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Behavior of cold-formed steel web elements with web openings subjected to web crippling and a combination of bending and web crippling for interior-one-flange loading

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Final Report

BEHAVIOR OF COLD-FORMED STEEL WEB ELEMENTS WITH WEB OPENINGS SUBJECTED TO WEB CRIPPLING AND A COMBINATION OF BENDING AND WEB CRIPPLING FOR INTERIOR-ONE-FLANGE LOADING

by

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PREFACE

An experimental investigation of the web crippling limit state was conducted on single web cold-formed steel flexural members with circular web openings in order to aid in the enhancement of the current AISI (1986) Specification provisions for web crippling. The current AISI ASD Specification (1986) and AISI LRFD Specification (1991a) have no specific design provisions for the reduction in web crippling capacity of flexural members caused by the presence of web openings.

The test specimens, constructed of C-sections, were subjected to a concentrated load applied to one flange which satisfied the AISI criteria for Interior-One-Flange loading. The research findings resulted in a new reduction factor equation which enveloped a wider range of values for the cross-section geometric parameters. The previous reduction factor equation developed by Langan, LaBoube, and Yu (1994) was originally developed for web openings that were rectangular with fillet corners. During the analysis of the current study, the Langan, LaBoube, and Yu reduction factor equation was found to be conservative for larger a/h values. The new reduction factor results in an equation to obtain the reduction in web crippling capacity for sections with web openings. The web crippling capacity is considered for the web capacity without the effects of the bending moment. For situations of combined bending and web crippling, the current AISI provisions for interaction are used with appropriate consideration given to the modifications for bending moment and web crippling capacities.

The final conclusions resulting from the experimental investigation were used to develop recommended design standards.

This report is based on a thesis presented to the Faculty of the Graduate School of the

University of Missouri-Rolla in partial fulfillment of the requirements for the degree of Masters of Science in Civil Engineering.

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I. INTRODUCTION

A. GENERAL

Conservation is becoming more prevalent in our society as it is a necessity to protect our environment and ensure our future. Recently, this growing environmental awareness has created concerns regarding the use of wood as an appropriate construction material. In addition, economic and safety concerns are pressuring the competitiveness of the wood industry. Timber prices have risen sharply as the result of a supply and demand crisis. Also, the recent devastation to wood structures by storms have led to the adoption of building codes which require engineered residential construction to minimize safety concerns.

To improve the feasibility of residential construction, alternative building materials are being explored. One such alternate material is cold-formed steel. Due to its recyclability it is an environmentally attractive solution. In addition to satisfying environmental concerns, cold formed steel members have many other positive physical characteristics. They are mass produced with consistent dimensional properties, as well as being non-combustible, and insect and rodent resistant. Cold-formed steel has long been the preferred construction material for commercial light-industrial construction because it is cost competitive, possesses a high strength-to-weight ratio, and is simple and fast to erect.

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 various editions of the "Specification for the Design of Cold-Formed steel Structural Members" of the American Iron and 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 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 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.

The foremost reason for conducting this investigation was the concern that the presence of 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 by the AISI specification provisions.

B. PURPOSE OF INVESTIGATION

This investigation had following two purposes:

1. Primary Purpose. The Primary purpose of this investigation was to study the structural behavior of single web cold-formed steel flexural members with unreinforced web openings subjected to web crippling and a combination of bending and web crippling for interior-one-flange loading condition.

The primary consideration of structural behavior was the failure load of the test 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. Secondary Purpose. 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 IOF tests performed during the investigation. This evaluation consisted of the following two tasks and objectives.

a. First Objective. To compare the test results for the specimens with no web openings in order to ensure good correlation with the currently existing AISI provisions.

b. Second Objective. To compare the test results for specimens with web openings in order to determine if the currently existing AISI provisions could adequately predict the web crippling capacity of the sections with web openings.

C. SCOPE OF INVESTIGATION

The elements of the scope of the investigation can be grouped into the following four areas.

1. Loading Condition. The loading condition used was Interior-One-Flange (IOF) loading condition as shown in Figure 1 and described in Table I.

2. Cross-Section Types. All cross sections tested were C-shaped sections with edge stiffened flanges as shown in Figure 2. However, the same web crippling behavior will exist for other single web sections. Therefore, the recommendations for the IOF reduction factor equation is valid for other single web cross-section shapes, with or without stiffened flanges.

3. Cross-section Properties. Table II provides the properties of the IOF unreinforced web sections while Table III gives the ranges of parameters for the tests.

All web openings were circular and located at mid-height of the web.

4. Range of α values. 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. As shown in Figure 3, α is

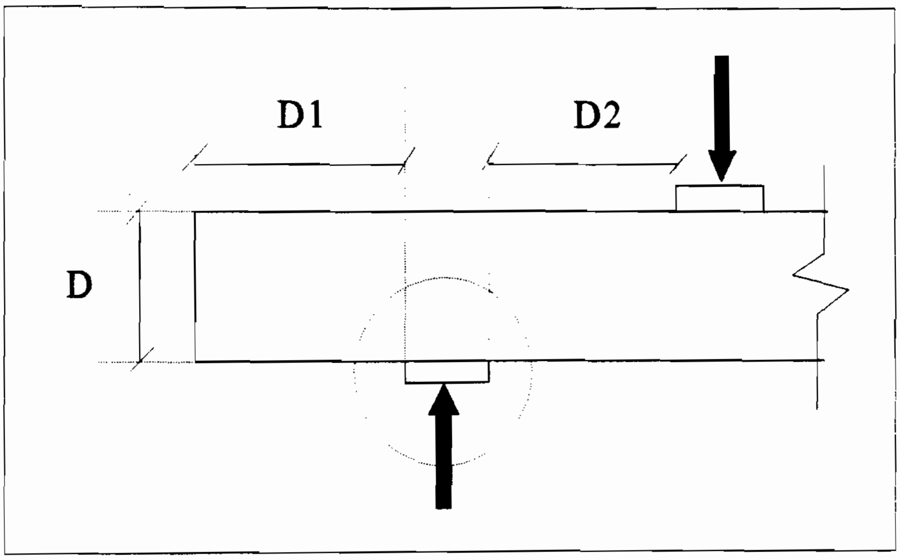

Figure 1. AISI Web Crippling Loading Definitions

Table I. AISI Web Crippling Loading Definitions

h = D - 2 (R + t)		
Loading Condition	End or Interior (D1)	One or Two Flange (D2)
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

where, h = depth of the flat portion of the web measured along the plane of the web

D = overall depth of the web

R = inside bent radius

t = thickness of the web

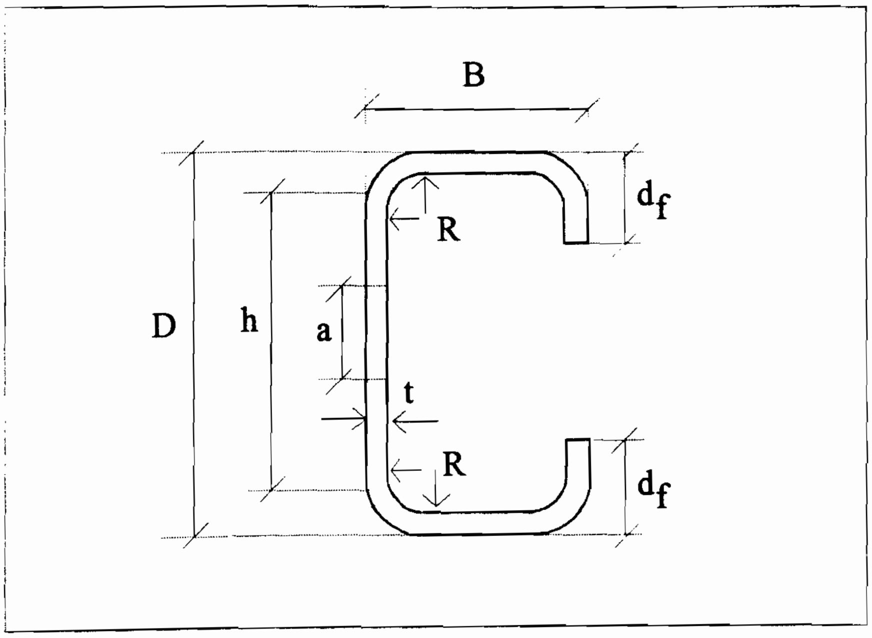

Figure 2. Specimen Cross-Section parameters

Table II. Unreinforced IOF Cross-Section Properties

Cross Section	D (in)	R (in)	t (in)	h (in)	B (in)	df (in)	F_y (ksi)	F_u	$(P_n)_{comp}$ (kips)	$(M_n)_{comp}$ (kips-in)
IOF C-6-20	5.961	0.172	0.0327	5.552	1.625	0.438	50.50	55.30	0.4223	11.58
IOF C-8-20	7.920	0.172	0.0335	7.509	1.650	0.500	47.00	58.90	0.3807	16.20
IOF C-6-18	5.965	0.141	0.0443	5.595	1.628	0.439	52.00	58.70	0.8442	20.05
IOF C-8-18	7.825	0.172	0.0439	7.393	1.620	0.504	52.00	57.40	0.7349	26.82
IOF C-6-16	6.017	0.188	0.0560	5.529	1.625	0.438	56.80	69.40	1.3133	25.96
IOF C-8-16	7.938	0.219	0.0559	7.388	1.625	0.438	56.80	69.40	1.1915	43.29

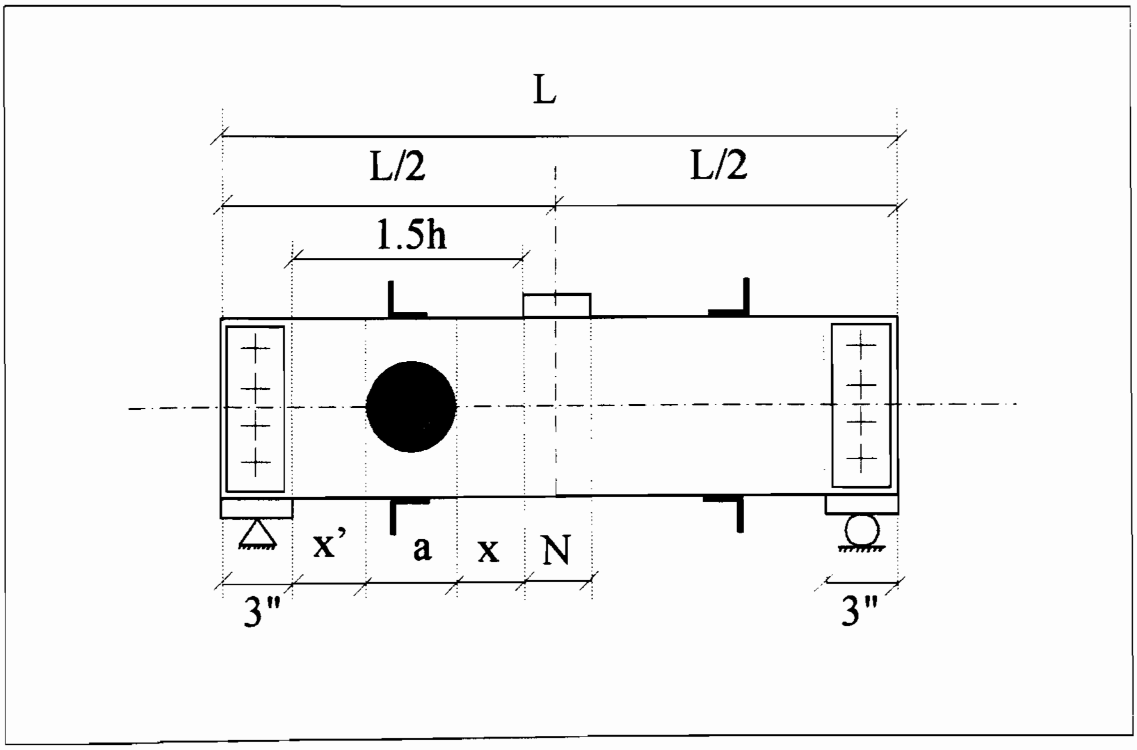

Figure 3. IOF Specimen parameters

Table III. Unreinforced Web IOF Cross-section Property Ranges

	h (in)	t (in)	F_y (ksi)	Fy/Fu	N (in)	α	a (in)	a/h	h/t	R/t	N/t
Minimum	5.529	0.0327	47.00	0.80	3.00	0.00	2.00	0.36	98.73	3.17	53.57
maximum	7.509	0.0560	56.80	0.91	3.00	0.70	6.00	0.81	224.15	5.26	91.74
Note: See Figures 2 and 3 for definition of dimensions.											

equal to the longitudinal clear distance between the edge of bearing and the web opening, x, divided by the height of the flat portion of the web, h. The value of α varied from 0 to 0.7 for the unreinforced IOF tests.

II. REVIEW OF LITERATURE

A. GENERAL

The literature pertinent to the investigation of web crippling behavior for IOF loading condition 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.

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

The use 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):

The 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 the 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, and by Zetlin in the 1940s and 1950s and more recently at the University of Missouri-Rolla by Hetrakul and Yu. In these experimental investigations, the web crippling tests have been carried out under the following four loading conditions for beams having single unreinforced webs and I-beams. All loading conditions are illustrated in Figure 1.

1. End one-flange (EOF) loading
2. Interior one-flange (IOF) loading
3. End two-flange (ETF) loading
4. Interior two-flange (ITF) loading

Yu's (1991) summary was made concerning the nature of the 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 (199lb), respectively.

Santaputra and Yu (1986) provide an overview of an investigation 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 associate 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, Pekoz, 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. PREVIOUS RESEARCH ON WEB CRIPPLING BEHAVIOR FOR SECTIONS WITH WEB OPENINGS

1. General. There is limited research on the web crippling behavior of sections with web openings. Yu and Davis (1973), Sivakumaran and Zielonka (1989), and Langan, LaBoube and Yu (1994) performed experimental studies on the web crippling behavior of cold-formed steel flexural members with web openings. All of these investigations will be discussed herein.

2. Yu and Davis. 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 buckling 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 equations, which are distinguished by whether or not the web opening is square or circular.

For circular web openings with $0 \leq d/h \leq 0.5$:

$$RF = 1.0 - 0.6\frac{d}{h} \tag{1}$$

where d=the diameter the circular web opening, and; h = the clear distance between flanges measured in the plane of the web.

For square web openings with $0 \leq h_s/h \leq 0.642$:

$$RF = 1.0 - 0.77\frac{h_s}{h} \tag{2}$$

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 1 and 2, no restriction is placed on the value of the bearing length for applicability of the equations. As can be seen by both Equations 1 and 2, 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:

$$RF = (1-0.197(\frac{a}{h})^2)(1-0.127(\frac{b}{n_1})^2) \tag{3}$$

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: $b/n1 \leq 2.0$, and; $a/h \leq 0.75$.

Equation 3 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 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 2 inches for all the 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 3 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:

$$0.9 \leq \frac{RF \times (P_n)_{test,solid\ web}}{(P_n)_{test,web\ opening}} \leq 1.1 \tag{4}$$

Thus the value of the above expression is ideally equal to unity.

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

$$RF = (1 - 0.197(\frac{a}{D})^2)(1 - 0.127(\frac{b}{n_1})^2) \tag{5}$$

where D = total depth of the section, and the remaining parameters are the same as for Equation 3.

5. Langan, LaBoube, and Yu (1994). A study of the structural behavior for single web cold-formed steel flexural members was conducted and design equations were developed that account for the degradation in web crippling capacity caused by the presence of web openings.

The web openings used for this investigation were rectangular with fillet corners and were located at midheight of the web. 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 a x b, a being the height of the web opening and b being the longitudinal length of the web opening. 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 bearing plate, N, used during the investigation was 3.0, 4.0, 5.0, and 6.0 inches.

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}, defined later, as dependent variable. The resulting reduction factor equation, with a maximum of 100 percent is:

$$RF = 96.44 - (27.20\frac{a}{h}) + (6.31\alpha) \leq 100\% \tag{6}$$

or,

$$RF = 0.964 - (0.272\frac{a}{h}) + (0.0631\alpha) \leq 1.00 \tag{7}$$

The Adjusted Percent of Solid Web Strength PSW_{adj} is the percent of solid web strength in the absence of significant bending moment and is given by:

$$PSW_{adj} = \frac{(P_n)_{test\ adj,web\ opening}}{(P_n)_{test\ adj,solid\ web}} \tag{8}$$

where, $(P_n)_{test\ adj}$ is the design web crippling strength in the absence of significant bending moment and is given by:

$$(P_n)_{test\ adj} = \left(\frac{1.07}{1.42-\frac{(M_n)_{test}}{(M_n)_{comp}}}\right)(P_n)_{test} \geq (P_n)_{test} \qquad \textbf{(9)}$$

where $(P_n)_{test}$ = the mid-span failure load, $(M_n)_{comp}$ = the nominal bending moment capacity, and, $(M_n)_{test}$ = the mid-span bending moment at the failure load given by:

$$(M_n)_{test} = (P_n)_{test} * \frac{L-3}{4} \qquad \textbf{(10)}$$

where L= length of the specimen. The subtraction of 3 inches from length L results from the presence of end bearing plates.

The parameters α and a/h only provided the conclusive correlation with PSW_{adj}. The effect of the parameters intrinsic to solid web sections of t, F_y, h/t, R/t and N/t is nullified by their having the same effect on both the numerator and denominator of the PSW_{adj} relationship. Conversely, α and a/h influenced PSW_{adj} since they are intrinsic to the web openings, and therefore they affected only the numerator of the PSW_{adj} relationship, $(P_n)_{test\ web\ opening}$. The influence of b is addressed by imposing an upper limit on b equal to the maximum permitted in standard practice.

6. Summary. The following conclusions result from the investigations by Yu and Davis (1973), Sivakumaran and Zielonka (1989) and Langan, LaBoube, and Yu (1994):

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

ii. Bending moment must be evaluated for its magnitude, and if greater than 35 percent of the ultimate nominal bending moment capacity of the section, must be considered for its degrading effect on web crippling capacity.

iii. There is precedence for the development and use of reduction factor equations 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) The testing procedure has variable centerline locations of the web opening relative to the load plate, therefore, the reduction factor equation contains 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, this parameter is 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.

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. Therefore, it is concluded that this research does not specifically address web crippling behavior of flexural members with web openings.

2. Perforated Plate Elements. 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 as 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.

The corresponding literature in this connection are Stiemer and Prion (1990), Narayanan and Chow (1984), and Yu (1991). They have not been reviewed here in detail.

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. AISC Guidelines. Much of the research conducted on thick web flexural members with web openings was performed for the American Institute of Steel Construction (AISC). 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).

The purpose of web openings in thick-walled hot-rolled sections is 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, unless cut into the field.

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 opening 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.

c. Thin-Walled Flexural Members with Web Openings. 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 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 showed that 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 2 to 5%. 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 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 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 (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 for single web or multiple web sections with or without edge-stiffened flanges. The equation which is applicable to the conditions of the current investigation, i.e. for single web sections subjected to the IOF loading condition, is provided as follows. The equations are given in pairs for each design situation addressed in this investigation. The first equation applies to the situation of $N/t \leq 60$ while the second equation applies to the situation of $N/t > 60$ in each pair.

IOF Loading of Single Unreinforced Web Sections with Stiffened or Unstiffened Flanges

For N/t $\leq$60:

$$(P_a)_{comp} = t^2\frac{F_y}{33}C_1C_2(291.06-0.4\frac{h}{t})(1+0.0069\frac{N}{t}), \quad kips \tag{11}$$

For N/t > 60:

$$(P_a)_{comp} = t^2\frac{F_y}{33}C_1C_2(291.06-0.4\frac{h}{t})(0.748+0.00111\frac{N}{t}), \quad kips \tag{12}$$

Where, C_1 = (1.22-0.22 Fy/33)

C_2 = (1. 06-0.06 R/t) $\leq$ 1.00

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

The above equations incorporate a factor of safety of 1.85. This factor of safety for web crippling is primarily attributed to the variance found in web crippling analysis. As stated by Hetrakul and Yu (1978), according to the scatter 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 of scatter.

The origins of the transition between one-flange and two-flange loading of a clear distance between oppositely directed load plates of 1.5h (Figure 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 limitation included in Section 3.5 of the AISI Specification (1968). 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>. Hetrakul and Yu (1978) provided separate bending and web crippling interaction equations 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:

$$1.22\left(\frac{P}{P_{max}}\right)+\left(\frac{M}{M_{max}}\right) \leq 1.53 \tag{13}$$

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 an application of the concentrated load or reaction, and; M_{max} = allowable bending moment permitted, if only bending stress exists.

Equation 13 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 13 incorporates the factors of safety of 1.67 for bending moment and 1.85 for web crippling. The above equation based on the nominal capacities will be given as:

$$1.07\frac{(P_n)_{test}}{(P_n)_{comp}}+\frac{(M_n)_{test}}{(M_n)_{comp}} \leq 1.42 \qquad \textbf{(14)}$$

According to Equation 13, bending moment causes degradation in web crippling capacity when M/M_{max} exceeds 0.31 while according to Equation 14, bending moment causes degradation in web crippling capacity when $(M_n)_{test}/(M_n)_{comp}$ exceeds 0.35.

Equation 14 was developed from a regression analysis of the test data which had scatter associated with the phenomenon of the interaction behavior. Essentially, this scatter superposes the variations associated with the separate web crippling and bending moment phenomenons. The magnitude of this scatter is closely related to the complexity of the 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."

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 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.

These 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), 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 $(P_n)_{comp, solid}$, in kips and the associated resistance factor to prevent web crippling failure.

b. Web Crippling Equations. 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 $\phi_w\ (P_n)_{comp,\ solid\ web}$ which is the right hand side of the equation:

$$\sum \gamma\ R_p \leq \phi_w\ R_n \tag{15}$$

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).

One of the web crippling design situations pertinent to this investigation is IOF Loading of Single Unreinforced Webs. The following equation applies to both the sections with stiffened or unstiffened flanges, AISI Equation C3.4-4:

$$(P_a)_{comp} = t^2 k C_1 C_2 C_\theta (291 - 0.40\frac{h}{t})(1 + 0.007\frac{N}{t}),\ \ kips \tag{16}$$

$$(P_n)_{comp} = t^2 k C_1 C_2 C_\theta (538 - 0.74\frac{h}{t})(1 + 0.007\frac{N}{t}),\ \ kips \tag{17}$$

For Equations 16 and 17, when N/t > 60, the factor [1+0.007(N/t)] may be increased to [0.75+0.011(N/t)].

For the above Equations 16 and 17:

$k = Fy/33$

$C_1 = (1.22-0.22k)$

$C_2 = (1.06-0.06\ R/t) < 1.00$

$C_\theta = 0.7 + 0.30\ (\theta/90)^2$

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 $\geq 45°$, but not more than $90°$

N = Bearing length of load or reaction.

c. Development of the AISI ASD Specifications. Each of the above AISI ASD Specification web crippling equations were 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 both the equations are the same except for a reduction in significant digits for the Specification adopted equations.

The equation of Hetrakul and Yu (1978), Equation 12 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 11 and 12. This can readily be seen by the coefficients of the two equations.

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 $k = Fy/33$ 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.

d. Development of the AISI LRFD Specifications. It is evident from a comparison of the LRFD equation (Equation 17) and its ASD counterpart (Equation 16) 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 were multiplied by 1.85. This is equivalent to:

$$(P_n)_{comp,LRFD} = 1.85(P_a)_{comp,ASD} \qquad \textbf{(18)}$$

e. 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 Fy value used in the development of the current AISI provisions was 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 value of 91.5 ksi when using Equations 16 and 17.

At higher F_y values than this 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 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-Interior equations:

$$\frac{d(Equns.)}{dF_y} = Kd\frac{kC_1}{dF_y} = Kd\left(\frac{(\frac{F_y}{33})(1.22-0.22(\frac{F_y}{33}))}{dF_y}\right) = 0 \qquad \textbf{(19)}$$

Solution: Fy = 91.5 ksi , 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 91.5 ksi. No provision is currently allowed for increasing the web crippling strength for higher Fy values. Therefore, the stated Fy value of 91.5 ksi should be used if the cross section has a yield strength which exceeds this value.

The equations by Santaputra, Parks, and Yu (1989) were developed primarily to account for higher Fy values, up to 190 ksi.

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:

$$M_a = \frac{M_n}{\Omega_f} \tag{20}$$

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 (199la), 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 0.9 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:

$$\sum \gamma M \le \phi_b M_n \qquad \textbf{(21)}$$

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 22 from the ASD Specification (1986) and LRFD Specification (199la), Equation C3.1.1-1:

$$M_n = S_e F_Y \tag{22}$$

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). Two interaction equations in terms of allowable and nominal capacities are provided in the subsequent paragraphs. Only single web unreinforced situation is reviewed herein.

b. Interaction Equation (Nominal Capacities). For beam specimens having single unreinforced webs subjected to combined bending and web crippling, the presence of bending moments will noticeably reduce the web crippling capacity when the ratio of $M_{test}/(M_n)_{comp}$ exceeds 0.35.

$$1.07\frac{P_{test}}{P_{n\ comp}} + \frac{M_{test}}{M_{n\ comp}} \leq 1.42 \tag{23}$$

where P_{test} = Maximum concentrated load or reaction in the presence of bending moment

$P_{n\,comp}$ = Computed maximum concentrated load or reaction in the absence of bending moment determined in accordance with Section C3.4 of AISI (1986)

M_{test} = Maximum bending moment at, or immediately adjacent to, the point of application of the concentrated load or reaction

$M_{n\,comp}$ = Computed maximum bending moment if only bending exists

c. Interaction Equation (Allowable Capacities). By using a safety factor of 1.85 for web crippling and a safety factor of 1.67 for bending moment, the following interaction Equation 24 is derived. Equation 24 can be seen under Section 3.5 of AISI ASD (1986) Specification provisions for Combined Bending and web Crippling:

$$1.2(\frac{P}{P_a})+(\frac{M}{M_a}) \leq 1.5 \tag{24}$$

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 of AISI (1986)

M = Applied bending moment at, or immediately adjacent to, the point of application of the concentrated load or reaction, and

M_a = Allowable moment about the centroidal axis determined in accordance with Section C3.1(only bending stress exists), excluding the provisions of Section C3.1.2 (Lateral buckling).

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 AISI ASD Specification (1986) Section B6, Stiffeners. The provisions ensure adequate strength and stability of transverse stiffeners.

d. Influence of Interaction. 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 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."

III. 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 (Figure 1).

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 and the limits of applicability of the reduction factor equation are based on the parameters of the design situation. The design recommendations are also summarized in Section F.

B. PURPOSE

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 16 and 17, which provide the web crippling capacity in the absence of bending moment.

C. EXPERIMENTAL INVESTIGATION

1. Test Specimens. The test specimens were fabricated from industry standard C-sections having edge-stiffened flanges. Therefore, the flanges are classified as partially-stiffened in accordance with the AISI Specification (1986, and 1991a). The web openings were circular and were located at mid-height of the web as shown in Figure 3. Figures 4 thru 7 show typical test specimens. See Figures 2 and 3 for the cross-section and longitudinal geometry of the test specimens, respectively. 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 III. Sizes of the web openings used in this test program, were 2, 4 and 6 inches, and are designated by dimension a as shown in Figure 3.

The sections were fabricated to ensure that the web opening in each test specimen was at the desired distance x (Figure 3) 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, (Figure 3). 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, and, 0.7. The length of the IOF load application plate, N, was a constant three inches throughout the investigation.

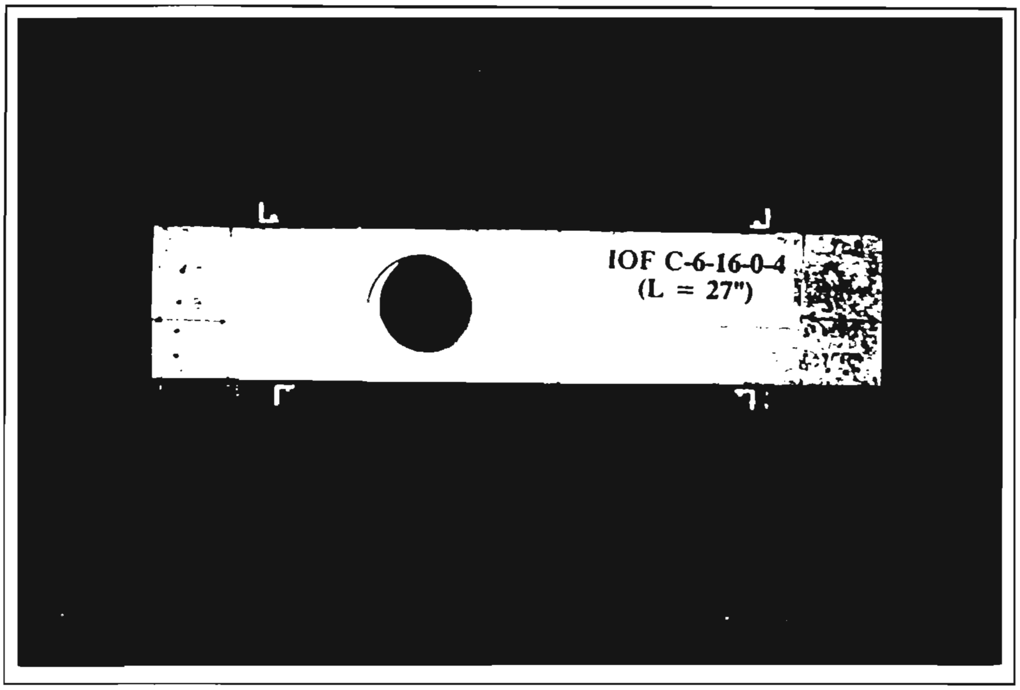

Figure 4. Typical Unreinforced IOF Specimen (IOF C-6-16-0-4, L=27")

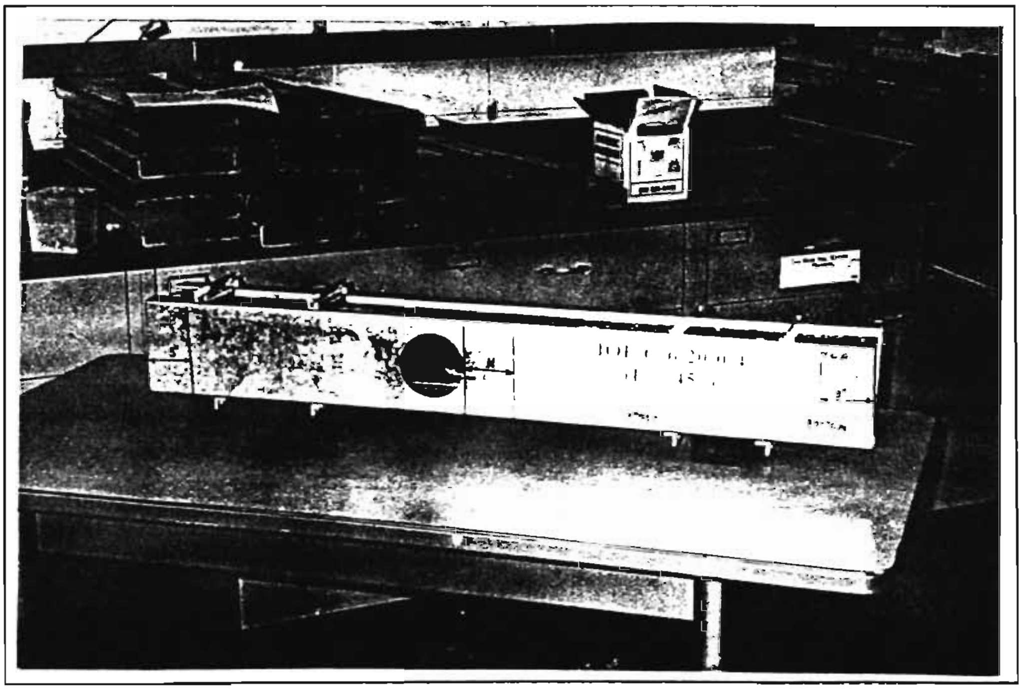

Figure 5. Typical Unreinforced IOF Specimen (IOF C-6-20-0-4, L=45")

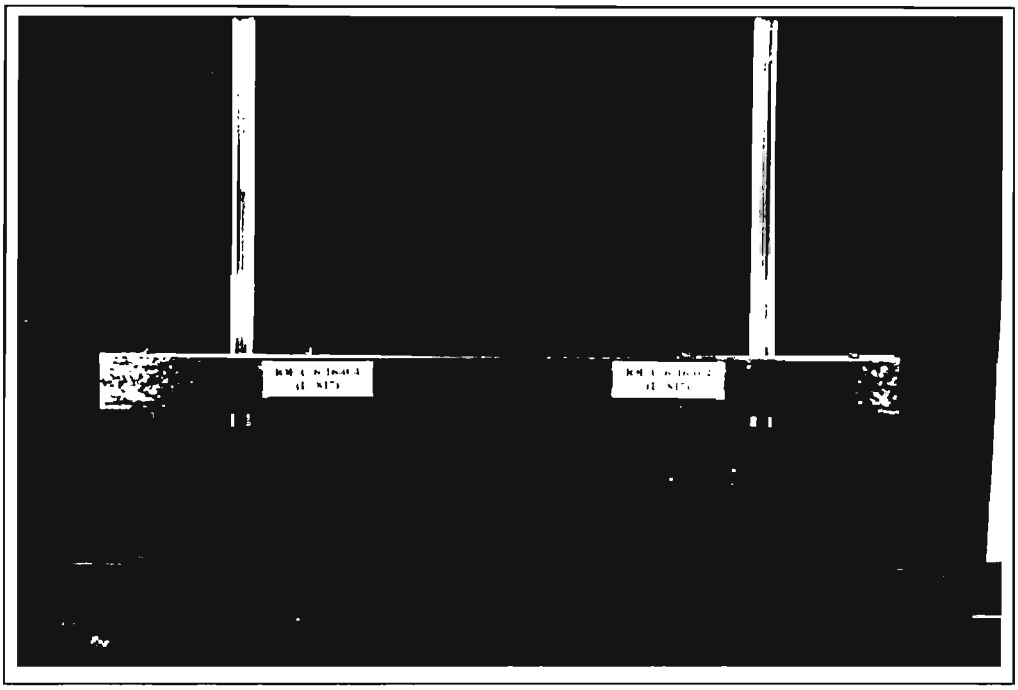

Figure 6. Typical Unreinforced IOF Specimen (IOF C-6-16-0-4, L=81")

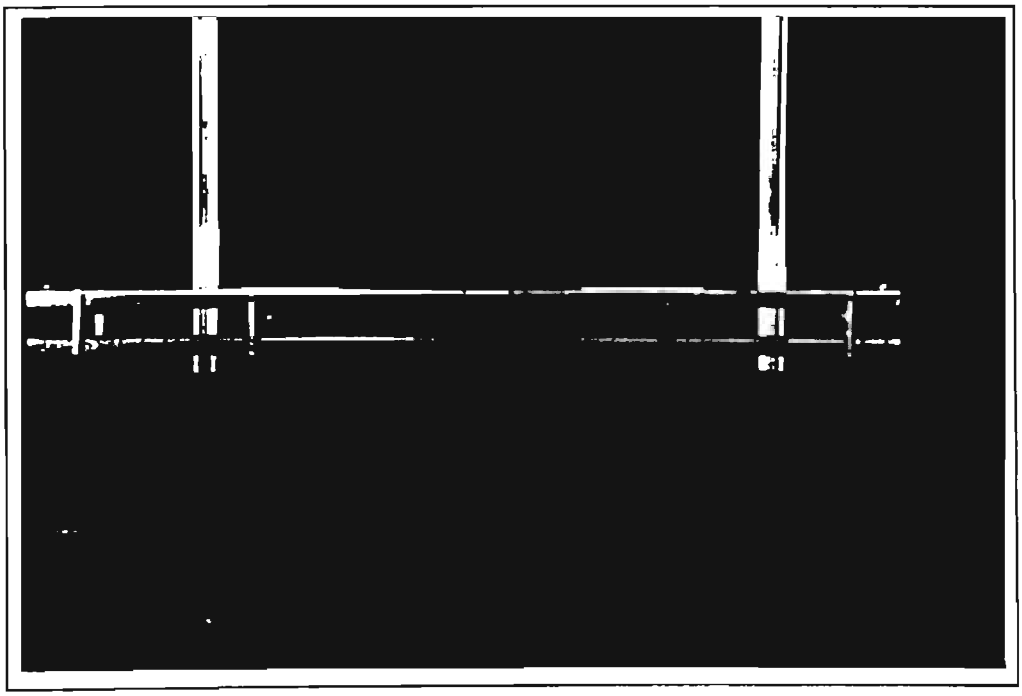

Figure 7. Top View of Typical Unreinforced IOF Specimen

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 (Figure 1). However, the value of L was also governed by the additional requirement that the value of x' (Figure 3) 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, a, (Figure 3) 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:

$$L_{min} = 2(1.5h) + N + 6 \tag{25}$$

and,

$$L_{min} = 2(x + b + x') + N + 6 \tag{26}$$

Equation 25 results from the requirements of one-flange loading (Figure 1). Equation 26 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 parameters which comprise the value of L can be seen in Figure 3.

The value of a is a cross-section parameter and thus invariant for a given cross section. For a given cross section, and therefore a given a value, at high α, or x/h, values, Equation 26 was expected to govern the L_{min} value as found in Langan, LaBoube, and Yu (1994). However α values considered under this investigation were such that Equation 25 governed the L_{min} value and, at the same time satisfied the requirement of Equation 26 that x' be greater than or equal to zero.

It was also observed that nominal bending moment resulting with the above mentioned L_{min} values was found to be less than 35 percent of the nominal bending moment capacity of the sections under consideration and, thus behavior included only web crippling without any bending interaction. Therefore in order to include bending interaction, some of the specimen lengths were increased on the trial basis, which resulted in the applied bending moment to be more than 35 percent of the nominal bending moment capacity and thus led to testify the present AISI (1986) web crippling and bending interaction equation.

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 Langan, LaBoube, and Yu (1994).

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 (Figure 3). Using a Tinius-Olsen testing machine as shown in Figs. 8 & 9, a concentrated load was applied at mid-span to the IOF load 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 a three inch bearing plate 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 as shown in Figs. 10 & 11. 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.

The experimental investigation by Langan, LaBoube and Yu (1994) has already proved that the gradual load application procedure used by Hetrakul and Yu (1978) for the development of the existing

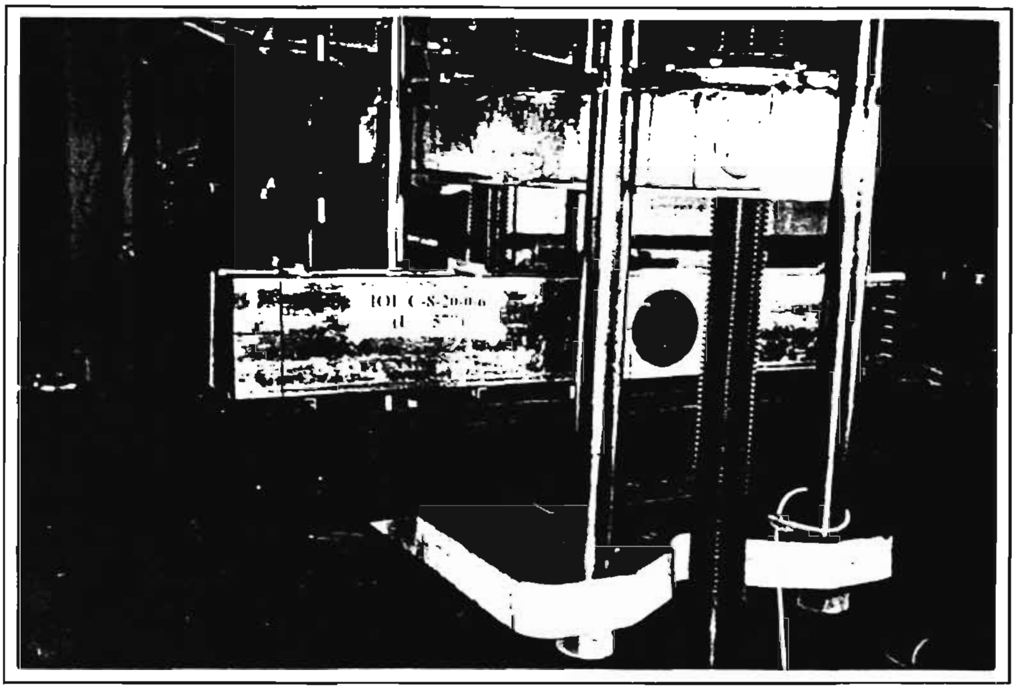

Figure 8. Tinius-Olsen Testing Machine with an Undisturbed IOF Specimen

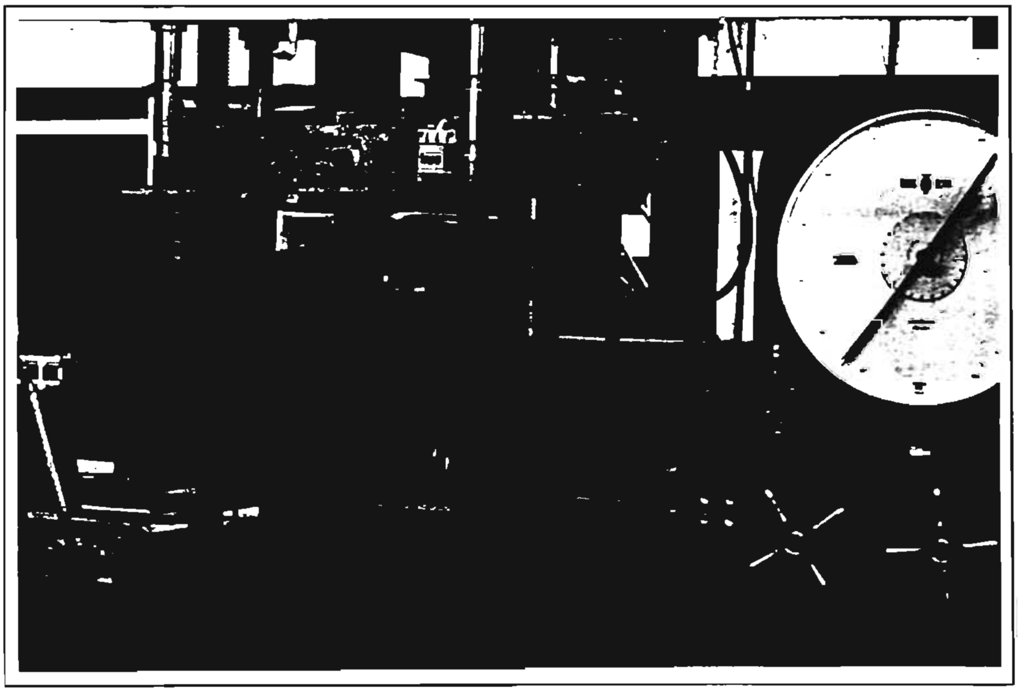

Figure 9. IOF Specimen Loaded under Tinius-Olsen Machine

Figure 10. Web Crippling of IOF Specimen during Loading Stage

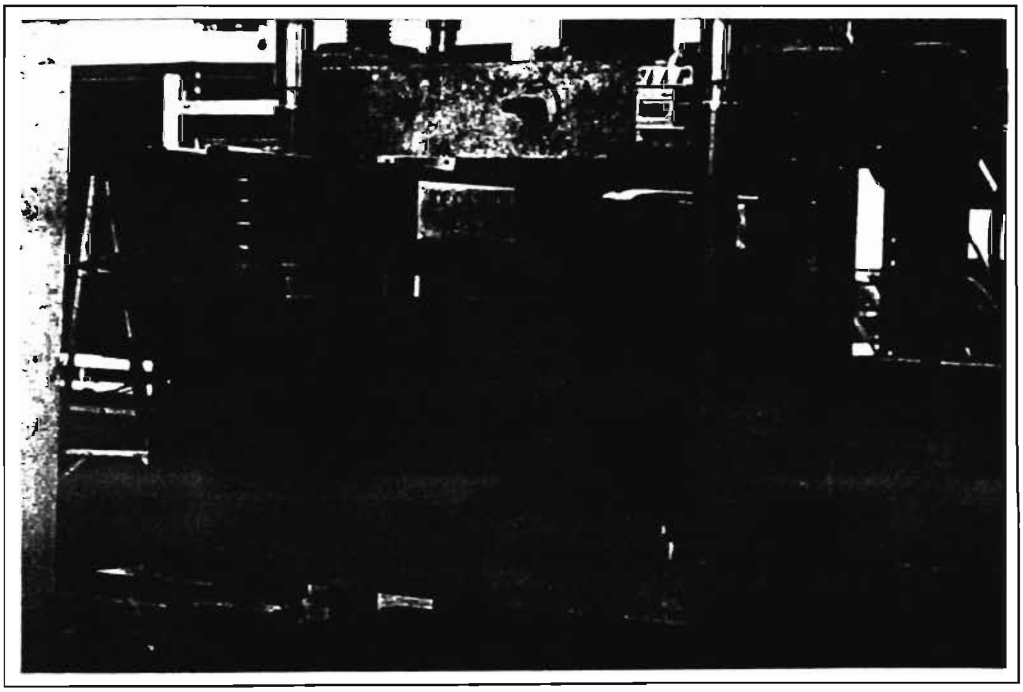

Figure 11. Combined Bending and Web Crippling of IOF Specimen during Loading Stage

AISI web crippling Specification provisions and the constantly increasing load application procedure used in the current investigation are equivalent in their effect on the web crippling behavior.

D. TEST RESULTS

1. General. Fifty Six unreinforced IOF web crippling tests were conducted. All of the specimens failed with intensive web crippling. None of the specimens failed in pure bending without significant IOF web crippling deformation.

Duplicate tests on identical specimens are identified by the specimen number designations in Tables IV thru XII. Tables IV, VII and VIII contain a summary of all the section parameters for 0.033 in thick, 0.044 in thick And 0.056 in thick sections respectively.

The tested failure load per web, $(P_n)_{test}$, for all tests is given in Tables V, IX and X for 0.033 in. thick, 0.044 in. thick, and 0.056 in. thick Sections respectively. The tested failure load per web is ½ 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 ½ 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 inertia forces.

Typical web crippling failures of the unreinforced IOF test specimens are shown in Figures 12 thru 15. In most of the test specimens, the parameters α and N were kept constant equal to 0 and 3 inches respectively.

2. Adjusted Tested Failure Load $(P_n)_{test\ adj}$. The values of the moment-adjusted tested failure load, $(P_n)_{test\ adj}$, as given in Tables V, IX and X for 0.033 in. thick, 0.044 in. thick, and 0.056 in. thick Sections respectively, have been determined from the Equation 9 defined previously under Section C5 Langan, LaBoube and Yu (1994).

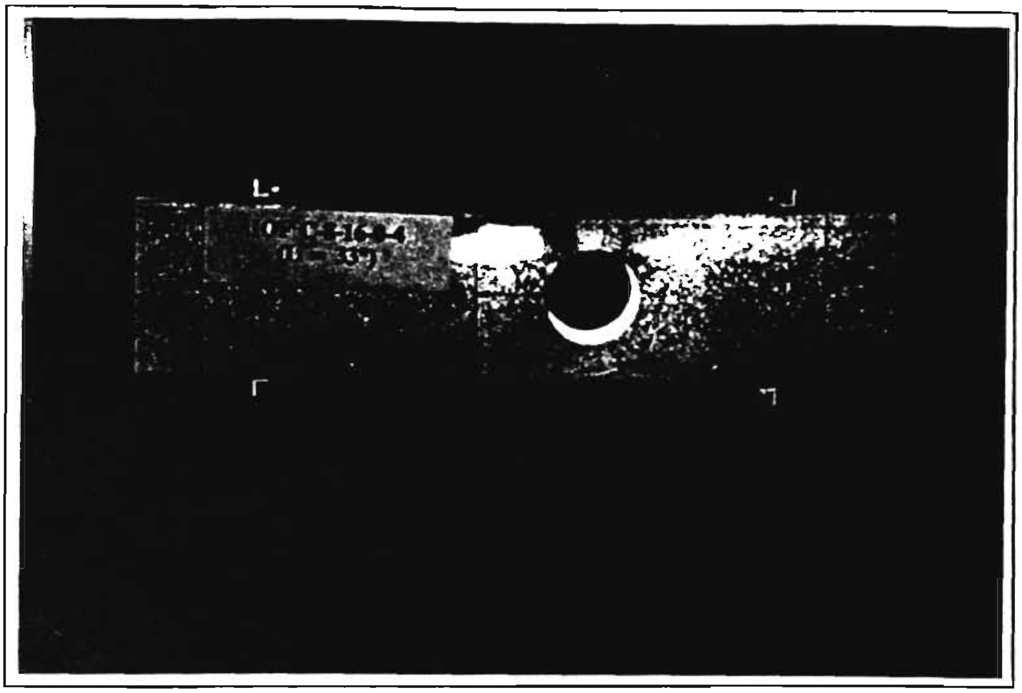

Figure 12. Typical Unreinforced Web Crippling Failure (IOF C-8-16-0-4, L=33")

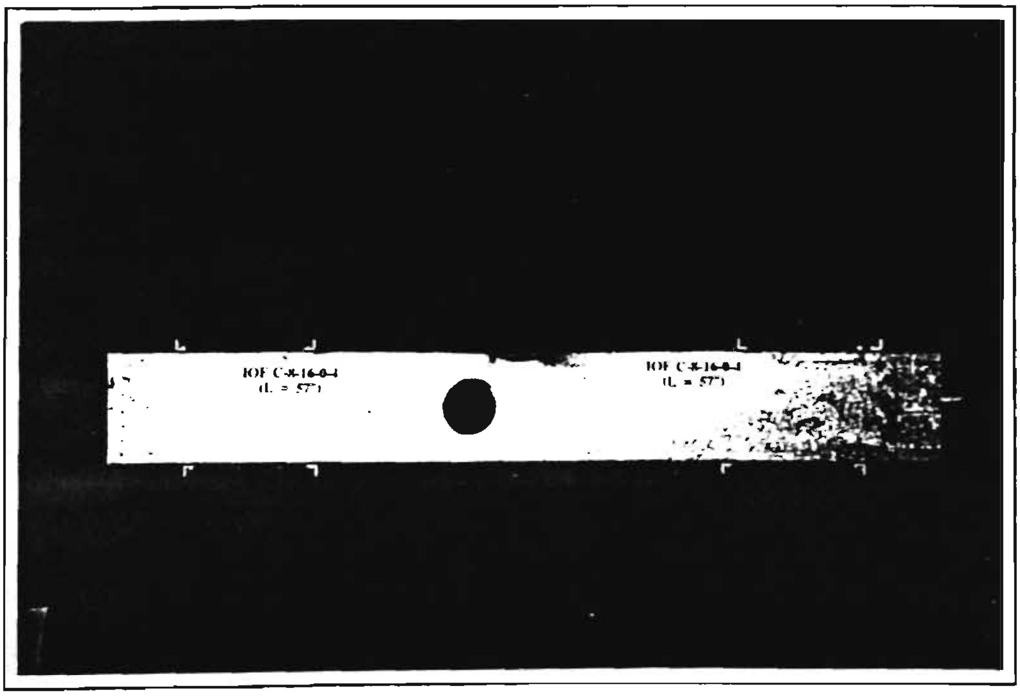

Figure 13. Typical Unreinforced Web Crippling Failure (IOF C-8-16-0-4, L=57")

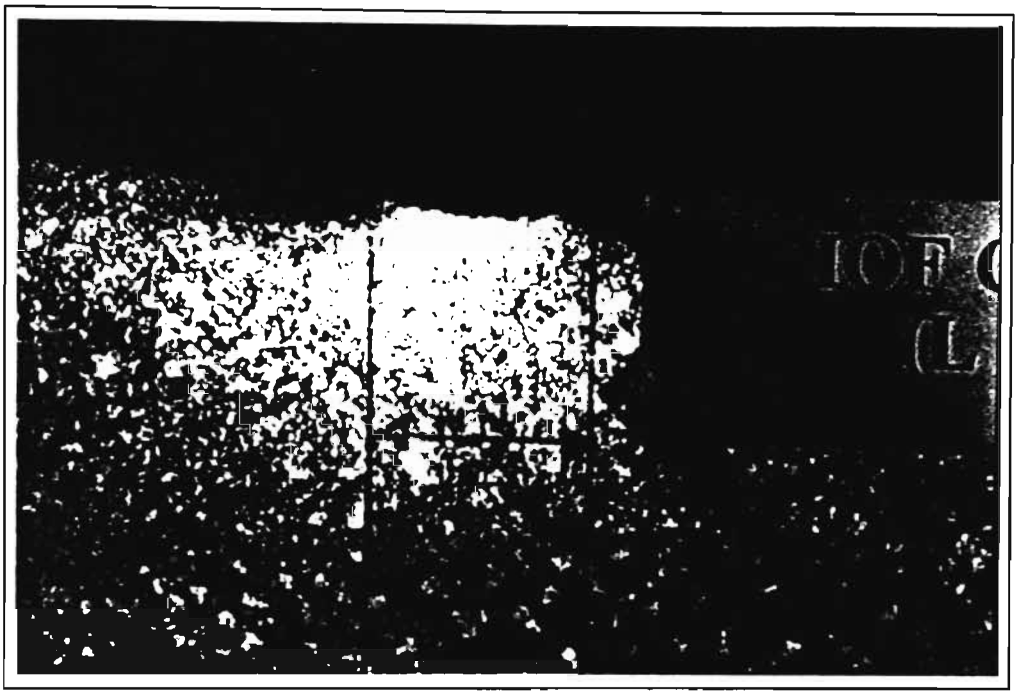

Figure 14. Typical Unreinforced Web Crippling Failure

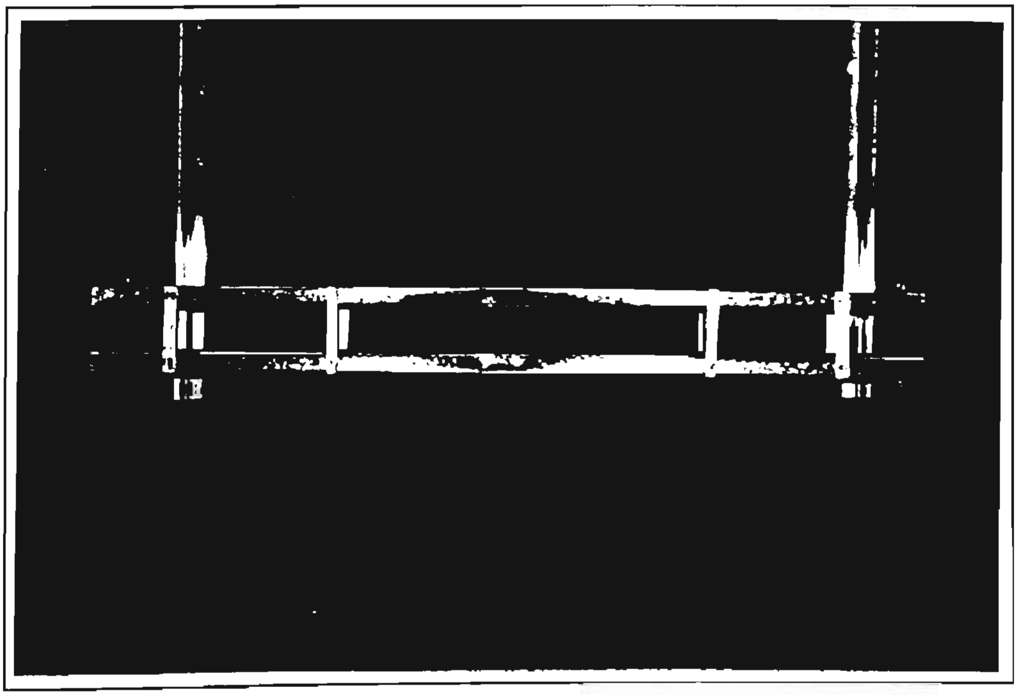

Figure 15. Typical Out-of Plane Deformation of the Web at Web Crippling Failure

Table IV. Unreinforced IOF Cross-Section Properties for 0.033 in. Thick Sections

No.	Specimen Number	D (in)	R (in)	t (in)	h (in)	B (in)	df (in)	a (in)	N (in)	Fy (ksi)	Fu (ksi)	h/t	a/h	R/t	N/t	P-allow (kips)	(M-allow)u (kips-in)	(M-allow)m (kips-in)
1	IOF-C6-20-0-0-1	5.961	0.172	0.033	5.552	1.625	0.438	SOLID	3.00	50.50	55.30	169.77	SOLID	5.26	91.74	0.4223	11.58	11.58
2	IOF-C6-20-0-0-2	5.961	0.172	0.033	5.552	1.625	0.438	SOLID	3.00	50.50	55.30	169.77	SOLID	5.26	91.74	0.4223	11.58	11.58
3	IOF-C6-20-0-0-3	5.961	0.172	0.033	5.552	1.625	0.438	SOLID	3.00	50.50	55.30	169.77	SOLID	5.26	91.74	0.4223	11.58	11.58
4	IOF-C6-20-0-2-1	5.961	0.172	0.033	5.552	1.625	0.438	2.00	3.00	50.50	55.30	169.77	0.36	5.26	91.74	0.4223	11.58	11.58
5	IOF-C6-20-0.7-2-1	5.961	0.172	0.033	5.552	1.625	0.438	2.00	3.00	50.50	55.30	169.77	0.36	5.26	91.74	0.4223	11.58	11.58
6	IOF-C6-20-0.7-2-2	5.961	0.172	0.033	5.552	1.625	0.438	2.00	3.00	50.50	55.30	169.77	0.36	5.26	91.74	0.4223	11.58	11.58
7	IOF-C6-20-0-4-1	5.961	0.172	0.033	5.552	1.625	0.438	4.00	3.00	50.50	55.30	169.77	0.72	5.26	91.74	0.4223	11.58	11.58
8	IOF-C6-20-0-4-2	5.961	0.172	0.033	5.552	1.625	0.438	4.00	3.00	50.50	55.30	169.77	0.72	5.26	91.74	0.4223	11.58	11.58
9	IOF-C6-20-0-4-3	5.961	0.172	0.033	5.552	1.625	0.438	4.00	3.00	50.50	55.30	169.77	0.72	5.26	91.74	0.4223	11.58	11.58
10	IOF-C6-20-0-4-1	5.961	0.172	0.033	5.552	1.625	0.438	4.00	3.00	50.50	55.30	169.77	0.72	5.26	91.74	0.4223	11.58	11.58
11	IOF-C6-20-0-4-2	5.961	0.172	0.033	5.552	1.625	0.438	4.00	3.00	50.50	55.30	169.77	0.72	5.26	91.74	0.4223	11.58	11.58
13	IOF-C6-20-0.5-4	5.961	0.172	0.033	5.552	1.625	0.438	4.00	3.00	50.50	55.30	169.77	0.72	5.26	91.74	0.4223	11.58	11.58
14	IOF-C6-20-0.7-4	5.961	0.172	0.033	5.552	1.625	0.438	4.00	3.00	50.50	55.30	169.77	0.72	5.26	91.74	0.4223	11.58	11.58
15	IOF-C8-20-0-0-1	7.920	0.172	0.034	7.509	1.650	0.500	SOLID	3.00	47.00	58.90	224.15	SOLID	5.13	89.55	0.3807	11.58	16.20
16	IOF-C8-20-0-0-2	7.920	0.172	0.034	7.509	1.650	0.500	SOLID	3.00	47.00	58.90	224.15	SOLID	5.13	89.55	0.3807	16.20	16.20
17	IOF-C8-20-0-4-1	7.920	0.172	0.034	7.509	1.650	0.500	4.00	3.00	47.00	58.90	224.15	0.53	5.13	89.55	0.3807	16.20	16.20
18	IOF-C8-20-0-4-2	7.920	0.172	0.034	7.509	1.650	0.500	4.00	3.00	47.00	58.90	224.15	0.53	5.13	89.55	0.3807	16.20	16.20
19	IOF-C8-20-0-4-1	7.920	0.172	0.034	7.509	1.650	0.500	4.00	3.00	47.00	58.90	224.15	0.53	5.13	89.55	0.3807	16.20	16.20
20	IOF-C8-20-0-4-2	7.920	0.172	0.034	7.509	1.650	0.500	4.00	3.00	47.00	58.90	224.15	0.53	5.13	89.55	0.3807	16.20	16.20
21	IOF-C8-20-0.7-4-1	7.920	0.172	0.034	7.509	1.650	0.500	4.00	3.00	47.00	58.90	224.15	0.53	5.13	89.55	0.3807	16.20	16.20
22	IOF-C8-20-0.7-4-2	7.920	0.172	0.034	7.509	1.650	0.500	4.00	3.00	47.00	58.90	224.15	0.53	5.13	89.55	0.3807	16.20	16.20
23	IOF-C8-20-0-6-1	7.920	0.172	0.034	7.509	1.650	0.500	6.00	3.00	47.00	58.90	224.15	0.80	5.13	89.55	0.3807	16.20	14.56
24	IOF-C8-20-0-6-2	7.920	0.172	0.034	7.509	1.650	0.500	6.00	3.00	47.00	58.90	224.15	0.80	5.13	89.55	0.3807	16.20	14.56
25	IOF-C8-20-0-6-1	7.920	0.172	0.034	7.509	1.650	0.500	6.00	3.00	47.00	58.90	224.15	0.80	5.13	89.55	0.3807	16.20	14.56
26	IOF-C8-20-0-6-2	7.920	0.172	0.034	7.509	1.650	0.500	6.00	3.00	47.00	58.90	224.15	0.80	5.13	89.55	0.3807	16.20	14.56
27	IOF-C8-20-0.7-6-1	7.920	0.172	0.034	7.509	1.650	0.500	6.00	3.00	47.00	58.90	224.15	0.80	5.13	89.55	0.3807	16.20	14.56
28	IOF-C8-20-0.7-6-2	7.920	0.172	0.034	7.509	1.650	0.500	6.00	3.00	47.00	58.90	224.15	0.80	5.13	89.55	0.3807	16.20	14.56

Cross-Section Designations: IOF-Ca-b-c-d-e
IOF - Interior-One-Flange C - Channel a - Overall Depth of the Web b- Gage Number c - Alpha Value d - Diameter of Hole e - No. of Test on an Identical Specimen

(M-allow)u - Unmodified allowable moment capacity (M-allow)m - Modified allowable moment capacity

Table V. Unreinforced IOF Test Results for 0.033 in. Thick Sections

No.	Date mm/dd/yy	Specimen Number	L (in.)	Alpha (x/h)	a/h	h/t	(Pn)test (lbs)	(Pn)test/Web (kips)	(Pn)test adj (kips)	PSWadj (kips)	Limit State	PSWadj %	Langan's RF	Modified RF
1	01/11/96	IOF-C6-20-0-0-1	27.00	SOLID	SOLID	169.77	1400	0.7000	0.7000	94.92	Web Crippling	0.95	1.00	1.00
2	02/01/96	IOF-C6-20-0-0-2	27.00	SOLID	SOLID	169.77	1550	0.7750	0.7750	105.08	Web Crippling	1.05	1.00	1.00
3	02/22/96	IOF-C6-20-0-0-3	27.00	SOLID	SOLID	169.77	1475	0.7375	0.7375	100.00	Web Crippling	1.00	1.00	1.00
4	01/13/96	IOF-C6-20-0-2-1	27.00	0.00	0.36	169.77	1425	0.7125	0.7125	96.61	Web Crippling	0.97	0.87	0.88
5	12/21/95	IOF-C6-20-0.7-2-1	27.00	0.70	0.36	169.77	1475	0.7375	0.7375	100.00	Web Crippling	1.00	0.91	0.92
6	01/11/96	IOF-C6-20-0.7-2-2	27.00	0.70	0.36	169.77	1475	0.7375	0.7375	100.00	Web Crippling	1.00	0.91	0.92
7	01/13/96	IOF-C6-20-0-4-1	27.00	0.00	0.72	169.77	1300	0.6500	0.6500	88.14	Web Crippling	0.88	0.77	0.88
8	01/20/96	IOF-C6-20-0-4-2	27.00	0.00	0.72	169.77	1400	0.7000	0.7000	94.92	Web Crippling	0.95	0.77	0.88
9	02/01/96	IOF-C6-20-0-4-3	27.00	0.00	0.72	169.77	1400	0.7000	0.7000	94.92	Web Crippling	0.95	0.77	0.88
10	02/10/96	IOF-C6-20-0-4-1	45.00	0.00	0.72	169.77	1250	0.6250	0.6250	84.75	Web Crippling	0.85	0.77	0.88
11	02/22/96	IOF-C6-20-0-4-2	45.00	0.00	0.72	169.77	1325	0.6625	0.6686	90.65	Web Crippling	0.91	0.77	0.88
12	03/18/96	IOF-C6-20-0-4-1	81.00	0.00	0.72	169.77	1000	0.5000	0.5842	79.21	Web Crippling	0.79	0.77	0.88
13	01/20/96	IOF-C6-20-0.5-4	27.00	0.50	0.72	169.77	1450	0.7250	0.7250	98.31	Web Crippling	0.98	0.80	0.90
14	01/20/96	IOF-C6-20-0.7-4	27.00	0.70	0.72	169.77	1450	0.7250	0.7250	98.31	Web Crippling	0.98	0.81	0.91
15	01/20/96	IOF-C8-20-0-0-1	33.00	SOLID	SOLID	224.15	1550	0.7750	0.7750	101.64	Web Crippling	1.02	1.00	1.00
16	02/01/96	IOF-C8-20-0-0-2	33.00	SOLID	SOLID	224.15	1500	0.7500	0.7500	98.36	Web Crippling	0.98	1.00	1.00
17	01/20/96	IOF-C8-20-0-4-1	33.00	0.00	0.53	224.15	1400	0.7000	0.7000	91.80	Web Crippling	0.92	0.82	0.88
18	02/01/96	IOF-C8-20-0-4-2	33.00	0.00	0.53	224.15	1400	0.7000	0.7000	91.80	Web Crippling	0.92	0.82	0.88
19	02/10/96	IOF-C8-20-0-4-1	57.00	0.00	0.53	224.15	1300	0.6500	0.6500	85.25	Web Crippling	0.85	0.82	0.88
20	02/22/96	IOF-C8-20-0-4-2	57.00	0.00	0.53	224.15	1325	0.6625	0.6625	86.89	Web Crippling	0.87	0.82	0.88
21	01/20/96	IOF-C8-20-0.7-4-1	33.00	0.70	0.53	224.15	1500	0.7500	0.7500	98.36	Web Crippling	0.98	0.86	0.92
22	01/25/96	IOF-C8-20-0.7-4-2	33.00	0.70	0.53	224.15	1500	0.7500	0.7500	98.36	Web Crippling	0.98	0.86	0.92
23	01/20/96	IOF-C8-20-0-6-1	33.00	0.00	0.80	224.15	1375	0.6875	0.6875	90.16	Web Crippling	0.90	0.75	0.88
24	02/01/96	IOF-C8-20-0-6-2	33.00	0.00	0.80	224.15	1425	0.7125	0.7125	93.44	Web Crippling	0.93	0.75	0.88
25	02/10/96	IOF-C8-20-0-6-1	57.00	0.00	0.80	224.15	1275	0.6375	0.6375	83.61	Web Crippling	0.84	0.75	0.88
26	02/22/96	IOF-C8-20-0-6-2	57.00	0.00	0.80	224.15	1225	0.6125	0.6125	80.33	Web Crippling	0.80	0.75	0.88
27	01/25/96	IOF-C8-20-0.7-6-1	33.00	0.70	0.80	224.15	1500	0.7500	0.7500	98.36	Web Crippling	0.98	0.79	0.91
28	02/01/96	IOF-C8-20-0.7-6-2	33.00	0.70	0.80	224.15	1500	0.7500	0.7500	98.36	Web Crippling	0.98	0.79	0.91

Table VI. Application of an Interaction Equation for 0.033 in. Thick Sections

No.	Specimen Number	L (in)	P-test (kips)	M-test (kips-in)	$\frac{\text{P-test}}{\text{P-comp}}$	$\frac{\text{Mtest}}{\text{(Mcomp)u}}$	Interaction Value I	$\frac{\text{Mtest}}{\text{(Mcomp)m}}$	Interaction Value II
1	IOF-C6-20-0-0-1	27.00	0.7000	4.2000	0.90	0.22	1.18	0.22	1.18
2	IOF-C6-20-0-0-2	27.00	0.7750	4.6500	0.99	0.24	1.30	0.24	1.30
3	IOF-C6-20-0-0-3	27.00	0.7375	4.4250	0.94	0.23	1.24	0.23	1.24
4	IOF-C6-20-0-2-1	27.00	0.7125	4.2750	1.03	0.22	1.33	0.22	1.33
5	IOF-C6-20-0.7-2-1	27.00	0.7375	4.4250	1.03	0.23	1.33	0.23	1.33
6	IOF-C6-20-0.7-2-2	27.00	0.7375	4.4250	1.03	0.23	1.33	0.23	1.33
7	IOF-C6-20-0-4-1	27.00	0.6500	3.9000	0.95	0.20	1.22	0.20	1.22
8	IOF-C6-20-0-4-2	27.00	0.7000	4.2000	1.02	0.22	1.31	0.22	1.31
9	IOF-C6-20-0-4-3	27.00	0.7000	4.2000	1.02	0.22	1.31	0.22	1.31
10	IOF-C6-20-0-4-1	45.00	0.6250	6.5625	0.91	0.34	1.32	0.34	1.32
11	**IOF-C6-20-0-4-2**	**45.00**	**0.6625**	**6.9563**	**0.97**	**0.36**	**1.39**	**0.36**	**1.39**
12	**IOF-C6-20-0-4-1**	**81.00**	**0.5000**	**9.7500**	**0.73**	**0.50**	**1.29**	**0.50**	**1.29**
13	IOF-C6-20-0.5-4	27.00	0.7250	4.3500	1.03	0.22	1.32	0.22	1.32
14	IOF-C6-20-0.7-4	27.00	0.7250	4.3500	1.02	0.22	1.31	0.22	1.31
15	IOF-C8-20-0-0-1	33.00	0.7750	5.8125	1.10	0.21	1.39	0.21	1.39
16	IOF-C8-20-0-0-2	33.00	0.7500	5.6250	1.06	0.21	1.35	0.21	1.35
17	IOF-C8-20-0-4-1	33.00	0.7000	5.2500	1.13	0.19	1.40	0.19	1.40
18	IOF-C8-20-0-4-2	33.00	0.7000	5.2500	1.13	0.19	1.40	0.19	1.40
19	IOF-C8-20-0-4-1	57.00	0.6500	8.7750	1.05	0.32	1.45	0.32	1.45
20	IOF-C8-20-0-4-2	57.00	0.6625	8.9438	1.07	0.33	1.47	0.33	1.47
21	IOF-C8-20-0.7-4-1	33.00	0.7500	5.6250	1.16	0.21	1.45	0.21	1.45
22	IOF-C8-20-0.7-4-2	33.00	0.7500	5.6250	1.16	0.21	1.45	0.21	1.45
23	IOF-C8-20-0-6-1	33.00	0.6875	5.1563	1.11	0.19	1.38	0.21	1.41
24	IOF-C8-20-0-6-2	33.00	0.7125	5.3438	1.16	0.20	1.43	0.22	1.46
25	**IOF-C8-20-0-6-1**	**57.00**	**0.6375**	**8.6063**	**1.03**	**0.32**	**1.42**	**0.35**	**1.46**
26	IOF-C8-20-0-6-2	57.00	0.6125	8.2688	0.99	0.31	1.37	0.34	1.40
27	IOF-C8-20-0.7-6-1	33.00	0.7500	5.6250	1.17	0.21	1.46	0.23	1.48
28	IOF-C8-20-0.7-6-2	33.00	0.7500	5.6250	1.17	0.21	1.46	0.23	1.48

(Mcomp)u - Unmodified Bending Moment Capacity   Interaction Value I - Corresponds to (Mcomp)u
(Mcomp)m - Modified Bending Moment Capacity   Interaction Value II - Corresponds to (Mcomp)m

Table VII. Unreinforced IOF Cross-Section Properties for 0.044 in. Thick Sections

No.	Specimen Number	D (in)	R (in)	t (in)	h (in)	B (in)	df (in)	a (in)	N (in)	Fy (ksi)	Fu (ksi)	h/t	a/h	R/t	N/t	P-allow (kips)	(M-allow)u (kips-in)	(M-allow)m (kips-in)
1	IOF-C6-18-0-0-1	5.965	0.141	0.0443	5.595	1.628	0.439	SOLID	3.00	52.00	58.70	126.30	SOLID	3.17	67.72	0.8442	20.05	20.05
2	IOF-C6-18-0-0-2	5.965	0.141	0.0443	5.595	1.628	0.439	SOLID	3.00	52.00	58.70	126.30	SOLID	3.17	67.72	0.8442	20.05	20.05
3	IOF-C6-18-0-4-1	5.965	0.141	0.0443	5.595	1.628	0.439	4.00	3.00	52.00	58.70	126.30	0.71	3.17	67.72	0.8442	20.05	15.09
4	IOF-C6-18-0-4-2	5.965	0.141	0.0443	5.595	1.628	0.439	4.00	3.00	52.00	58.70	126.30	0.71	3.17	67.72	0.8442	20.05	15.09
5	IOF-C6-18-0-4-1	5.965	0.141	0.0443	5.595	1.628	0.439	4.00	3.00	52.00	58.70	126.30	0.71	3.17	67.72	0.8442	20.05	15.09
6	IOF-C6-18-0-4-2	5.965	0.141	0.0443	5.595	1.628	0.439	4.00	3.00	52.00	58.70	126.30	0.71	3.17	67.72	0.8442	20.05	15.09
8	IOF-C8-18-0-0-1	7.825	0.172	0.0439	7.393	1.620	0.504	SOLID	3.00	52.00	57.40	168.42	SOLID	3.92	68.34	0.7349	20.05	26.82
9	IOF-C8-18-0-0-2	7.825	0.172	0.0439	7.393	1.620	0.504	SOLID	3.00	52.00	57.40	168.42	SOLID	3.92	68.34	0.7349	26.82	26.82
10	IOF-C8-18-0-4-1	7.825	0.172	0.0439	7.393	1.620	0.504	4.00	3.00	52.00	57.40	168.42	0.54	3.92	68.34	0.7349	26.82	25.90
11	IOF-C8-18-0-4-2	7.825	0.172	0.0439	7.393	1.620	0.504	4.00	3.00	52.00	57.40	168.42	0.54	3.92	68.34	0.7349	26.82	25.90
12	IOF-C8-18-0-4-1	7.825	0.172	0.0439	7.393	1.620	0.504	4.00	3.00	52.00	57.40	168.42	0.54	3.92	68.34	0.7349	26.82	25.90
13	IOF-C8-18-0-4-2	7.825	0.172	0.0439	7.393	1.620	0.504	4.00	3.00	52.00	57.40	168.42	0.54	3.92	68.34	0.7349	26.82	25.90
14	IOF-C8-18-0-6-1	7.825	0.172	0.0439	7.393	1.620	0.504	6.00	3.00	52.00	57.40	168.42	0.81	3.92	68.34	0.7349	26.82	20.95
15	IOF-C8-18-0-6-2	7.825	0.172	0.0439	7.393	1.620	0.504	6.00	3.00	52.00	57.40	168.42	0.81	3.92	68.34	0.7349	26.82	20.95
16	IOF-C8-18-0-6-1	7.825	0.172	0.0439	7.393	1.620	0.504	6.00	3.00	52.00	57.40	168.42	0.81	3.92	68.34	0.7349	26.82	20.95
17	IOF-C8-18-0-6-2	7.825	0.172	0.0439	7.393	1.620	0.504	6.00	3.00	52.00	57.40	168.42	0.81	3.92	68.34	0.7349	26.82	20.95

Cross-Section Designations: IOF-Ca-b-c-d-e
IOF - Interior-One-Flange C - Channel a - Overall Depth of the Web b- Gage Number c - Alpha Value d - Diameter of Hole e - No. of Test on an Identical Specimen

(M-allow)u - Unmodified allowable moment capacity (M-allow)m - Modified allowable moment capacity

Table VIII. Unreinforced IOF Cross-Section Properties for 0.056 in. Thick Sections

No	Specimen Number	D (in)	R (in)	t (in)	h (in)	B (in)	df (in)	a (in)	N (in)	Fy (ksi)	Fu (ksi)	h/t	a/h	R/t	N/t	P-allow (kips)	(M-allow)u (kips-in)	(M-allow)m (kips-in)
1	IOF-C6-16-0-0-1	6.017	0.188	0.0560	5.529	1.625	0.438	SOLID	3.00	56.80	69.40	98.73	SOLID	3.36	53.57	1.3133	25.96	25.96
2	IOF-C6-16-0-0-2	6.017	0.188	0.0560	5.529	1.625	0.438	SOLID	3.00	56.80	69.40	98.73	SOLID	3.36	53.57	1.3133	25.96	25.96
3	IOF-C6-16-0-4-1	6.017	0.188	0.0560	5.529	1.625	0.438	4.00	3.00	56.80	69.40	98.73	0.72	3.36	53.57	1.3133	25.96	22.32
4	IOF-C6-16-0-4-2	6.017	0.188	0.0560	5.529	1.625	0.438	4.00	3.00	56.80	69.40	98.73	0.72	3.36	53.57	1.3133	25.96	22.32
5	IOF-C8-16-0-0-1	7.938	0.219	0.0559	7.388	1.625	0.438	SOLID	3.00	56.80	69.40	132.17	SOLID	3.92	53.67	1.1915	25.96	43.29
7	IOF-C8-16-0-0-2	7.938	0.219	0.0559	7.388	1.625	0.438	SOLID	3.00	56.80	69.40	132.17	SOLID	3.92	53.67	1.1915	43.29	43.29
8	IOF-C8-16-0-4-1	7.938	0.219	0.0559	7.388	1.625	0.438	4.00	3.00	56.80	69.40	132.17	0.54	3.92	53.67	1.1915	43.29	36.24
9	IOF-C8-16-0-4-1	7.938	0.219	0.0559	7.388	1.625	0.438	4.00	3.00	56.80	69.40	132.17	0.54	3.92	53.67	1.1915	43.29	36.24
10	IOF-C8-16-0-6-1	7.938	0.219	0.0559	7.388	1.625	0.438	6.00	3.00	56.80	69.40	132.17	0.81	3.92	53.67	1.1915	43.29	29.89
11	IOF-C8-16-0-6-1	7.938	0.219	0.0559	7.388	1.625	0.438	6.00	3.00	56.80	69.40	132.17	0.81	3.92	53.67	1.1915	43.29	29.89

Cross-Section Designations: IOF-Ca-b-c-d-e
IOF - Interior-One-Flange C - Channel a - Overall Depth of the Web b- Gage Number c - Alpha Value d - Diameter of Hole e - No. of Test on an Identical Specimen

(M-allow)u - Unmodified allowable moment capacity (M-allow)m - Modified allowable moment capacity

Table IX. Unreinforced IOF Test Results for 0.044 in. Thick Sections

No.	Date mm/dd/yy	Specimen Number	L (in.)	Alpha (x/h)	a/h	h/t	(Pn)test (lbs)	(Pn)test/Web (kips)	(Pn)test adj (kips)	PSWadj (kips)	Limit State	PSWadj %	Langan's RF	Modified RF
1	01/11/96	IOF-C6-18-0-0-1	27.00	0.00	SOLID	126.30	2800	1.4000	1.4000	100.00	Web Crippling	1.00	1.00	1.00
2	02/01/96	IOF-C6-18-0-0-2	27.00	0.00	SOLID	126.30	2800	1.4000	1.4000	100.00	Web Crippling	1.00	1.00	1.00
3	02/22/96	IOF-C6-18-0-4-1	27.00	0.00	0.71	126.30	2600	1.3000	1.3000	92.86	Web Crippling	0.93	0.77	0.88
4	01/13/96	IOF-C6-18-0-4-2	27.00	0.00	0.71	126.30	2600	1.3000	1.3000	92.86	Web Crippling	0.93	0.77	0.88
5	12/21/95	IOF-C6-18-0-4-1	45.00	0.00	0.71	126.30	2350	1.1750	1.1956	85.40	Web Crippling	0.85	0.77	0.88
6	01/11/96	IOF-C6-18-0-4-2	45.00	0.00	0.71	126.30	2375	1.1875	1.2129	86.63	Web Crippling	0.87	0.77	0.88
7	03/18/96	IOF-C6-18-0-4-1	81.00	0.00	0.71	126.30	1775	0.8875	1.0515	75.10	Web Crippling	0.75	0.77	0.88
8	01/13/96	IOF-C8-18-0-0-1	33.00	0.00	SOLID	168.42	2725	1.3625	1.3625	100.46	Web Crippling	1.00	1.00	1.00
9	01/20/96	IOF-C8-18-0-0-2	33.00	0.00	SOLID	168.42	2700	1.3500	1.3500	99.54	Web Crippling	1.00	1.00	1.00
10	02/01/96	IOF-C8-18-0-4-1	33.00	0.00	0.54	168.42	2625	1.3125	1.3125	96.77	Web Crippling	0.97	0.82	0.88
11	02/10/96	IOF-C8-18-0-4-2	33.00	0.00	0.54	168.42	2625	1.3125	1.3125	96.77	Web Crippling	0.97	0.82	0.88
12	02/22/96	IOF-C8-18-0-4-1	57.00	0.00	0.54	168.42	2350	1.1750	1.1750	86.64	Web Crippling	0.87	0.82	0.88
13	01/20/96	IOF-C8-18-0-4-2	57.00	0.00	0.54	168.42	2350	1.1750	1.1750	86.64	Web Crippling	0.87	0.82	0.88
14	01/20/96	IOF-C8-18-0-6-1	33.00	0.00	0.81	168.42	2475	1.2375	1.2375	91.24	Web Crippling	0.91	0.74	0.88
15	01/20/96	IOF-C8-18-0-6-2	33.00	0.00	0.81	168.42	2475	1.2375	1.2375	91.24	Web Crippling	0.91	0.74	0.88
16	02/01/96	IOF-C8-18-0-6-1	57.00	0.00	0.81	168.42	2225	1.1125	1.1125	82.03	Web Crippling	0.82	0.74	0.88
17	01/20/96	IOF-C8-18-0-6-2	57.00	0.00	0.81	168.42	2225	1.1125	1.1125	82.03	Web Crippling	0.82	0.74	0.88

Table X. Unreinforced IOF Test Results for 0.056 in. Thick Sections

No.	Date mm/dd/yy	Specimen Number	L (in.)	Alpha (x/h)	a/h	h/t	(Pn)test (lbs)	(Pn)test/Web (kips)	(Pn)test adj (kips)	PSWadj (kips)	Limit State	PSWadj %	Langan's RF	Modified RF
1	01/23/96	IOF-C6-16-0-0-1	27.00	0.00	SOLID	98.73	4200	2.1000	2.1000	100.60	Web Crippling	1.01	0.96	0.89
2	01/23/96	IOF-C6-16-0-0-2	27.00	0.00	SOLID	98.73	4150	2.0750	2.0750	99.40	Web Crippling	0.99	0.96	0.89
3	01/23/96	IOF-C6-16-0-4-1	27.00	0.00	0.72	98.73	3975	1.9875	1.9875	95.21	Web Crippling	0.95	0.77	0.88
4	01/23/96	IOF-C6-16-0-4-2	45.00	0.00	0.72	98.73	3350	1.6750	1.7669	84.64	Web Crippling	0.85	0.77	0.88
5	03/18/96	IOF-C6-16-0-4-1	81.00	0.00	0.72	98.73	2575	1.2875	1.6383	78.48	Web Crippling	0.78	0.77	0.88
6	01/23/96	IOF-C8-16-0-0-1	33.00	0.00	SOLID	132.17	4025	2.0125	2.0125	99.08	Web Crippling	0.99	0.96	0.89
7	01/23/96	IOF-C8-16-0-0-2	33.00	0.00	SOLID	132.17	4100	2.0500	2.0500	100.92	Web Crippling	1.01	0.96	0.89
8	01/23/96	IOF-C8-16-0-4-1	33.00	0.00	0.54	132.17	3900	1.9500	1.9500	96.00	Web Crippling	0.96	0.82	0.88
9	01/23/96	IOF-C8-16-0-4-1	57.00	0.00	0.54	132.17	3425	1.7125	1.7125	84.31	Web Crippling	0.84	0.82	0.88
10	01/23/96	IOF-C8-16-0-6-1	33.00	0.00	0.81	132.17	3450	1.7250	1.7250	84.92	Web Crippling	0.85	0.74	0.88
11	01/23/96	IOF-C8-16-0-6-1	57.00	0.00	0.81	132.17	3150	1.5750	1.5750	77.54	Web Crippling	0.78	0.74	0.88

Table XI. Application of an Interaction Equation for 0.044 in. Thick Sections

No.	Specimen Number	L (in)	P-test (kips)	M-test (kips-in)	P-test P-comp	Mtest (Mcomp)u	Interaction Value I	Mtest (Mcomp)m	Interaction Value II
1	IOF-C6-18-0-0-1	27.00	1.4000	8.4000	0.90	0.25	1.21	0.25	1.21
2	IOF-C6-18-0-0-2	27.00	1.4000	8.4000	0.90	0.25	1.21	0.25	1.21
3	IOF-C6-18-0-4-1	27.00	1.3000	7.8000	0.95	0.23	1.25	0.31	1.33
4	IOF-C6-18-0-4-2	27.00	1.3000	7.8000	0.95	0.23	1.25	0.31	1.33
5	**IOF-C6-18-0-4-1**	**45.00**	**1.1750**	**12.3375**	**0.86**	**0.37**	**1.29**	**0.49**	**1.41**
6	**IOF-C6-18-0-4-2**	**45.00**	**1.1875**	**12.4688**	**0.87**	**0.37**	**1.30**	**0.49**	**1.42**
7	**IOF-C6-18-0-4-1**	**81.00**	**0.8875**	**17.3063**	**0.65**	**0.52**	**1.21**	**0.69**	**1.38**
8	IOF-C8-18-0-0-1	33.00	1.3625	10.2188	1.00	0.23	1.30	0.23	1.30
9	IOF-C8-18-0-0-2	33.00	1.3500	10.1250	0.99	0.23	1.29	0.23	1.29
10	IOF-C8-18-0-4-1	33.00	1.3125	9.8438	1.10	0.22	1.39	0.23	1.40
11	IOF-C8-18-0-4-2	33.00	1.3125	9.8438	1.10	0.22	1.39	0.23	1.40
12	**IOF-C8-18-0-4-1**	**57.00**	**1.1750**	**15.8625**	**0.98**	**0.35**	**1.41**	**0.37**	**1.42**
13	**IOF-C8-18-0-4-2**	**57.00**	**1.1750**	**15.8625**	**0.98**	**0.35**	**1.41**	**0.37**	**1.42**
14	IOF-C8-18-0-6-1	33.00	1.2375	9.2813	1.04	0.21	1.32	0.27	1.38
15	IOF-C8-18-0-6-2	33.00	1.2375	9.2813	1.04	0.21	1.32	0.27	1.38
16	**IOF-C8-18-0-6-1**	**57.00**	**1.1125**	**15.0188**	**0.93**	**0.34**	**1.34**	**0.43**	**1.43**
17	**IOF-C8-18-0-6-2**	**57.00**	**1.1125**	**15.0188**	**0.93**	**0.34**	**1.34**	**0.43**	**1.43**

(Mcomp)u - Unmodified Bending Moment Capacity Interaction Value I - Corresponds to (Mcomp)u
(Mcomp)m - Modified Bending Moment Capacity Interaction Value II - Corresponds to (Mcomp)m

Table XII. Application of an Interaction Equation for 0.056 in. Thick Sections

No.	Specimen Number	L (in)	P-test (kips)	M-test (kips-in)	P-test P-comp	Mtest (Mcomp)u	Interaction Value I	Mtest (Mcomp)m	Interaction Value II
1	IOF-C6-16-0-0-1	27.00	2.1000	12.6000	0.97	0.29	1.33	0.29	1.33
2	IOF-C6-16-0-0-2	27.00	2.0750	12.4500	0.96	0.29	1.32	0.29	1.32
3	IOF-C6-16-0-4-1	27.00	1.9875	11.9250	0.93	0.28	1.27	0.32	1.32
4	**IOF-C6-16-0-4-2**	**45.00**	**1.6750**	**17.5875**	**0.79**	**0.41**	**1.25**	**0.47**	**1.31**
5	**IOF-C6-16-0-4-1**	**81.00**	**1.2875**	**25.1063**	**0.60**	**0.58**	**1.23**	**0.67**	**1.32**
6	IOF-C8-16-0-0-1	33.00	2.0125	15.0938	1.03	0.21	1.31	0.21	1.31
7	IOF-C8-16-0-0-2	33.00	2.0500	15.3750	1.05	0.21	1.33	0.21	1.33
8	IOF-C8-16-0-4-1	33.00	1.9500	14.6250	1.01	0.20	1.28	0.24	1.32
9	**IOF-C8-16-0-4-1**	**57.00**	**1.7125**	**23.1188**	**0.88**	**0.32**	**1.27**	**0.38**	**1.33**
10	IOF-C8-16-0-6-1	33.00	1.7250	12.9375	0.89	0.18	1.14	0.26	1.22
11	**IOF-C8-16-0-6-1**	**57.00**	**1.5750**	**21.2625**	**0.82**	**0.29**	**1.17**	**0.43**	**1.30**

(Mcomp)u - Unmodified Bending Moment Capacity Interaction Value I - Corresponds to (Mcomp)u
(Mcomp)m - Modified Bending Moment Capacity Interaction Value II - Corresponds to (Mcomp)m

Equation 9 has been derived from Equation 23 and therefore, is based on the procedure currently used in the AISI Specification provisions for combined bending and web crippling. The derivation of Equation 9 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.

3. Percent of Solid Web Strength PSW and PSW_{adj}. 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 solid web tests for a given cross section, N value, and loading condition is considered a PSW value of 100 percent.

Each PSW value has an unique corresponding bending moment adjusted PSW value, PSWadj, which is the percent of solid web strength in the absence of significant bending moment and is given by Equation 8, defined earlier in previous chapter under section C5.

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. 12 thru 15).

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. Although, Hetrakul and Yu (1978) state that the primary justification for the high

ASD factor of safety is caused by the variance of web crippling test results, and hence is not based on the amount of deformation.

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 the 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 safety factor 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_{adj} values were calculated by using Equation 23, which accounts for the degradation caused by bending moment. The test results were evaluated to determine the factors which influenced PSW_{adj} values and therefore influenced web crippling behavior, it was concluded that the web opening parameters a/h and α and section parameter h/t were significant influencing factors.

2. Effect of Web Opening Parameters on Web Crippling Behavior.

a. Effect of α on Web Crippling Behavior. As seen in Figure 16, a notable trend exists within the test results for a graph of location of web opening α vs. PSW_{adj} values for typical 0.033 in. thick IOF sections at N equal to 3 inches. The PSW_{adj} values increase with an increase in α values upto 0.7.

For α values greater than zero, the reduction in the allowable web crippling capacity was negligible after studying the trend in the data obtained for 0.033 in. thick sections as seen in Figure 16. Therefore, the rest of the investigation for 0.044 in. thick and 0.056 in. thick sections was carried out for α value at zero.

b. Effect of a/h on Web Crippling Behavior. Figures 17 and 18 show the results of size of web opening a/h vs. PSW_{adj} values for the 0.044 in. thick and 0.056 in. thick sections respectively, which failed in web crippling at N equal to 3 inches and α equal to zero. Based on the results of the specimens

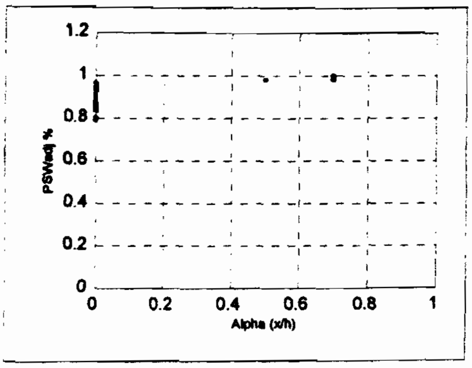

Figure 16. Graph of α vs. PSW_{adj}% for Typical 0.033 in. thick IOF Sections at N=3 inches.

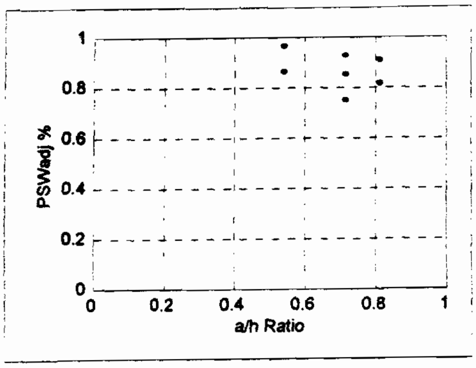

Figure 17. Graph of a/h vs. PSW_{adj}% for Typical 0.044 in. thick IOF Sections at N=3 inches and α=0.

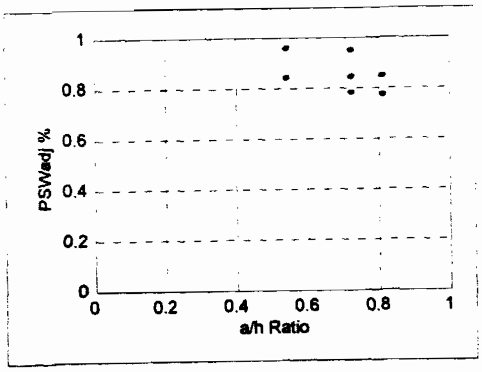

Figure 18. Graph of a/h vs. PSW_{adj}% for Typical 0.056 in. thick IOF Sections at N=3 inches and α=0.

tested during this investigation, a trend existed in which the value of PSW_{adj} decrease with an increase in the a/h value.

3. Modification of the Reduction Factor Equation Given by Langan, LaBoube and Yu (1994).

a. General. The consideration of web opening parameters α and a/h as discussed above gave a good correlation with PSW_{adj} values. Based on the trends seen above, Equation 7, the reduction factor equation given by Langan, LaBoube and Yu (1994) defined previously under the section C5 can be applied to the current investigation.

After an application of the reduction factor equation, Equation 7 to the current investigation, it was found that the web crippling capacity for the unreinforced sections with web openings was being underestimated as tabulated under Tables V, IX and X. Because of the conservatism in Equation 7, a comprehensive analysis of the test results was initiated. Both a/h and α were considered.

It should be also noted that the scatter found under the web crippling is generally high. Therefore, the analysis will always include the combined study of the current investigation and the investigation by Langan, LaBoube and Yu (1994). This was done to develop a general reduction factor equation.

b. Effect of a/h in detail on Web Crippling Behavior. To study the effect of web opening parameter a/h on the web crippling behavior, the combined graph of a/h vs (PSW_{adj}%/Equation 7) for the current as well as Langan's investigation was plotted as shown in Figure 19. The following conclusions can be drawn from Figure 19:

1. The parameter a/h used in the Langan's investigation ranged from a minimum of 0.13 to a maximum of 0.466 while the a/h for the current investigation ranged from a minimum of 0.36 to a maximum of 0.81.

2. The reduction factor equation given by Langan, LaBoube and Yu (1994), Equation 7 is a best fit for Langan's data which had low values of web opening parameter a/h while the same equation

underestimates the data of the current investigation which had higher values of web opening parameter a/h.

The reduction factor equation given by Langan, LaBoube and Yu (1994) results from a regression analysis of the data with independent variables α and a/h while dependent variable PSW_{adj}. A similar regression analysis was carried out in which the input for the regression analysis included the data from the current as well as Langan's investigation. The following resulting equation is a modified reduction factor equation:

$$RF = 0.900-(0.047a/h)+(0.053\alpha) \leq 1.0 \qquad (27)$$

The Figure 20 shows the combined graph of a/h vs (PSW_{adj}%/Equation 27) for current as well as Langan's investigation which justifies Equation 27, a modified form of the reduction factor equation given by Langan, LaBoube and Yu (1994).

4. <u>Effect of Section Parameters on Web Crippling Behavior</u>.

a. <u>General</u>. The factor N, bearing length of the load plate was kept constant throughout the investigation, and therefore, the possibility of its effect on web crippling behavior for sections with web openings can be violated. The factors such as R/t, N/t or N/h used in this investigation were within the limits prescribed by the present AISI (1986) Specification provisions for web crippling, thus these parameters did not alter the web crippling behavior for sections with web openings.

However, h/t was the only factor in the investigation, which showed a wide variety in its range and also crossed the limit 200 prescribed in the present AISI (1986) Specification provisions for web crippling. Also, h/t factor used under the investigation by Langan, LaBoube and Yu (1994) was subjected to a maximum of 100 with very few values above 100. But, in the current investigation h/t value used ranged from a low of 98.73 and a high of 224.15.

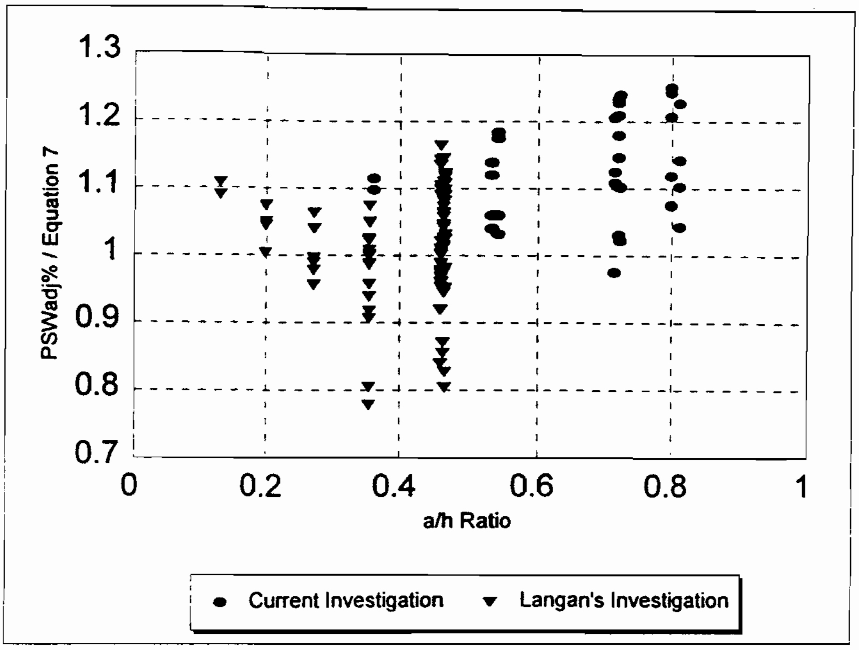

Figure 19. Combined Graph of a/h vs. (PSW$_{adj}$% / Equation 7) for Current Investigation and Langan, LaBoube and Yu (1994) Investigation.

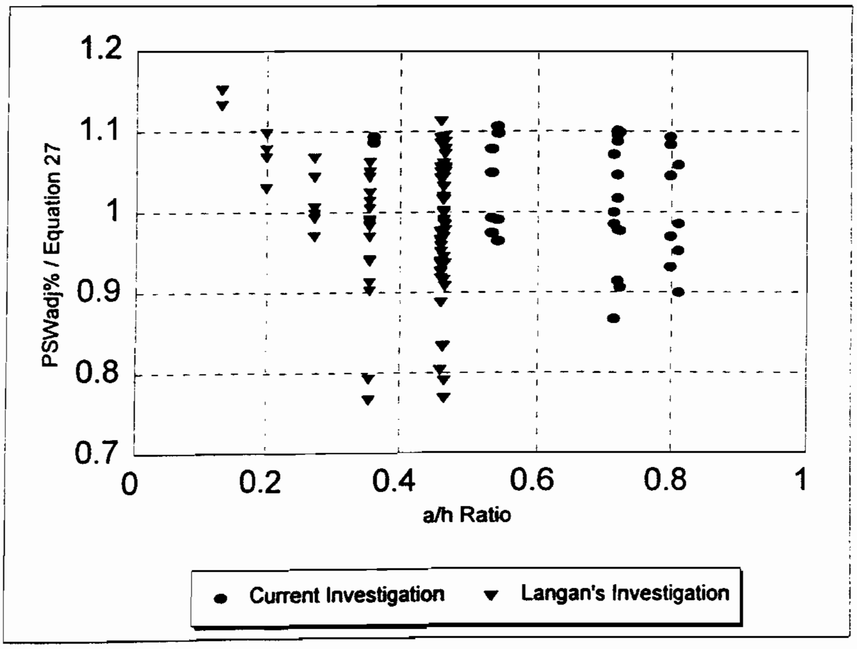

Figure 20. Combined Graph of a/h vs. (PSW$_{adj}$% / Equation 27) for Current Investigation and Langan, LaBoube and Yu (1994) Investigation.

b. Effect of h/t on Web Crippling Behavior. In order to investigate the effect of h/t on the web crippling behavior for the sections with web openings, a combined graph of h/t vs. (PSW_{adj} % / Equation 7) was plotted for the present study as well as the study conducted by Langan, LaBoube and Yu (1994) as shown in Figure 21. The following observations can be made from Figure 21:

1. The factor h/t used in the study conducted by Langan, LaBoube and Yu (1994) was comparatively low with few exceptions subjected to a maximum of 98 and did not affect the web crippling behavior for sections with web openings.
2. The h/t factor used in the current investigation was high (with a low of 98.73 and a high of 224.15) compared to the study conducted by Langan, LaBoube and Yu (1994), and, influenced the web crippling behavior for sections with web openings.
3. The section parameter h/t does not affect the web crippling behavior for sections with web openings, if it falls below 100. However, it does affect the same, if it is above 100.

Even though the above observations are true, they are based on the Equation 7, the reduction factor equation given by Langan, LaBoube and Yu (1994). However, the result of the current investigation suggests Equation 27, the modified form of the Equation 7, therefore, a similar graph, i.e. a combined graph of h/t vs. (PSW_{adj} % / Equation 27) was plotted in Figure 22 for the present study as well as the study conducted by Langan, LaBoube and Yu (1994) to investigate the effect of h/t on the web crippling behavior for the sections with web openings. From this figure, it is evident that the section parameter h/t did not influence the web crippling behavior for the sections with web openings. The result of the Figure 22 is in contrast with the one in Figure 21, however it can be justified as follows:

Equation 27 considers the data generated by Langan's as well as the current investigation, therefore, its a more generalized form of Equation 7, which justifies Langan's data only. Also, Equation 27 covers a more general range of the section parameters as well as the web opening parameters relating to the web crippling behavior for sections with web openings as compared to Equation 7.

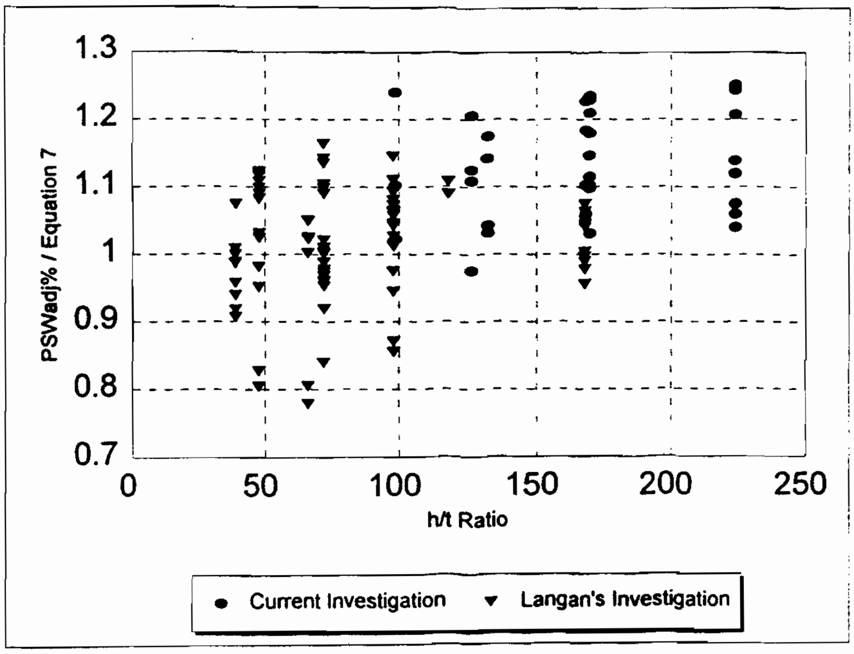

Figure 21. Combined Graph of h/t vs. (PSW$_{adj}$% / Equation 7) for Current Investigation and Langan, LaBoube and Yu (1994) Investigation.

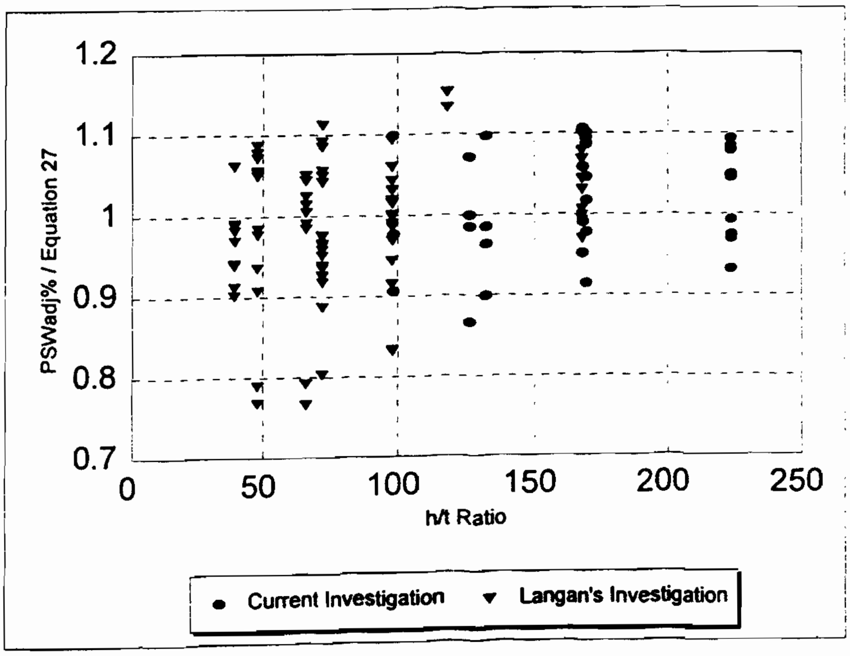

Figure 22. Combined Graph of h/t vs. (PSW$_{adj}$% / Equation 27) for Current Investigation and Langan, LaBoube and Yu (1994) Investigation.

Considering that the factor h/t showed a wide variety in its range and also crossed the limit 200 prescribed in the present AISI (1986) Specification provisions for web crippling, a regression analysis was carried out with the factor h/t was also included as an independent variable. The resulting equation can be considered as the modified form of the Equation 27 as it considers the same data again, except the factor h/t is also incorporated in the new equation, the new equation is as follows:

$$RF = 0.873 - (0.113a/h) + (0.063\alpha) + (0.0005h/t) \leq 1.0 \qquad \textbf{(28)}$$

The graphs as shown in Figures 20 and 22 were plotted again as shown in Figures 23 and 24 respectively, the only difference was, Equation 28 was used instead of Equation 27. The results obtained from the Figures 23 and 24 were similar to those obtained from Figures 20 and 22, respectively.

Therefore, in order to compare the performance of Equation 27 to that of Equation 28, the statistical analysis as shown in Table XIII was carried out. The table also contains the analysis of Equation 7. The series considered under the analysis was PSW_{adj} % over Equation 7, Equation 27 and Equation 28, respectively. The following conclusions can be drawn from the Table XIII.

1. Equation 7, the reduction factor equation given by Langan, LaBoube and Yu (1994) for reducing the web crippling strength for the sections with web openings is conservative in its performance compared to that of Equations 27 and 28. The same fact has been already backed up by the graphs discussed previously.
2. The results obtained by Equation 28 are better than that of Equation 27, however, they are very close to each other.

With the above conclusions, either Equation 27 or Equation 28 are acceptable equations for reducing the web crippling strength for the sections with web openings. However, comparing Equation 28 with Equation 27 results in the following observations:

1. The Equation 28 includes the section parameter h/t while the Equation 27 does not.

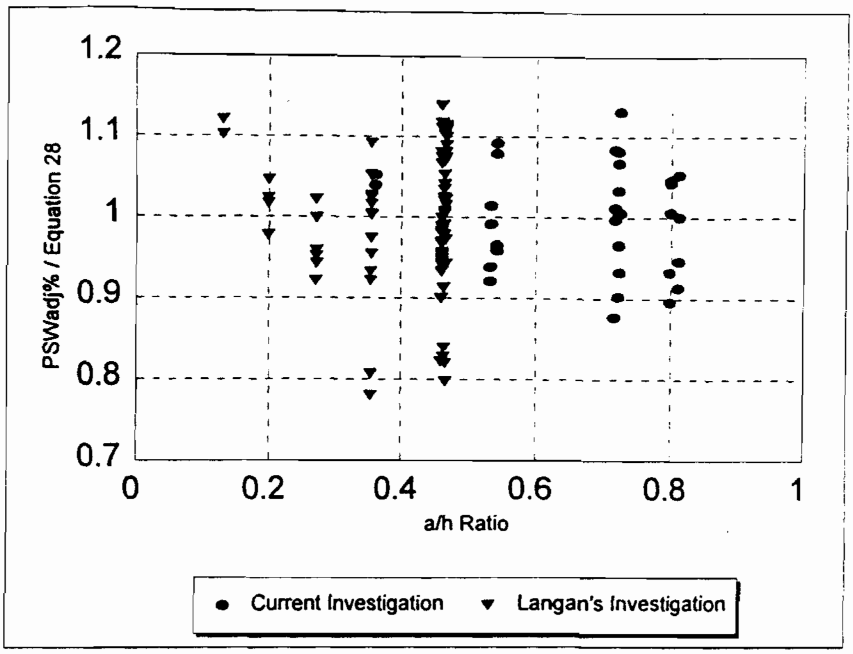

Figure 23. Combined Graph of a/h vs. (PSW$_{adj}$% / Equation 28) for Current Investigation and Langan, LaBoube and Yu (1994) Investigation.

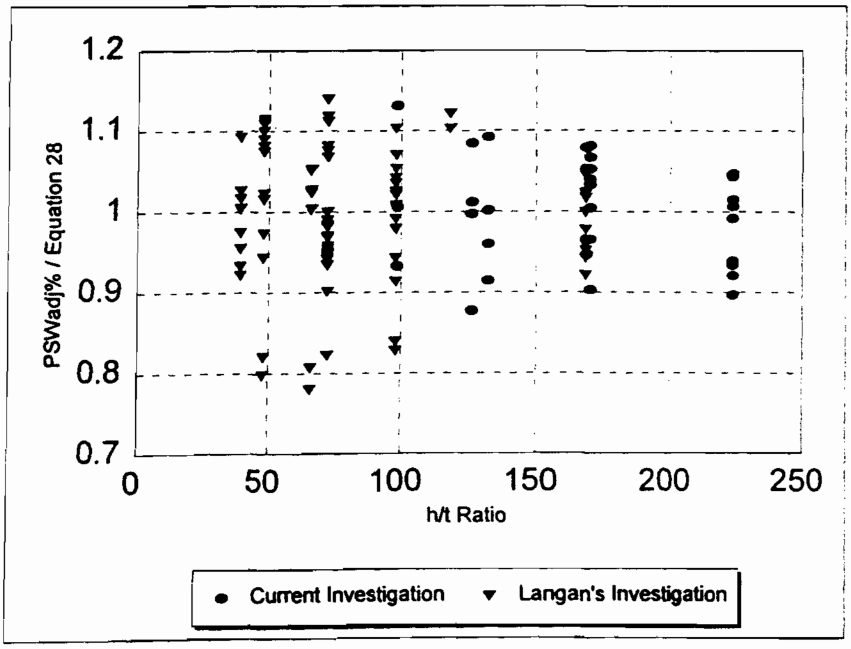

Figure 24. Combined Graph of h/t vs. (PSW$_{adj}$% / Equation 28) for Current Investigation and Langan, LaBoube and Yu (1994) Investigation.

2. The current, as well as Langan's investigation, specifically dealt with the study of web crippling behavior for flexural members with web openings, but the parameter h/t is not an intrinsic parameter to the web opening like α or a/h. Therefore, the inclusion of the parameter h/t in the reduction factor equation relating to the web opening as in Equation 28 is questionable.

The following point should be also noted in this regard: The similar study relating to the present investigation was carried out by Uphoff (1996) at the University of Missouri-Rolla, the only difference was that the loading condition was EOF, i.e. end-one-flange loading. This study had the similar trends as seen under the present investigation. However, as far as the factor h/t was concerned, it did not have a significant effect on the web crippling behavior for sections with web openings in the Uphoff (1996) investigation. Therefore, in order to correlate the present investigation to that of the Uphoff (1996) investigation, and with above mentioned observations, reduction factor equation, Equation 27 is considered to be the appropriate equation based on the present investigation.

Table XIII. Statistical Analysis for Different Reduction Factor Equations

PSW_{adj}% / Equation 7 or 27 or 28			
	Equation 7	Equation 27	Equation 28
Mean	1.0505	0.9999	1.0049
Standard Deviation	0.1005	0.0818	0.0771
Coefficient of Variation	0.0956	0.0818	0.0768

5. Bending Interaction.

a. General. 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. 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. 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.

The AISI Specification web crippling interaction equation, Equation 23, results from a regression analysis of the scattered data associated with the interaction phenomenon. Therefore, use of an interaction equation 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 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.

b. Bending Capacity. The value of $(M_n)_{comp}$ for the test specimen with web openings was reduced. This reduction in the bending moment capacity is justified as it happened to be significant for the test parameters used under the current investigation. This was the development over the study conducted by Langan, LaBoube and Yu (1994).

The web element was divided into two segments, one above and the other below the web opening. Both of the elements were assumed as unstiffened elements with a plate buckling coefficient k as 0.43. In most of the cases, the web part in compression was found to be fully effective and the moment capacity was determined at the very first iteration performed by the procedure of Initiation of Yielding.

c. Validity of Interaction Equation. 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 allowable or nominal bending moment capacity entry into the interaction equations for sections with web openings is also affected as discussed in the Section III-E-5-b.

However, the AISI interaction equation for combined bending and web crippling remains unchanged by the findings of the current UMR investigation; the only difference is that the capacity entries into the interaction equation are affected by the findings of the UMR investigations. This conclusion is more evident from the interaction diagram plotted for the current investigation as shown in Figure 25. The values shown on Figure 25 are listed in Tables VI, XI and XII for 0.033 in. thick, 0.044 in. thick, and 0.056 in. thick sections respectively, and are designated in bold type.

The reduction in the bending moment capacity, as discussed in the above paragraph, is justified because as seen in Figure 26, interaction diagram with nonreduced bending moment capacities led to an erroneous results.

F. DESIGN RECOMMENDATIONS

1. General. Fifty six tests were conducted on specimens with web openings that failed in web crippling. At every stage, the current investigation was compared with the study conducted by Langan, LaBoube and Yu (1994). In the conclusive part of an investigation, the modification of the current

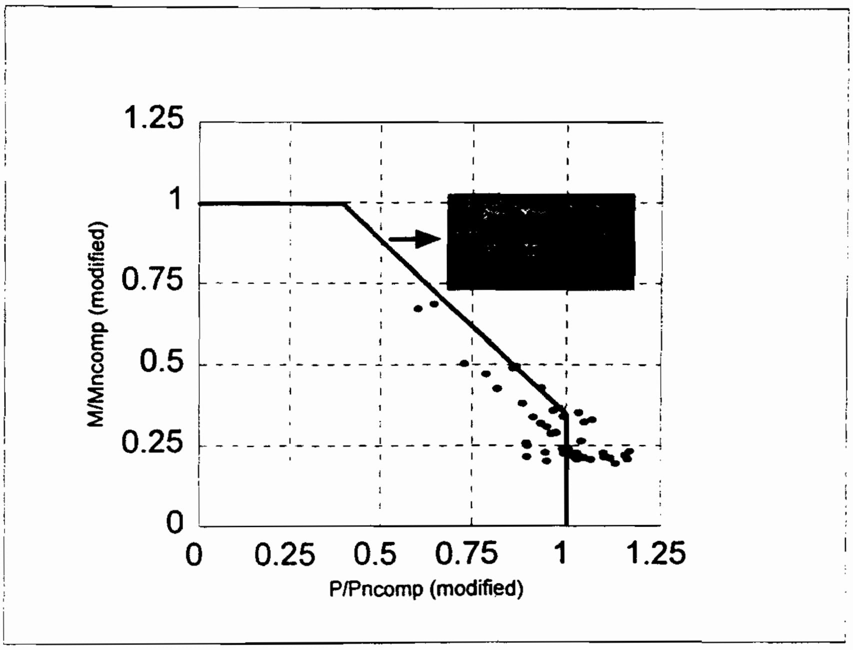

Figure 25. Interaction Diagram for Combined Bending and Web Crippling with Modified Web Crippling Capacity and Modified Bending Moment Capacity.

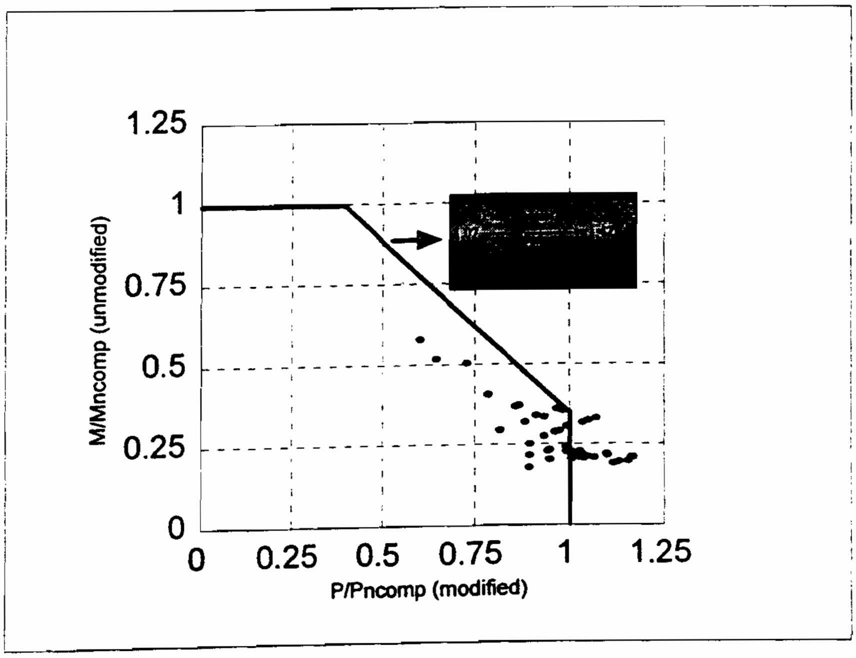

Figure 26. Interaction Diagram for Combined Bending and Web Crippling with Modified Web Crippling Capacity and Unmodified Bending Moment Capacity.

reduction factor equation given by Langan, LaBoube and Yu (1994) has been suggested and is discussed herein.

2. Recommendation for Reduction Factor Equation. After a thorough analysis of the current investigation data, along with the data generated by the study of Langan, LaBoube and Yu (1994), it was concluded that the following equation should be used as a reduction multiplier to the solid web equations given in the present AISI (1986) Specification provisions in order to obtain the reduced web crippling strength for the sections with web openings:

$$RF = 0.900-(0.047a/h)+(0.053\alpha) \leq 1.00 \qquad \textbf{(29)}$$

Thus the web crippling load for specimens with web openings can be obtained by applying the above reduction factor equation, Equation 29 to the allowable or nominal strength in web crippling for solid web sections given by Equations 16 and 17, respectively. It should be noted that the value of the above mentioned reduction factor equation will be always less than or equal to unity.

3. Limitations of Reduction Factor. Equation 29 is applicable to all the cross sections and conditions that meet the following ranges. The justification of these ranges is based on the following four factors:

a. Limits imposed on the existing AISI Specification web crippling provisions

b. Industry standards imposed on web opening parameters

c. Engineering judgement, and

d. Range of parameters for the test specimens (Table III).

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.

a. Current AISI Web Crippling Provisions. Although the testing was limited to specimens with edge-stiffened flanges, the same percent reduction in the web crippling strength is expected for the sections with unstiffened flanges.

If Equation 29 is used to reduce the web crippling strength of Equations 16 or 17, the limits on the 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:

(1) h/t: Although the maximum h/t ratio tested was 224.15, the h/t ratio must be limited to 200 as prescribed for Equations 16 or 17 for the use of Equation 29. No minimum h/t needs to be prescribed.

(2) N/t: The tested range for N/t was 53.57 to 91.74, however, all N/t values less than or equal to 210 are valid for the use of Equation 29, because this is the maximum limit imposed for the Equations 16 or 17.

(3) R/t: The tested range for R/t was 3.17 to 5.26. However, all R/t values less than or equal to 6.0 are valid for use of Equation 29, because this is the maximum limit imposed for the Equations 16 or 17.

(4) N/h: The tested range for N/h was 0.4 to 0.54. However, all N/h values less than or equal to 3.5 are valid for use of Equation 29, because this is the maximum limit imposed for the Equations 16 or 17.

(5) θ: Theta equaled 90° for all tests. However, it is assumed that all θ values within the allowable limits of Equations 16 or 17 of 45° to 90° are valid for use of Equation 29.

b. Web Opening Parameter a/h. The maximum a/h value tested which failed in web crippling was 0.81.

c. Web Opening Parameter α. Alpha ranged from 0 to 0.7 for all tests with web openings. The recommended minimum value for α in the Equations 29 is zero.

d. Bearing Length N. Although Equations 29 is primarily based on the tests at N equal to three inches, they are 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 of the situations. As provided in the review of the investigations performed by Yu and Davis (1973) and Sivakumaran and Zielonka (1989), 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 16 or 17.

e. Height of the Flat Portion of the Web h. The tested range of h for specimens that exhibited web crippling failure was 5.529 to 7.509 inches. However, all h values are valid for use of Equation 29 if the h/t maximum limit of 200 is not exceeded.

f. Base Metal Thickness t. The tested range of base metal thickness was 0.033 to 0.056 inches. However, all t values are valid for use of Equation 29 if the h/t maximum limit of 200 is not exceeded.

g. Yield Strength F_y. The tested range of yield strength F_y was 47 to 56.8 ksi. However, all Fy are valid for use of Equation 29. For cross sections with F_y greater than 91.5 ksi, 91.5 ksi may be used in Equations 16 or 17 as discussed under the Section II-F-2f. However, for Grade E materials, the F_y and F_u values must be adjusted in accordance with the Section A3.2.2 of the Specification.

IV. FUTURE RESEARCH

Future Studies should benefit from not only the theoretical and analytical conclusions of this research, but also from the logistic developments achieved throughout this investigation. This investigation was specifically meant for the one-flange loading condition. Also, only single web sections (channels) with web hole located only at one side of the IOF load bearing plate were considered.

Future studies may include:

1. Two-flange loading condition
2. Different single web sections other than channels and also multiple web sections
3. Extension of Sivakumaran and Zielonka (1989) studies for higher h/t parameter
4. Symmetric sections with location of holes at both sides of the IOF load bearing plate
5. Closely spaced holes
6. Web reinforcement to prevent the degradation in the web crippling strength resulting from the presence of a hole

V. CONCLUSIONS

A total of 56 unreinforced web tests were performed on single web sections. The loading condition used was IOF, i.e. interior-one-flange loading. Analysis of the test results provided a reduction factor equation for the IOF loading. To provide the modified web crippling capacity for the sections with web openings, the reduction factor equation should be applied to the AISI Specification web crippling equations (Equations 11 and 12), for design situations that satisfy the ranges of applicability given herein. Bending and web crippling interaction must be checked using Equations 13 and 14 using the reduced web crippling and bending capacities for web openings in the absence of each other.

The reduction factor equation is a function of the web opening parameters α and a/h. Use of the reduction factor 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. Design recommendations are summarized in Section III-F in a format intended for consideration for adoption into the AISI Specification provisions.

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