement Configurations (cont.)

Notes: 1. CS__ is the cross-section number

2. N_{vr} and N_{hr} are the number of vertical and horizontal rows, respectively, of screw connections.

3. $(P_a)_{test} = (P_n)_{test}/1.85$. These are the tested counterparts of $(P_a)_{comp,\ solid\ web}$ and are based on performance of the solid web tests. The $(P_n)_{test}$ values for the solid web tests are from Table XV.

4. Items which are underlined did not meet the provisions due to the factor of safety of 3.00. Subsequent rows show improved and acceptable design.

5. Screw information for screw washer diameter, d_w, and provided screw shear and tension strengths are from manufacturer information (Buildex, 1979).
   a. #12 screws were used unless stated otherwise: d = 0.2160 in., d_w = 0.415 in.
   b. 1/4" screws: d = 0.2500 in., d_w = 0.415 in.
   c. Shear and tension strengths of screws are not provided explicitly in Buildex (1979). Strengths are based on test results reported for the applicable screw diameter.

6. See Table III for cross-section information used to compute the shear and tension loads and shear and tension capacities.

Equations 84 and 85 were used to determine the shear and tension forces for each screw.

Analysis of the self-drilling screw connections was not performed prior to testing the configurations. Cross-section 3 did not meet the specifications for pull out tension force due to the factor of safety of 3.00 for connections for both the EOF (Table XVIII) and IOF (Table XIX) loading conditions. However, the factor of safety was well in excess of unity. Because the test specimens' structural performance was adequate with the smaller factors of safety, adequate connections will be ensured when the design requires a factor of safety of 3.00.

Although cross-section 3 did not meet the Specification provisions for connections, Tables XVIII and XIX show that this cross section could have readily and economically been made to comply with the provisions of CCFSS (1993). The items of the tested designs which failed to meet the provisions are given in Tables XVIII and XIX, and these items are underlined. The designs which met the provisions are given on subsequent lines of the tables.

The design which met the Specification provisions for the EOF Type 1b and EOF Type 2b web reinforcement configurations consisted of using the next larger screw size, d equal to 1/4 inch (Table XVIII). The designs which met the Specification provisions for the IOF Type 1b and IOF Type 2b web reinforcement configurations consisted of using an additional vertical row of connections (Table XIX).

The factor of safety achieved during the testing for the EOF Type 1b and EOF Type 2b web reinforcement configurations for cross-section 3 was P_{nt}, 0.726, divided by $P_{tension}$, 0.273, which is equal to 2.66 (Table XVIII). The factor of safety achieved during the testing for the IOF Type 1b and IOF Type 2b web reinforcement configurations for cross-section 3 was P_{nt}, 0.726, divided by $P_{tension}$, 0.312 which is equal to 2.33 (Table XIX). Both of these factors of safety were well in excess of unity, but failed to meet the provision value of 3.00. The calculations in Tables XVIII and XIX confirm that reasonable connection designs can be readily and economically obtained which meet the requirements stated herein. Furthermore, these were accomplished using the conservative relationships for the forces in the connections (Eqs. 84 and 85).

G. SUMMARY OF THE EOF AND IOF REINFORCED WEB OPENING STUDY

Web reinforcement configurations have been developed which will ensure that the EOF or IOF web crippling strength for sections with web openings will reach the strength of the solid web-unreinforced specimen. The configurations are practical and can readily be assembled using web reinforcement material from the cross section of the structural member, and minimal number of self-drilling screw connections.

SECTION VI. DESIGN RECOMMENDATIONS

The design recommendation given herein consist of reduction factor equations and web reinforcement configurations. The full parameter ranges of applicability of the current AISI Specification, as given in Section II.F, web crippling and combined bending and web crippling provisions apply to these design recommendations. Additional limitations are given herein for the bearing length and web opening parameters. The parameter ranges of applicability of the current AISI Specification web crippling and combined bending and web crippling provisions are not repeated in this section.

The following design recommendations are provided in a format intended for adoption into the AISI Specification provisions for web crippling. The terminology used in the design recommendations applies to the LRFD Specification. However, substitution of the allowable capacities instead of the nominal capacities, as used herein, will permit adoption into the ASD Specification.

It is implied that the current Specification provisions for combined bending and web crippling (Section II.F) apply to the design recommendations. However, the web crippling capacity entry into the combined bending and web crippling provisions are modified, as given herein, to account for the presence of web openings. Furthermore, it assumed that the Specification provisions for screw fasteners will be included, as given in Appendix B, in Section E4 of future editions of the Specification.

The following design recommendations apply only to single web sections with punchouts spaced no closer than 24 inches on center:

(1) For end-one-flange loading conditions when the punchout is not within the bearing length, P_n shall be multiplied by the following:

$$R_c = 1.08 - 0.630(a/h) + 0.120(x/h) \leq 1.0 \quad \text{(Eq. 86)}$$

The reduction factor, R_c, shall be limited to the following conditions: $b \leq 4.5$ in.; $N \geq 1$ in., and; $a/h \leq 0.50$.

(2) For interior-one-flange loading conditions when the punchout is not within the bearing length, P_n shall be multiplied by the following:

$$R_c = 0.96 - 0.272(a/h) + 0.063(x/h) \leq 1.0 \quad \text{(Eq. 87)}$$

The reduction factor, R_c, shall be limited as given for Eq. 86, except that $N \geq 3$ in.

(3) For interior-one-flange loading conditions with punchouts which are symmetric about the centerline of bearing, P_n shall be multiplied by the following:

$$R_c = [1-0.197(a/h)^2]\ [1-0.127(b/n_1)^2] \leq 1.0 \quad \text{(Eq. 88)}$$

The reduction factor, R_c, shall be limited as given for Eq. 86, except that $N \geq 3$ in., and $b/n_1 \leq 2.0$.

where, for Equations 86 thru 88:

- a = twice the maximum distance from punchout edges to the mid-height of the web. For punchouts symmetric about the mid-height of the web, this is equal to the maximum depth of the punchout.
- b = maximum length of the punchout
- h = depth of the flat portion of the web
- x = smallest distance between punchout edges and the edge of bearing
- n_1 = N+h-a

(4) For interior-one-flange loading conditions with any portion of the punchout within the length of bearing and punchouts which are not symmetric about the centerline of bearing, P_n shall be multiplied by the lesser of Eq. 87 with x = 0 and Eq. 88.

(5) For two flange loading conditions with punchouts, tests must be performed in accordance with Section F1.

(6) Web reinforcement may be used to enhance the web crippling strength of sections. The cross section of the web reinforcement must have a cross section equivalent to the member cross section. For both the end-one-flange and interior-one-flange conditions, the full depth of the web reinforcement must extend the length of bearing. The attachment of the web reinforcement to the member shall be as close to the top and bottom flanges of the member as possible. In such case the value of P_n requires no modification. The limits of $a/h \le 0.50$ and $b \le 4.5$ in. shall apply.

Web reinforcement attached to the member using screw fasteners shall be in accordance with Section E4 and as given herein.

Screw connections shall be placed in N_{vr}, number of vertical rows, and N_{hr}, number of horizontal rows as defined by (a), (b), and (c):

(a) The center of the connection to the nearest vertical edge of web reinforcement, S_H, is given by Table XX.

Table XX: Values of N_{vr} and S_H

Bearing length, N (in.)	Minimum N_{vr} (1)	S_H value of each vertical row (2) (3)
≤ 2	1	N/2
> 2 to ≤ 6	2	both rows: 1/2 in.
> 6 to ≤ 9	3	both exterior rows: 1/2 in.
		interior row: N/2
> 9 (4)	----	----

where d = nominal screw diameter

Notes:

1. N_{vr} shall be increased as necessary to ensure that the shear and tension forces in the connections are in compliance with Sections E4.3 and E4.4.

2. S_H shall be increased to 1.5d as necessary to ensure compliance with Section E4.2

3. In no case will the distance between centerlines of connectors be less than 3d.

4. Tests must be conducted in accordance with Section F1.

(b) The center of the connection to the nearest horizontal edge of web reinforcement, S_V, is given by Table XXI:

Table XXI: Values of N_{hr} and S_V

Depth of section, D (in.)	Minimum N_{hr} (1)	S_V value of each horizontal row (2) (3)
≤ 6	2	both rows: 1/2 in.
> 6 to ≤ 9	3	both top and bottom row: 1/2 in.
		interior row: D/2
> 9 (4)	----	----

Notes:

1. N_{hr} shall be increased as necessary to ensure compliance with Section E4.3.

2. The distance between the center of each fastener and the edge of a punchout shall not be less than 3d. The location of an interior horizontal row of fasteners shall be at mid-height of the web unless the center of the connection is closer than a distance of 3d to a punchout edge. When the punchout is located at mid-height of the web, the connection shall be located in the half of the member closer to the bearing.

3. In no case shall the distance between centerlines of fasteners be less than 3d.

4. Tests shall be conducted in accordance with Section F1.

(c) The design forces in a connection shall be determined as follows:

$$P_{shear} = P_a \;/\; (N_{hr} \times N_{vr}) \qquad \text{(Eq. 89)}$$

$$P_{tension} = \frac{P_a}{N_{vr}} \left(\frac{\frac{B}{2} + R + t}{D - 2S_v} \right) \qquad \text{(Eq. 90)}$$

where $P_a = P_n / 1.85$
P_n = nominal web crippling capacity in accordance with Section C3.4 for the solid web section
B = width of the loaded region of the flange
R = inside bend radius
t = thickness of the section
D = total depth of section
S_v = distance between the center of the top and bottom rows of connections to the top and bottom, respectively, of the section
N_{vr} = number of vertical rows of connections
N_{hr} = number of horizontal rows of connections.

SECTION VII. CONCLUSIONS

A total of 305 unreinforced web tests were performed on single web sections. Of these, 157 and 148 tests were performed using the EOF and IOF loading conditions, respectively. Analysis of the test results provided reduction factor equations for both the EOF (Eq. 68) and IOF (Eqs. 6 and 68) loading conditions. To provide the modified web crippling capacity for sections with web openings, the reduction factor equations may be applied to the AISI Specification web crippling equations (Eqs. 30 thru 35), for design situations that satisfy the ranges of applicability given herein. Bending and web crippling interaction must be checked using Equations 42 and 43 using the reduced web crippling and bending capacities for web openings in the absence of each other.

The reduction factor equations are a function of the α and a/h values (Figs. 3 and 4) of the design situation. A joint region of α and a/h was identified that requires no strength reduction. Use of the reduction factor equation can readily be implemented in practice to ensure that the design for the limit states of web crippling and combined bending and web crippling can be accomplished with adequate strength, stability, and serviceability for sections with web openings. Other failure modes, i.e. shear, flexure, and combinations thereof, must be checked separately.

The results of the tests performed on test specimens without web openings showed good correlation with the AISI Specification web crippling provisions. However, the AISI Specification web crippling provisions were found inadequate to predict the web crippling capacity of sections with web openings.

Web reinforcement configurations have been developed which will ensure that the EOF or IOF web crippling strength for sections with web openings will reach the strength of the solid web-unreinforced section. The configurations are practical and can readily be assembled using web reinforcement material from the cross section of the structural member, and minimal number of self-drilling screw connections.

Design recommendations are summarized in Section VI in a format intended for consideration for adoption into the AISI Specifications provisions.

The following areas pertaining to the web crippling behavior of single web sections with web openings are worthy of investigation: 1. the End-Two-Flange (ETF) and Interior-Two-Flange (ITF) loading conditions, 2. the effect of web openings which are not located at mid-height of the web, 3. partial rotational end restraint caused by the placement of a member inside a C-shaped section 'track' with fasteners placed in both flanges of the member.

APPENDIX A

NOTATION

The following symbols are used in this document:

a — height of web opening, or shear panel length for unreinforced web elements, or, distance between transverse stiffeners for web elements;

a_o — length of a web opening;

b — length of a web opening;

c_{11} — parameter $1 + 0.0122(N/t) \leq 2.22$;

c_{12} — parameter $1 + 0.0122(N/t) \leq 3.17$;

c_{21} — parameter $1 - 0.247\ (R/t) \geq 0.32$;

c_{22} — parameter $1 - 0.0814\ (R/t) \geq 0.43$;

c_{32} — parameter $1 + 2.4\ (N/h) \leq 1.96$;

c_{41} — parameter $1 - 0.00348\ (h/t) \geq 0.32$;

c_{42} — parameter $1 - 0.00170\ (h/t) < 0.81$;

c_{51} — parameter $1 - 0.298\ (e/h) \geq 0.52$;

c_{52} — parameter $1 - 0.120\ (e/h) \geq 0.40$;

C_p — correction factor;

C_1 — parameter $(1.22-0.22\ F_y/33)$;

C_2 — parameter $1.06-0.06\ R/t \leq 1.00$;

C_3 — parameter $(1.33-0.33\ F_y/33)$;

C_4 — parameter $(1.15-0.15\ R/t) \leq 1.0$;

C_θ — parameter $0.7 + 0.30\ (\theta/90)^2$;

d — diameter of a circular web opening, or, nominal screw diameter, or, depth of steel section, or, distance between edge of bearing and a web opening;

$d_{opening}$ — diameter of a circular perforation;

d_1 — parameter defined in Figure 1;

d_2 — parameter defined in Figure 1;

D	total depth of a section;
D_n/L_n	the dead load to live load ratio;
D_o	diameter of a circular web opening;
e	parameter defined in Figure 9;
E	modulus of elasticity;
E_t	tangent modulus of elasticity;
f_{cr}	critical plate buckling stress;
f_x	compressive stress in the x direction;
F_m	mean value of the fabrication factor for the type of component involved;
$(F.S.)_{LRFD}$	factor of safety based upon the value of the LRFD resistance factor
F_u	ultimate strength of web reinforcement and base section material;
F_{u1}	tensile strength of member in contact with the screw head;
F_{u2}	tensile strength of member not in contact with the screw head;
F_y	design yield stress of a section;
h	height of the flat portion of a web;
h_o	depth of a web opening;
$h_{opening}$	width of a square perforation;
h_s	width of a square web opening;
k	plate buckling coefficient, or parameter $F_y/33$;
k_c	plate buckling coefficient due to a perforation;
L	length of a test specimen;
L_{min}	minimum required length of a test specimen;
L_{span}	distance between support rollers for a test specimen;

M	applied bending moment at, or immediately adjacent to, the point of application of a concentrated load or reaction;
M_{axo}	allowable flexural strength about the centroidal x-axis;
M_m	mean value of the material factor for the type of component involved;
M_{max}	allowable bending moment permitted if bending stress only exists;
M_n	nominal moment capacity of a section;
$(M_n)_{comp}$	computed nominal moment capacity of a section;
$(M_n)_{test}$	tested nominal moment capacity of a section;
M_{nxo}	nominal flexural strength about the centroidal x-axis;
M_p	applied service moment;
M_u	required flexural strength at, or immediately adjacent to, the point of application of a concentrated load;
n	number of test values;
n_1	parameter N + h - a;
N	load or bearing length;
N_{hr}	number of horizontal rows of connections;
N_{vr}	number of vertical rows of connections;
P	concentrated load or reaction in the presence of bending moment;
P_a	allowable concentrated load or reaction in the absence of bending moment;
$(P_a)_{comp,\ solid\ web}$	allowable web crippling capacity of a solid web section;
$(P_a)_{comp,\ web\ opening}$	allowable web crippling capacity of a section with a web opening;
P_{as}	allowable shear strength per screw;

P_{at} allowable tension strength per screw;

P_{cb} the ultimate web crippling capacity, per web, caused by buckling;

P_{cy} the ultimate web crippling capacity, per web, caused by bearing;

P_{HOR} horizontal force per screw;

P_m mean value of the tested-to-predicted load ratios;

P_{max} allowable concentrated load or reaction in the absence of bending moment;

P_n nominal strength for concentrated load or reaction in the absence of bending moment;

$(P_n)_{comp}$ computed web crippling capacity of a section;

$(P_n)_{comp,\ solid\ web}$ nominal web crippling capacity of a solid web section;

$(P_n)_{comp,\ web\ opening}$ nominal web crippling capacity of a section with a web opening;

P_{not} pull-out strength per screw;

P_{nov} pull-over strength per screw;

P_{ns} nominal shear strength per screw;

P_{nt} nominal tension strength per screw;

$(P_n)_{test}$ tested capacity of a section;

$(P_n)_{test\ adj,\ solid\ web}$ moment adjusted web crippling capacity for a solid web section;

$(P_n)_{test\ adj,\ web\ opening}$ moment adjusted web crippling capacity for a section with a web opening;

P_{shear} applied shear force per screw;

$P_{solid\ web}$ web crippling capacity of a solid web section;

PSW percent of solid web strength;

PSW_{adj} moment adjusted percent of solid web strength;

$P_{tension}$ applied tension force per screw;

P_u	required strength for a concentrated load, or reaction in the presence of bending moment;
P_{VERT}	vertical force per screw;
$P_{web\ opening}$	web crippling capacity of a section with a web opening;
R	inside bend radius of a section;
RF	reduction factor;
R_n	nominal capacity or resistance;
R_p	service load;
s	depth of a tee;
s_b	depth of the bottom of a tee;
s_t	depth of the top of a tee;
S	clear distance between web openings;
S_e	elastic section modulus of the effective section calculated with the extreme compression or tension fiber at F_y;
t	thickness of a section, plate, or web reinforcement;
t_f	thickness of a flange;
t_w	thickness of a web;
t_1	thickness of member in contact with a screw head;
t_2	thickness of member not in contact with a screw head;
v	aspect ratio of tee of a web, a_o/s;
V_F	coefficient of variation of the fabrication factor for the type of component involved;
V_m	maximum nominal shear capacity of a section;
V_M	coefficient of variation of the material factor for the type of component involved;
V_P	coefficient of variation of the tested-to-predicted load ratios;

$\bar{V}_p$	plastic shear capacity of an unperforated web;
V_Q	coefficient of variation of the load effect;
V_u	factored shear force, or, nominal shear capacity of a section;
w_{plate}	width of a plate;
x'	parameter defined in Figures 3 and 4;
Z	parameter defined in Figure 9;
α	parameter defined in Figures 3 and 4;
β_o	target reliability index;
γ	load factor;
μ	Poisson's ratio;
ω	deflection of plate perpendicular to surface;
Ω	factor of safety;
Ω_f	factor of safety for bending;
ϕ	resistance factor;
Φ	resistance factor;
Φ_b	bending moment resistance factor;
Φ_w	web crippling resistance factor;
θ	angle between the plane of the web and the plane of the bearing surface;

APPENDIX B

AISI SPECIFICATION PROVISIONS FOR SCREW CONNECTIONS

a. E4 Screw Connections

Notation:

d = nominal screw diameter
Ω = factor of safety = 3.0
P_{as} = allowable shear strength per screw
P_{at} = allowable tension strength per screw
P_{ns} = nominal shear strength per screw
P_{nt} = nominal tension strength per screw
P_{not} = pull-out strength per screw
P_{nov} = pull-over strength per screw
t_1 = thickness of member in contact with the screw head
t_2 = thickness of member not in contact with the screw head
F_{u1} = tensile strength of member in contact with the screw head
F_{u2} = tensile strength of member not in contact with the screw head

All requirements apply to self-drilling screws with $0.08 \le d \le 0.25$ in. Screws shall be installed and tightened in accordance with the manufacturer's recommendations.

b. E4.1 Minimum Spacing

The distance between the centers of fasteners shall not be less than 3d.

c. E4.2 Minimum Edge and End Distance

The distance between the center of a fastener to the edge of any part shall not be less that 3d. If the connection is subjected to shear force in one direction only, the minimum edge distance shall be reduced to 1.5d in the direction perpendicular to the force.

d. E4.3 Shear

(1) E4.3.1 Connection Shear

The shear force per screw, P_{shear}, shall not exceed:

$$P_{as} = P_{ns} / \Omega \qquad (88)$$

where for the situation where $t_2 = t_1$, i.e. when both connected parts have the same properties, P_{ns} shall be taken as the smallest of:

$$P_{ns} = 4.2\ (t^3\ d)^{1/2}\ F_u \tag{89}$$

$$P_{ns} = 2.7\ t_1\ d\ F_{u1} \tag{90}$$

and,

$$P_{ns} = 2.7\ t_2\ d\ F_{u2} \tag{91}$$

Equation 89 considers the reduction in connection shear strength caused by tilting of the screw followed by threads tearing out of the material not in contact with the screw head. Equations 90 and 91 represent the connection bearing strength of the connected parts required for connection shear forces.

(2) E4.3.2 Shear in Screws

The shear capacity of the screw shall be determined by test according to Section F1(a) [AISI, 1986, and 1991a]. The shear capacity of the screw shall not be less than 1.25 P_{ns}.

The Commentary states, "Screw strength should be well established and published by the manufacturer."

e. E4.4 Tension

The head of the screw or washer, if a washer is provided, shall have a diameter d_w not less than 5/16 in. Washers shall be at least 0.050 in.

The tension force per screw, $P_{tension}$, shall not exceed P_{at}, calculated as follows:

$$P_{at} = P_{nt}\ /\ \Omega \tag{92}$$

P_{nt} = shall be taken as the lesser of P_{not} and P_{nov} as determined in Sections E4.4.1 and E4.4.2.

(1) E4.4.1 Pull-Out

The pull-out force, P_{not}, shall be calculated as follows:

$$P_{not} = 0.85\ t_c\ d\ F_{u2} \tag{93}$$

where t_c is the lesser of the depth of penetration and the thickness t_2.

(2) E4.4.2 Pull-Over

The pull-over force, P_{nov}, shall be calculated as follows:

$$P_{nov} = 1.5\ t_1\ d_w\ F_{u1} \tag{94}$$

where d_w is the larger of the screw head diameter or the washer diameter, and shall be taken not larger than 1/2 in.

(3) E4.4.3 Tension is Screws

The shear capacity of the screw shall be determined by test according to Section F1(a) [AISI 1986, and AISI 1991a]. The shear capacity of the screw shall not be less than 1.25 P_{nt}.

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