01 Aug 1996

# Structural behavior of circular holes in web elements of cold-formed steel flexural members subjected to web crippling for end-one-flange loading

Craig Uphoff

Roger A. LaBoube
*Missouri University of Science and Technology*, laboube@mst.edu

Wei-Wen Yu
*Missouri University of Science and Technology*, wwy4@mst.edu

CCFSS LIBRARY Uphoff, Craig A.; Research
23 1 * 3860 Assistant LaBoube, Roger A.;
1996 STRUCTURAL BEHAVIOR OF CIRCULAR
HOLES IN WEB ELEMENTS OF
COLD-FORMED STEEL FLEXURAL
C2 MEMBERS SUBJECTED TO WEB
CRIPPLING FOR END-ONE FLANGE

Civil Engineering Study 96-2
Cold-Formed Steel Series

Final Report

# STRUCTURAL BEHAVIOR OF CIRCULAR HOLES IN WEB ELEMENTS OF COLD-FORMED STEEL FLEXURAL MEMBERS SUBJECTED TO WEB CRIPPLING FOR END-ONE-FLANGE LOADING

by

Craig A. Uphoff
Research Assistant

Roger A. LaBoube
Wei-Wen Yu
Project Directors

August 1996

Department of Civil Engineering
University of Missouri-Rolla
Rolla, Missouri

# 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 End-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.

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.

Technical guidance for this investigation was provided by the American Iron and Steel

Intstitute's Subcommittee on Stud Design: Perforated Elements. The Subcommittee's guidance is gratefully acknowledged. Thanks is also extened to R. B. Haws, K. L. Slaughter, and S. P. Bridgewater, AISI Staff, for their assistance.

TABLE OF CONTENTS

# LIST OF ILLUSTRATIONS

# LIST OF TABLES

# I. INTRODUCTION

## A. GENERAL

An environmental concern regarding the use of wood being an appropriate construction material has become a contemporary issue. The depletion of forests, caused not only by the building construction industry, but also by natural disasters such as forest fires, has raised many questions about the conservation of the environment. Trees are being re-planted in an effort to make up for the loss, but trees take many years to mature.

Therefore, in an attempt to improve the environment and the feasibility of building construction, alternative materials for residential construction are being investigated. One material that is being researched extensively is cold-formed steel. Cold-formed steel has many advantages over other building materials. The foremost advantage is its recyclability, which is an environmentally attractive advantage. Other advantages of cold-formed steel are that it has a very high weight-to-strength ratio, construction is fast and easy, it can be mass produced with consistent cross-sectional properties, it is termite proof and rotproof, it is economic in transportation and handling, and it is noncombustible. Cold-formed steel has been preferred in light-industrial construction for many years because it is cost competitive and because of the aforementioned advantages.

The use of cold-formed steel members in building construction began around the 1850's in the United States and Great Britain. Although cold-formed steel building construction began in the 1850's, cold-formed steel was not widely used until around 1940.

Since 1946 the use and the development of thin-walled cold-formed steel construction in the United States have been accelerated by the printing 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 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 subsequently revised editions of the Specification pertain only to flexural members without web openings.

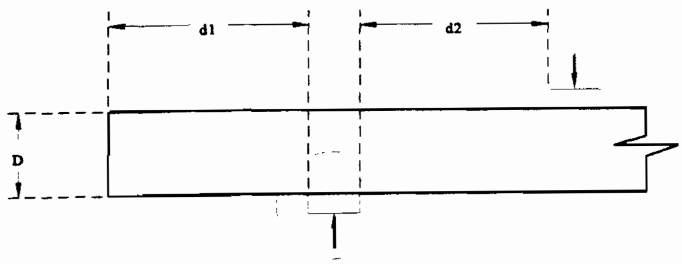
Since 1990, the University of Missouri-Rolla has conducted a comprehensive study of the behavior of web elements of flexural members with web openings subjected to loads causing bending, shear, and web crippling, and combinations thereof. The current AISI ASD Specification (1986) and AISI LRFD Specification (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 web openings spaced at intervals along the longitudinal axis of the section provides passages for conduits frequently used in building construction.

The most significant reason for conducting this research investigation was the concern that the presence of web opening(s) would have a degrading effect on the 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 research investigation had the 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 for End-One-Flange (EOF) loading condition (Figure 1). Design recommendations were developed which consider the web crippling limit state and EOF loading. The primary consideration of structural behavior was the failure load of the test specimens. This failure load quantified the web crippling strength.




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

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

**Figure 1** Loading Condition Criteria

2. Secondary Purpose. The secondary purpose of the investigation was to evaluate the adequacy of the current AISI provisions and conclusions from previous studies for single web sections based on the results of the unreinforced EOF tests performed during the

investigation. In order to perform this evaluation, a comparison of test results for specimens with no web openings was performed to make sure there was a good correlation with the current AISI provisions. Then, a comparison of test results for specimens with web openings was performed to determine if the current AISI provisions could adequately predict the web crippling capacity of sections with web openings. Finally, a comparison of test results for specimens with web openings was performed to determine the adequacy of the reduction factor developed by Langan, LaBoube, and Yu (1994) for rectangular holes with fillet corners.

## C. SCOPE OF INVESTIGATION

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

1. Loading Condition. End-One-Flange loading condition was used, and the criteria for this condition is illustrated in Figure 1. The reduction factor equation developed for EOF loading condition is valid only for the EOF loading condition.

2. Cross-Section Types. All cross sections tested were C-shaped sections with edge-stiffened flanges. However, the same web crippling behavior will exist for other single web elements with unstiffened flanges. Therefore, the recommendations for the EOF reduction factor equation are valid for other single web cross-section shapes, with or without stiffened flanges.

3. Cross-Section Properties. Table I provides the properties of the EOF unreinforced web test specimens and Table II gives the ranges of parameters of tests. The type of web openings that were used in this investigation were circular in shape and were located at mid-height of the test specimen. Figure 2 illustrates a typical cross-section used in this investigation.

4. Range of α Values. The value of α varied from 0 to 1 for the unreinforced EOF tests. The parameter α is equal to the longitudinal clear distance between the edge of the bearing and the web opening, *x*, divided by the height of the flat portion of the web, *h* (Figure 3).

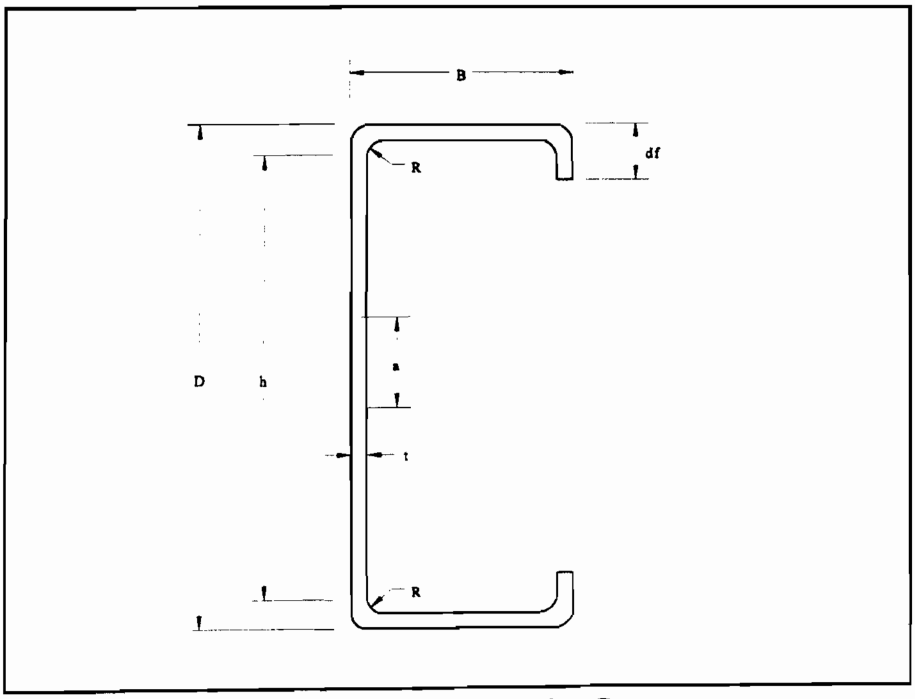



**Figure 2** Typical Cross-Section Parameters

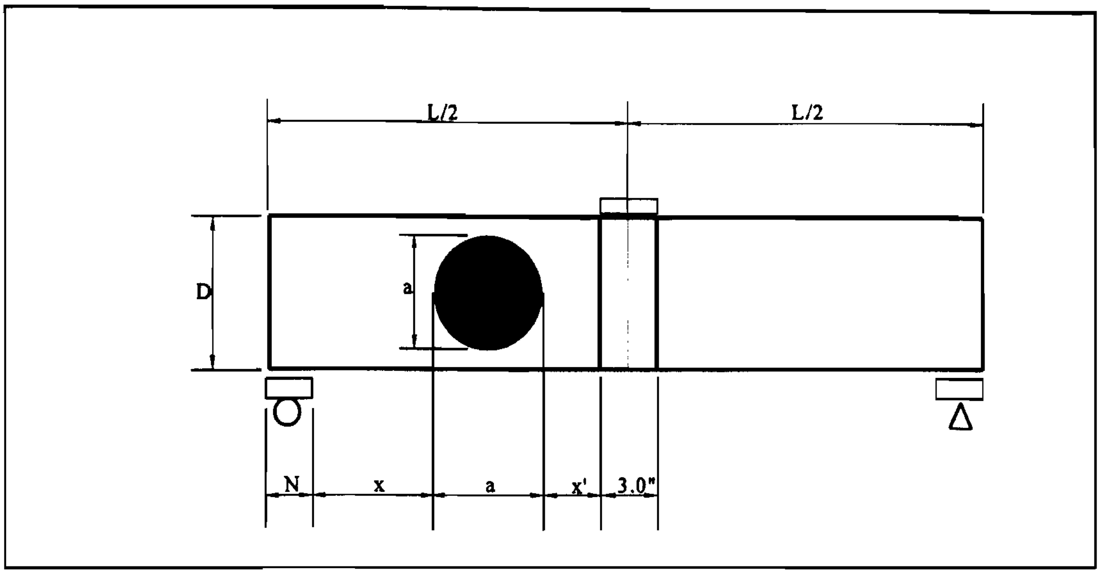



**Figure 3** Typical Test Specimen Parameters ($\alpha$ = x/h)

**Table I** Cross-Sectional Properties for End-One-Flange Test Specimens

| Specimen | D (in.) | R (in.) | t (in.) | h (in.) | B (in.) | $d_f$ (in.) | a (in.) | $F_y$ (in.) | h/t | a/h | R/t | N/t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EOF-C8-16 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 0,2,4,6 | 56.8 | 132.1 | ---- | 3.918 | 17.889 |
| EOF-C8-20 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 0,2,4,6 | 47.0 | 224.1 | ---- | 5.134 | 29.851 |
| EOF-C6-16 | 6.017 | 0.188 | 0.056 | 5.530 | 1.625 | 0.438 | 0,2,4 | 69.4 | 98.3 | ---- | 3.336 | 17.794 |
| EOF-C6-20 | 7.938 | 0.172 | 0.033 | 5.961 | 1.625 | 0.438 | 0,2,4 | 55.3 | 169.8 | ---- | 5.256 | 30.581 |

**Table II** Unreinforced Web EOF Cross-Section Parameter Ranges

| | h (in) | t (in) | $F_y$ (ksi) | N (in) | α | a (in) | a/h | h/t | R/t | N/t |
|---|---|---|---|---|---|---|---|---|---|---|
| minimum | 5.961 | 0.033 | 47 | 1 | 0.0 | 0.00 | 0.266 | 98.4 | 3.336 | 17.794 |
| maximum | 7.509 | 0.056 | 56.8 | 1 | 1.0 | 6.00 | 0.812 | 224.1 | 5.256 | 30.581 |

# II. REVIEW OF LITERATURE

## A. GENERAL

The following topics pertain to and are applicable to the investigation of web crippling for the EOF loading condition:

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 web crippling and bending.
5. AISI Specification provisions for web crippling, bending, and combined bending and web crippling.
6. Langan, LaBoube, and Yu reduction factor equations for web crippling of unreinforced single web members with web openings.

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

In using theoretical mechanics of deformable and ductile materials, the prediction of web crippling behavior of cold-formed steel flexural members is very difficult 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 load application.
> 4. Bending produced by eccentric load (or reaction) when it is applied on the bearing flange at a distance beyond the curve 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.

Because of the above complexities, the current AISI Specification (1986) provisions for web crippling were initially based on the experimental investigations performed at Cornell University by Winter and Pian (1946), and by Zetlin in the 1940's and 1950's because of the difficulties stated above. The current AISI Specification (1986) is based on a study performed at the University of Missouri-Rolla (UMR) by Hetrakul and Yu (1978). In both the Cornell and UMR investigations, the web crippling tests were carried out under four loading conditions; (1) End-One-Flange (EOF) loading, (2) Interior-One-Flange (IOF) loading, (3) End-Two-Flange (ETF) loading, and (4) Interior-Two-Flange (ITF) loading. The loading conditions are defined in Figure 1.

Hetrakul and Yu (1978) and Santaputra and Yu (1986) presented a summary of previous theoretical research for the study of the web crippling behavior of solid web flexural members. Both of these investigations provide equations that address web crippling behavior and combined bending and web crippling behavior; however, the equations provided were strictly empirical and were not based on theoretical analysis. The Hetrakul and Yu equations were adopted by the AISI Allowable Stress Design (ASD)Specification (1986) and AISI Load and Resistance Factor Design (LRFD) Specification (1991a).

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. Analytical results were compared to experimental test results for determining the ultimate capacity, and the results were within 21 and 23 percent of 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 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 investigations on the web crippling behavior of cold-formed steel flexural members with web openings. All of these investigations will be discussed in this review.

2. Yu and Davis. Yu and Davis (1973) provided the results for 20 IOF web crippling tests conducted on cold-formed steel members. The tests specimens that were used were composed of two channels with square or circular web openings. The web openings were placed at mid-height of the web and were longitudinally centered on the IOF load plate. The channels were constructed by connecting them back-to-back, as I-beams, or connected through the simple lip edge stiffeners. The depth to thickness ratios ranged from 66.7 to 101,

the web opening depth-to-web ratio ranged from 0 to 0.641, and $F_y$ values ranged from 57.9 to 70.7 ksi. The tests were performed with a constant bearing length of 3.5 inches. The failure loads were the only recorded results, and therefore were the primary measure of the web crippling limit state. The research was preliminary in nature and was intended to provide design information for engineers.

Two reduction factor equations were provided by Yu and Davis (1973) which are distinguished from each other by whether or not the web opening is square or circular. The reduction factor, RF, for circular web openings with $0 \leq d/h \leq 0.5$ is as follows:

$$RF = 1.0 - 0.6\frac{d}{h} \quad (1)$$

where $d$ = diameter of the circular web opening

$h$ = clear distance between flanges measured in the plane of the web

The equation for square web openings with $0 \leq h_s/h \leq 0.642$ is as follows:

$$RF = 1.0 - 0.77\frac{h_s}{h} \quad (2)$$

where $h_s$ = width of the square web opening

$h$ = clear distance between flanges measured in the plane of the web

Equations 1 and 2 have no restriction on the value of the bearing length for applicability of the equations. In the limiting case of a value of $d$ or $h_s$ equal to zero, the reduction factor equations, for both Equations 1 and 2, produce a value of unity, therefore 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 localized stress and the removal of a greater amount of material for square openings resulted in a greater tendency 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:

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

where $n_l = N + h - a$

$N$ = bearing load length

$h$ = flat height of web

$a$ = height of web opening

$b$ = longitudinal length of web opening

Limits of Equation 3 are: $b/n_l \leq 2.0$, and $a/h \leq 0.75$

Equation 3 is always less than unity for sections with web openings. This reduction factor equation was developed based on the results of 103 tests with the web opening centered on the longitudinal location of the load plate. This experimental research was performed on C-shaped, edge-stiffened, channel sections subjected to IOF loading condition, and having rectangular web openings at mid-height of the web. The value of N was equal to 2.0 inches for all of 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 we 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, therefore insignificant bending moment was created in the specimen at the mid-span region of the web opening and web crippling failures. The reduction factor equation was based on the assumption that the distribution 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:

$$0.9 \leq \frac{RF \ x \ (P_n)_{test,solid\ web}}{(P_n)_{test,web\ opening}} \leq 1.1 \qquad \textbf{(4)}$$

A proposal by LaBoube (1990a) was made to use a modified form of the Sivakumaran and Zielonka reduction factor equation as a provisional 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.

4. Langan, LaBoube, and Yu. A study on the web crippling behavior of single unreinforced webs for cold-formed steel flexural members with web openings subjected to EOF loading condition, Figure 1, was conducted and reduction factor equations were developed that account for the degradation in web strength due to the presence of web openings.

The test specimens were constructed of C-shaped sections with edge stiffened flanges. The web openings were rectangular with fillet corners and were located at mid-height of the web. Two sizes of web openings were used in the Langan, LaBoube, and Yu (1994) experimental investigation, 0.75 x 2 inches and 1.50 x 4 inches, and are designated by dimensions *a* and *b,* where *a* is the height of the web opening and *b* is the longitudinal dimension of the web opening. Tests were conducted for $\alpha$ values in increments of 0, 0.5, 0.7, 1.0, and 1.5. The non-dimensional value of $\alpha$ is the ratio $x/h$, where $x$ is the longitudinal distance from the bearing edge to the edge of the web opening and $h$ is the height of the flat portion of the web.

Langan, LaBoube, and Yu (1994) conducted 157 tests during their investigation of which, 108 failed in web crippling, 34 failed in shear, 4 failed by flexure at mid-span in the compression flange, and 11 were conducted to perform diagnostic tests to ensure the validity of the testing procedure. The primary measure of the effect of the web openings on web crippling behavior was the failure load of the test specimens. Langan, LaBoube, and Yu (1994) determined the degradation of web strength was associated with the specimen parameters of *a/h* and $\alpha$.

Langan, LaBoube, and Yu (1994) concluded that since the test specimens were configured as simply supported spans, zero moment is considered to have been present at the EOF failure locations. Therefore, the interaction of bending was not considered for the test specimens.

Seventy-eight tests were conducted in which all failed due to the web crippling limit state. A bivariate linear regression was performed on the 78 test results with $\alpha$ and a/h as the independent variables. The resulting reduction factor equation, with a maximum limit of 100%, was found to be:

$$RF = 107.91 - (62.95\frac{a}{h}) + (12.06\alpha) \leq 100\% \quad (6)$$

or,

$$RF = 1.08 - (0.630\frac{a}{h}) + (0.120\alpha) \leq 1.00 \quad (7)$$

Equation 7 is applicable to all cross sections and conditions that meet the ranges of applicability: (1) the limits imposed on the existing Specification web crippling provisions, (2) the industry imposed limits on web opening parameters, (3) engineering judgement, and (4) the range of parameters for the test specimens provided by the Langan, LaBoube, and Yu (1994) experimental investigation.

5. 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. The effect of bending moment on the web crippling limit state for EOF loading condition is negligible.

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.

(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 equation 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 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 limit on web opening length.

(h) The testing procedure has variable centerline locations of the web opening relative to the bearing reaction plates, therefore, the reduction factor equation contains a parameter which considers the relative locations of the web openings with respect to the bearing reaction plates. In keeping with the convention of other parameters in the reduction factor equation, this parameter is non-dimensional.

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

1. General. A number of 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.

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, do not thoroughly incorporate the complexities of web crippling behavior. Therefore, it is concluded that research on plate elements 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 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: whereas, a web of a flexural member typically does not satisfy any of these ideal conditions. The web of a flexural member is provided some degree of rotational stiffness by the flanges, and the magnitude of the restraint is between that of the simply supported and fixed conditions. Also, the support will vary depending upon the state of stiffness due to elastic or plastic behavior.

Also, the loading conditions for plate research can be made ideal. 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 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. Additionally, the large deflections typically exhibited during web crippling analysis change the equilibrium relationship and the resultant location of flange load application.

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

a. Narayanan and Chow. Experimental research, performed by Narayanan and Chow (1984), was conducted on the ultimate capacity and post-buckling behavior of perforated steel plates. Narayanan and Chow provide design curves for perforated square plates with either circular or square holes in the center of the simply supported plate subjected to uniform compression. These curves provide an approximate method of evaluating the ultimate capacity of the plates.

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

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

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

3. Perforated Web Elements of Flexural Members. A large number of investigators have performed analytical and verification test on the behavior of web elements with openings of flexural members. The previous research performed on perforated webs of flexural members avoided the web crippling limit state being influenced by the web openings. This was accomplished insuring 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.

Yu (1991) states, that 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 complicated. Even though limited information is available for relatively thick steel sections, on the basis of previous research, these design criteria may not be applicable completely to perforated cold-formed steel sections due to the fact that local buckling is usually only a major concern for thin-walled 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 brief summary of the research performed on the effect of web openings on thick-walled sections and the practical implementation of the results.

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 at only needed locations, instead of at 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 size web opening, unless the opening is cut in the field.

The considerations included in the AISC Guidelines most closely related to the concerns of the current study 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 area 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 as suggested by Redwood and Shrivastava (1980). These criteria are applied to composite and non-composite members with and without reinforcement. The requirement that openings be placed no closer than 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.

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, Branda, 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 was far from the web opening and therefore, prevented web crippling in the area 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 area of the web opening.

In the portion of the member located in the area 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, Branda, and Daly (1978), state that the most critical factors influencing the behavior of 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 sections formed by the part of the beam above or below the hole
5. The length of the hole
6. The shape of the hole
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 greatly reduced.

E. DEVELOPMENT OF CURRENT AISI SPECIFICATION PROVISIONS FOR 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 University of Missouri-Rolla. All tests were performed on solid web specimens, and the resulting equations were intended for use on solid web sections.

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

2. Web Crippling Capacity. Hetrakul and Yu (1978) provide equations for the allowable web crippling capacity of cold-formed steel members subjected to EOF, IOF, ETF, and ITF loading conditions for single web of multiple web sections with or without edge-stiffened flanges. The equations provide the maximum allowable web crippling capacity. Since the equations compute the maximum allowable web crippling capacity a factor of safety must be incorporated into the equations. The factor of safety for the equations of EOF loading condition is 1.85 and is attributed for the common high variance found in web crippling analysis. The equation which is applicable to the conditions for the current investigation is for EOF loading and is provided as follows:

a. Sections with Edge Stiffened Flanges.

For $N/t \leq 60$:

$$(P_a)_{comp} = t^2 \frac{F_y}{33} C_3 C_4 (178.70 - 0.33\frac{h}{t})(1 + 0.0102\frac{N}{t}),\ kips \qquad (8)$$

For $N/t > 60$:

$$(P_a)_{comp} = t^2 \frac{F_y}{33} C_3 C_4 (178.70 - 0.33 \frac{h}{t})(0.922 + 0.0115 \frac{N}{t}), \ kips \tag{9}$$

b. <u>Sections without Edge-Stiffened Flanges</u>.

For $N/t \leq 60$:

$$(P_a)_{comp} = t^2 \frac{F_y}{33} C_3 C_4 (117.19 - 0.15 \frac{h}{t})(1 + 0.0099 \frac{N}{t}), \ kips \tag{10}$$

For $N/t > 60$:

$$(P_a)_{comp} = t^2 \frac{F_y}{33} C_3 C_4 (178.70 - 0.33 \frac{h}{t})(0.706 + 0.0148 \frac{N}{t}), \ kips \tag{11}$$

Where, $C_3 = (1.33 - 0.33\ F_y/33)$

$C_4 = (1.15 - 0.15\ R/t) \leq 1.0$

$F_y$ = Design yield stress of the web, ksi

h = Depth of the flat portion of the web, inches

t = web thickness, inches

R = Inside bend radius, inches

N = Bearing length of load or reaction, inches

The above equations for the EOF loading condition for single web members are distinguished by whether or not the flange is unstiffened for edge-stiffened. This is done because members with stiffened and unstiffened flanges have a considerable difference in load-carrying capacities when looking at the web crippling limit state.

F. AISI SPECIFICATION PROVISIONS FOR 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 in this section. The areas of the provisions reviewed in this paragraph pertain to the web crippling limit state.

The current AISI ASD Specification (1986) for web crippling was adopted from the investigation by Hetrakul and Yu (1978). Some minor differences are present between the equations for web crippling limit state given by Hetrakul and Yu (1978) and what was adopted in the current AISI ASD Specification provisions (1986). The AISI LRFD Specification (1991a) web crippling provision equations were adopted from the AISI ASD Specification and will be discussed in this section.

The web crippling equations of the AISI ASD Specification are based on allowable load capacity and not allowable stress. Stress is not directly calculated for the failure mode of web crippling. The AISI LRFD Specification (1991a) equations that were adopted from the AISI ASD Specification (1986) disregards the factor of safety and performs a statistical analysis to determine the LRFD resistance factor.

2. Web Crippling Capacity.

a. General. The current AISI ASD (1986) and AISI LRFD (1991a) Specifications 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. The limits on the ASD and LRFD web crippling equations for application to beams are: *h/t*, *R/t*, *N/t*, and *N/h* parameters with maximum values of 200, 6, 210, and 3.5, respectively.

The *h/t* limit of 200 is a general requirement for flexural members. This *h/t* limit can be increased to 260 when transverse bearing stiffeners are used, and to 300 when transverse along with intermediate stiffeners are used. The other parameters, *R/t*, *N/t*, and *N/h*, are limited as a result of the test parameters used in the web crippling studies by Hetrakul and Yu (1978).

The web crippling equations of the AISI ASD Specification (1986) calculate the maximum allowable load per web, $P_a$, in kips to prevent web crippling failure of sections without web openings. The web crippling equations of the AISI LRFD Specification provide the maximum nominal load per web, $P_n$, in kips and the associated resistance factor to prevent web crippling failure.

b. Web Crippling Equations. Depending on the design situation, there are nine applicable web crippling equations. There are four factors that control which web crippling equation is to be used and they are as follows: (1) one-versus two flange loading, (2) end versus interior loading, (3) flange edge stiffening, and (4) single versus multiple web. All nine equations are located in Section C3.4 of the Specification.

The AISI ASD Specification (1986) equations use a factor of safety of 1.85 for single web sections which results in an allowable web crippling load, $P_a$ or $(P_a)_{comp,\ solid\ web}$. The nominal load, $P_n$ or $(P_n)_{comp,\ solid\ web}$, can be calculated by multiplying $P_a$ by the safety factor of 1.85.

The AISI LRFD Specification (1991a) equation for single web sections is to be used with a resistance factor, $\Phi_W$, of 0.75. The LRFD design format is as follows:

$$\Sigma \gamma R_p \leq \Phi_W R_n \tag{12}$$

Where, $\gamma$ = load factor

$R_p$ = service load

$\Phi_W$ = web crippling resistance factor = 0.75 for single web sections

$R_n$ = nominal capacity, $(P_n)_{comp,\ solid\ web}$

The reason for the low value of $\Phi_W$ is the same as for the high value for the ASD Specification factor of safety discussed in the review of Hetrakul and Yu (1978).

The web crippling design equations relative to the current study come from Section C3.4 of the AISI ASD Specification (1986). The equations for EOF Loading of Single Unreinforced Webs are as follows:

i. <u>For Sections with Partially Stiffened or Stiffened Flanges, AISI Equation C3.4-1:</u>

$$(P_a) = t^2 k C_3 C_4 C_\theta (179 - 0.33\frac{h}{t})(1 + 0.01\frac{N}{t}),\ kips \tag{13}$$

$$(P_n) = t^2 k C_3 C_4 C_\theta (331 - 0.61\frac{h}{t})(1 + 0.01\frac{N}{t}),\ kips \tag{14}$$

ii. <u>For sections with unstiffened flanges, AISI Equation C3.4-2:</u>

$$(P_a) = t^2 k C_3 C_4 C_\theta (117 - 0.15\frac{h}{t})(1 + 0.01\frac{N}{t}),\ kips \tag{15}$$

$$(P_n) = t^2 k C_3 C_4 C_\theta (217 - 0.28\frac{h}{t})(1 + 0.01\frac{N}{t}),\ kips \tag{16}$$

Where, $k = F_y/33$

$C_3 = (1.33 - 0.33k)$

$C_4 = 0.50 < (1.15 - 0.15R/t) \leq 1.0$

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

$F_y$ = Design yield stress of the web, ksi

$h$ = Depth of the flat portion of web, inches

$t$ = Web thickness, inches

$R$ = Inside bend radius, inches

$\theta$ = 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, inches

For equations 15 and 16, when $N/t > 60$, the factor $[1+0.01N/t]$ may be changed to $[0.71+0.015N/t]$.

c. 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 exceed those used in the development of the equations by Hetrakul and Yu (1978). The highest $F_y$ value used in the development of the current AISI provisions is 54.0 ksi (Hetrakul and Yu, 1978, and Yu, 1991). However, the current web crippling provisions are still applicable for any $F_y$ value of sections that meet the requirements of Section A of the Specification (AISI, 1986, and AISI, 1991a). For values of $F_y$ greater than 91.5 ksi the current AISI provision equations will produce an incorrect decrease the $P_a$. No provision is currently allowed for increasing the web crippling strength for higher $F_y$ values. Therefore, the $F_y$ value of 91.5 ksi should be used if the cross section has a yield strength greater than this value (Yu 1991).

# III. END-ONE FLANGE UNREINFORCED SINGLE WEB OPENING STUDY

## A. INTRODUCTION

This section includes the results of the UMR study on web crippling behavior of single unreinforced webs for cold-formed steel flexural members with circular web openings subjected to the EOF loading condition (Figure 1). This study is a follow-up investigation to the study conducted by Langan, LaBoube, and Yu (1994).

Based on the results of this web crippling behavior study, design recommendations are given in the form of a reduction factor equation developed from the current study and a previous EOF web crippling study by Langan, LaBoube, and Yu (1994). The limits of the reduction factor equation are based on the range of parameters used during the investigation. The design recommendations are summarized in Section H of this chapter.

The reduction factor equation is to be used when a web opening causes a reduced EOF web crippling capacity for a section with single unreinforced webs with web openings. The solid web capacity, $(P_n)_{comp,\ solid\ web}$, is to be multiplied by the reduction factor in order to compute the reduced web capacity.

## B. PURPOSE

The purposes of the investigation for the EOF loading condition for single unreinforced web sections with circular web openings are as follows:

1. To study the web crippling behavior of single unreinforced webs of cold-formed steel flexural members with circular openings subjected to the EOF loading condition and to develop a design equation to apply in practice.

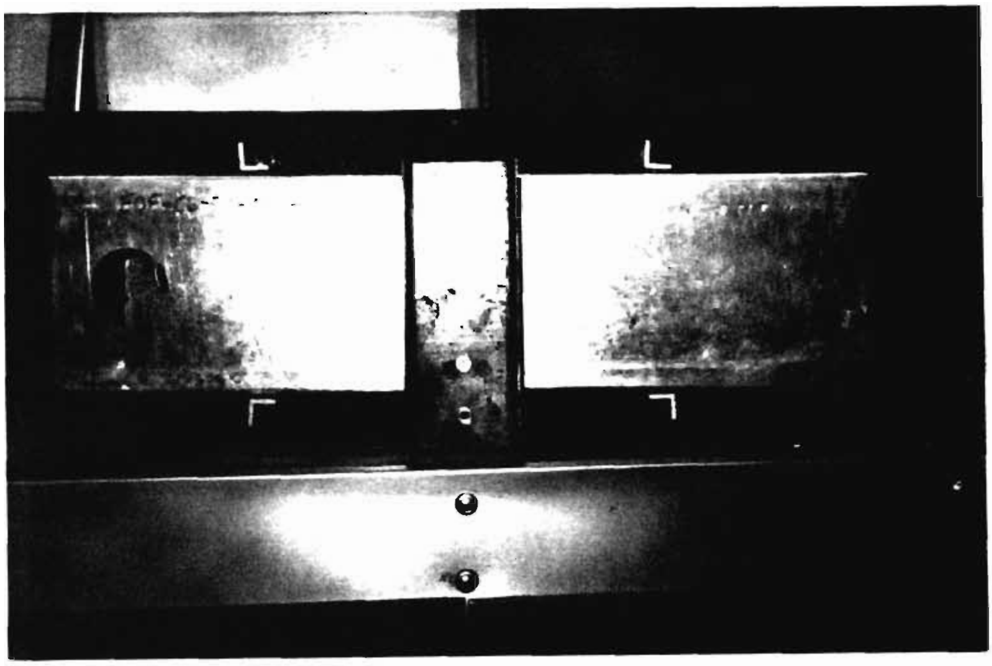
2. To evaluate the reduction factor equation developed by Langan, LaBoube, and Yu (1994) by comparing tests results to see if modifications to the Langan, LaBoube, and Yu reduction factor are needed.

The current AISI Specification provisions for web crippling provide the web crippling capacities for solid web sections in absence of bending moment. All EOF tests conducted throughout the current investigation had no degradation of the web crippling capacity due to bending moment. This was accomplished by the failure plane being located at the supports of a simply supported test specimen.

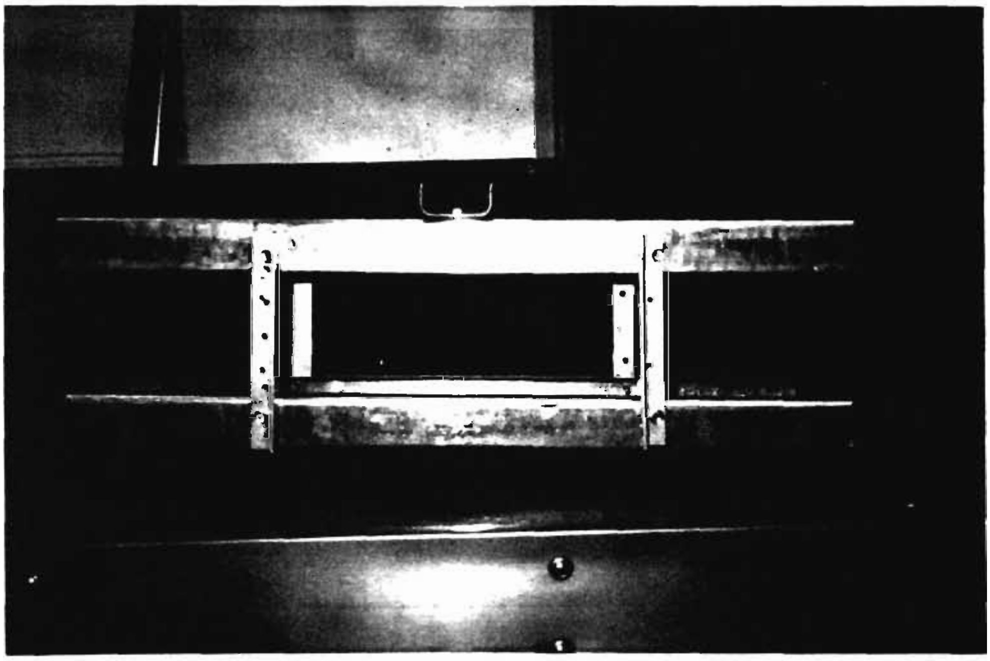
## C. EXPERIMENTAL INVESTIGATION

1. Test Specimens. The test specimens were fabricated in the Engineering Research Laboratory at the University of Missouri-Rolla. The specimens were fabricated from industry standard C-sections with edge-stiffened flanges. The web openings were circular in shape and located at mid-height of the web. See Figures 2 and 3 for the cross-section and longitudinal geometry of the test specimens, respectively. Figure 4 shows a typical test specimen that was used. The range of parameters of the test specimens is given in Table II. Circular holes of 2, 4, and 6 inch diameter were used in the tests conducted for this investigation.

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



(a)



(b)

**Figure 4** Typical EOF Test Specimens, (a) side view, (b) plan view.

The length of the EOF bearing reaction plate, $N$ (Figure 3), was kept at a constant value of 1 inch. The value of $N$ and the value of $x$ determine the longitudinal distance between the end of the section and the web opening.

The length of each test specimen was determined in order to satisfy the requirement for one-flange loading; greater than or equal to $1.5h$ clear distance between the end plate and the mid-span loading plate. End-one-flange loading criteria is given in Figure 1. The greater value of the following two equations was used to determine the minimum length of each test specimen:

$$L_{min} = 2(1.5h + N) + 3, \ inches \tag{17}$$

and,

$$L_{min} = (2(x + b)) + 2N + 3, \ inches \tag{18}$$

The value of $x$ is the clear distance between the edge of bearing to the edge of the hole. The parameter $b$ is the diameter of the hole in the web.

2. Test Setup. In order to be able to conduct the tests, two C-sections of the same minimum length were spaced approximately 6 ½ inches apart, parallel in the longitudinal direction, and interconnected with one inch aluminum angle, screwed to the top and bottom flanges of each section. This was done in order to prevent lateral-torsional buckling of the specimens. To prevent web crippling beneath the load point, a stiffener was connected vertically at mid-span of each C-section with screws. These bearing stiffeners were also used to transfer the applied load to the web so that the flange was not being loaded. This method was used in previous web crippling studies by Langan, LaBoube, and Yu (1994).

Using a Tinius-Olsen machine, Figure 5, a concentrated load was applied at mid-span to a three inch bearing plate in contact with the web stiffeners. The reactions creating the EOF loading were introduced to the specimen by bearing plates flush with the ends of the specimen, Figure 3. Therefore, the value of $d_1$, Figure 1, was equal to zero for all tests.

3. Test Procedure. The test specimens were loaded under a steady and gradual load until failure. Load was applied to a 25 pound plate placed on the top of the web stiffners at mid-span of the specimen. Failure occurred when the test specimen could no longer carry any additional load. At least two tests were conducted for each test specimen. Tests without holes in the web were conducted on each C-section specimen to serve as the control specimens. This testing procedure was used in previous studies by Langan, LaBoube, and Yu (1994).

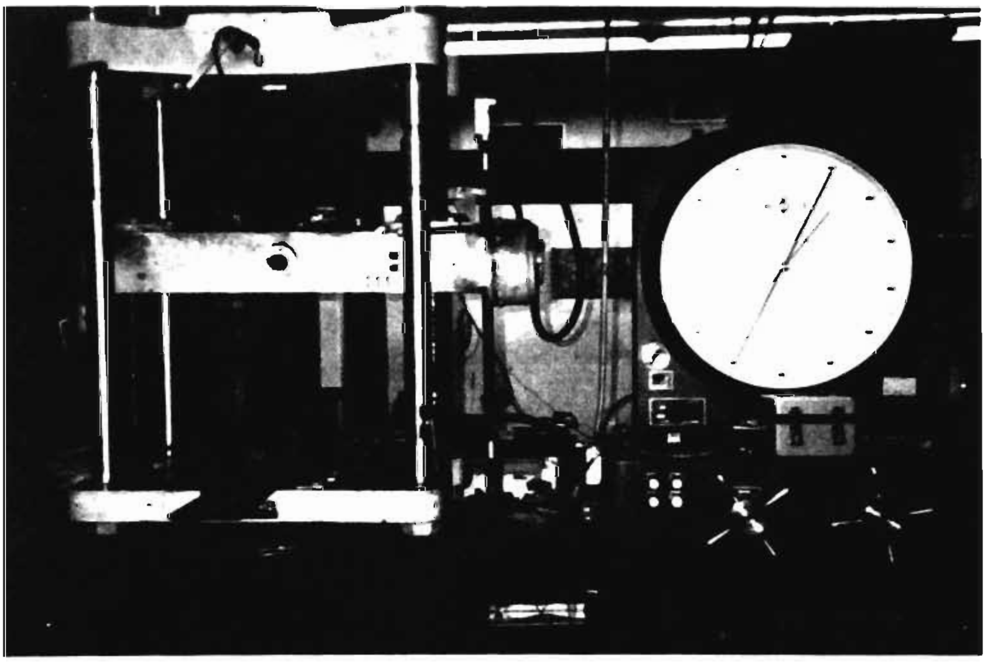


**Figure 5** Tinius Olsen Testing Machine

D. TEST RESULTS

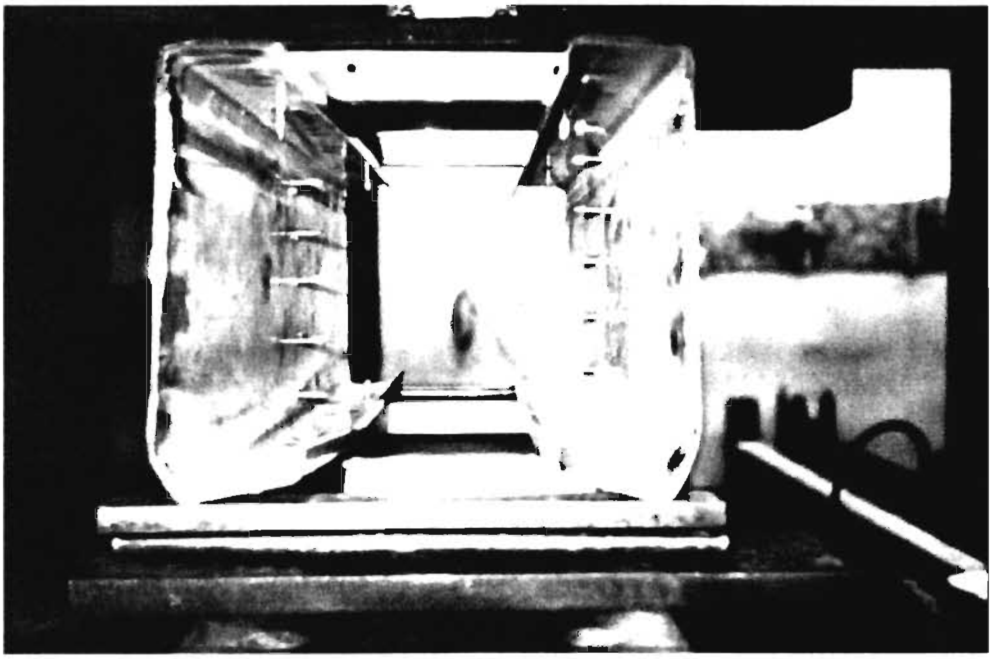
1. General. Fifty-Five unreinforced single web EOF tests were conducted during this investigation. Of these, 52 failed in web crippling and the other three failed due to an over-all stability.

The test failure load per web, $(P_n)_{test}$, for specimens failing due to web crippling was recorded and is shown for each specimen in Table III. It is assumed that the value of $(P_n)_{test}$ is equal to 1/4 of the mid-span applied load. Therefore, each of the tests specimen's four contact points with the EOF loading plates is assumed to equally support the applied load.

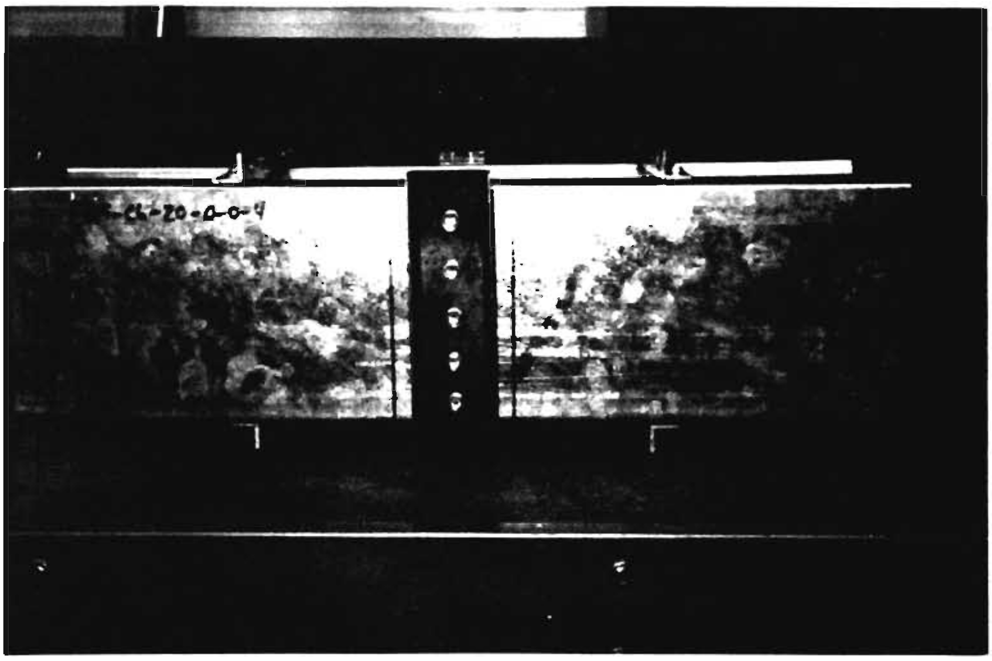
2. Typical Failures. Typical web crippling failures of the unreinforced EOF test specimens are shown in Figures 6, 7, 8, and 9. Figure 6 shows a solid web specimen, with a typical EOF web crippling failure. Figures 7 and 8 show a typical web crippling failure for a specimen with a web opening that has an $\alpha$ value equal to one. Figure 9 shows a specimen with the failure load still applied.

3. Web Crippling Deformation at Failure. At failure, the specimens were permanently deformed and would be considered unserviceable under most applications. This is an important consideration in the selection of the ASD Specification (1986) factor of safety and the LRFD Specification (1991a) resistance factor. Due to the complexity of determining the deformation due to web crippling, the AISI Specifications do not have serviceability criteria for web crippling. This helps explain the conservative factors of safety, 1.85, used by AISI ASD provisions and the resistance factor, 0.75, used by AISI LRFD provisions.

The web crippling deformation for tests without web openings were very localized at the bearing reaction plate, Figure 6. As the a/h ratio increased the web crippling occurred

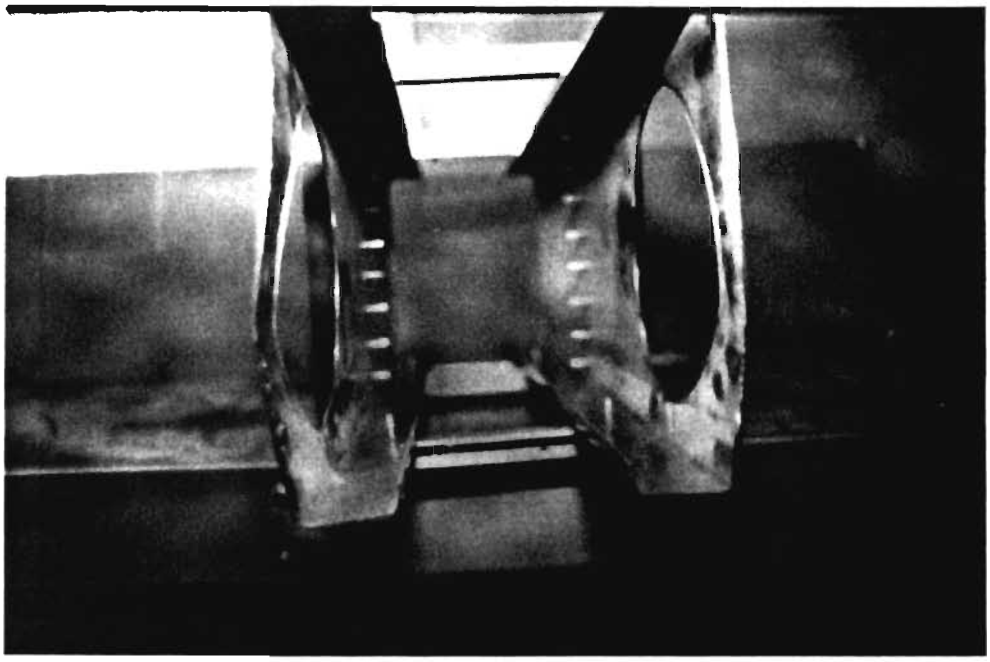


(a)

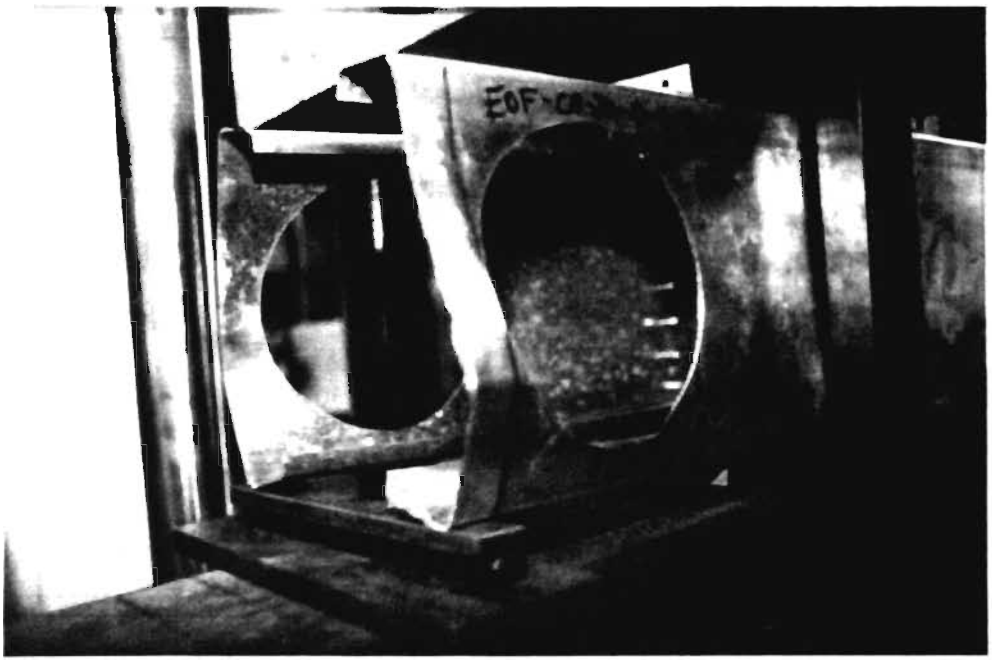


(b)

**Figure 6** Typical EOF Solid Web Specimen Failures: (a) end view, (b) side view

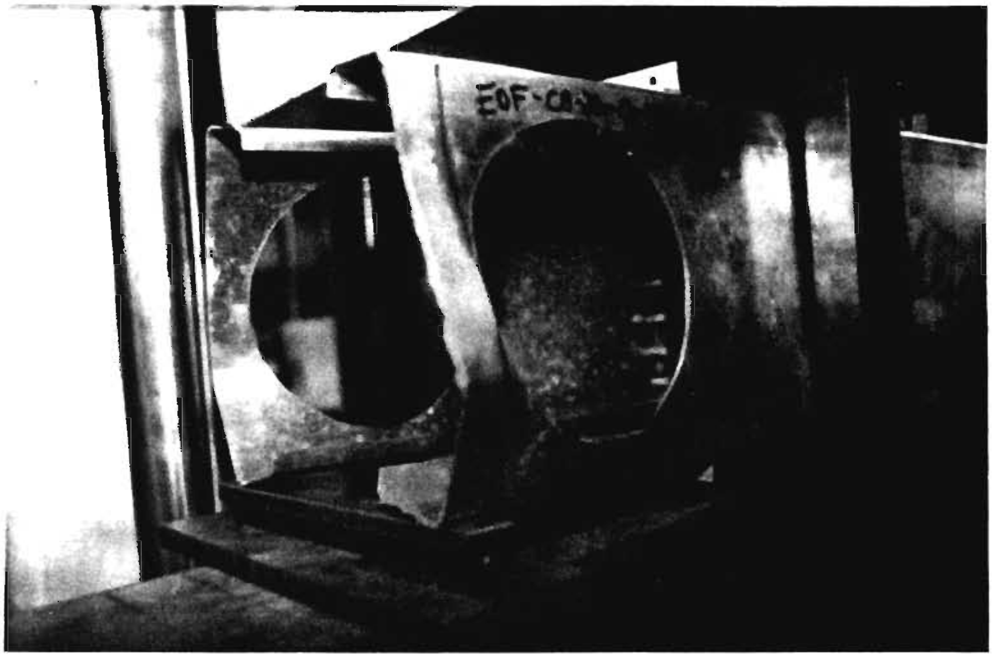


(a)

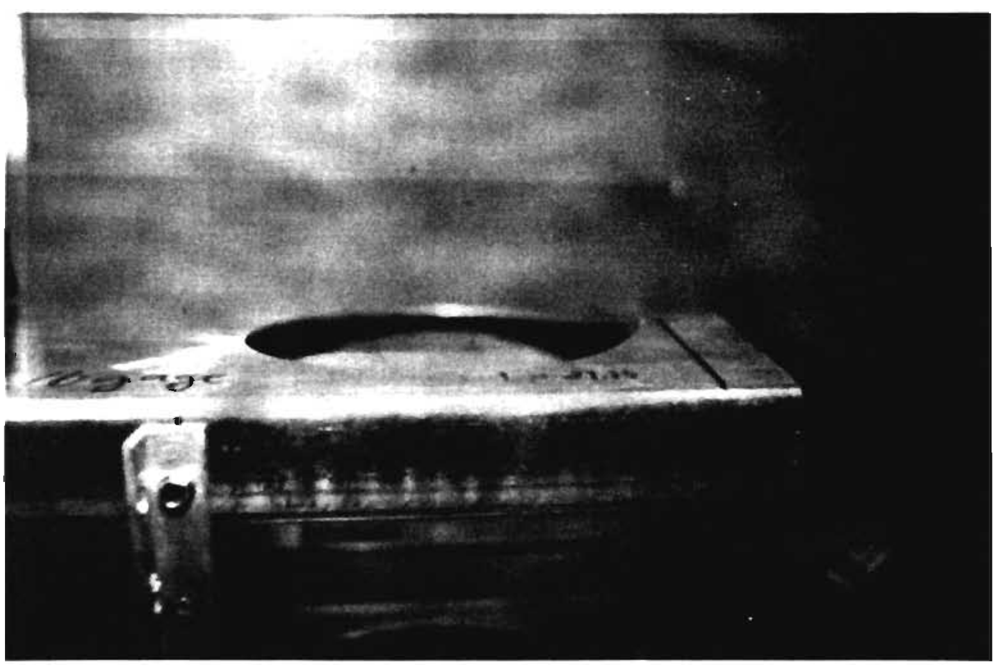


(b)

**Figure 7** Typical EOF Web Crippling Failure with High *a/h* ratio and $\alpha$ equal to 1: (a) end view, (b) side view



(a)



(b)

**Figure 8** Out-of-plane Web View of Web Crippling Failure

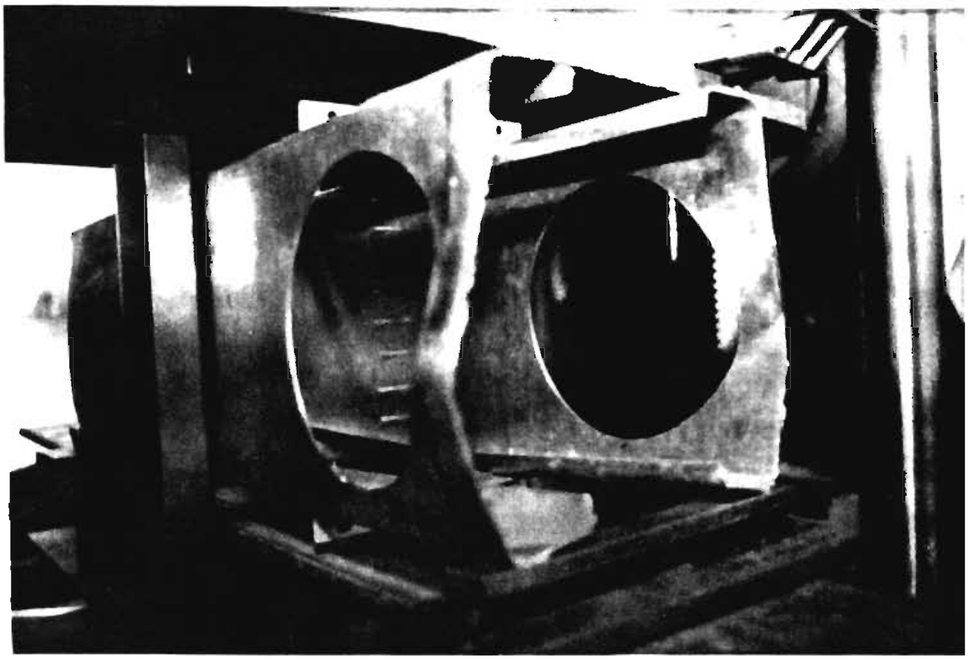


**Figure 9** Failure Load Applied to Specimen

further away from the bearing reaction plate and moved up into the edge of the web opening, Figure 7. For test specimens with $\alpha$ values of 1.0 the web crippling was located locally at the bearing reaction plate as in the solid web sections.

E. EVALUATION OF TEST RESULTS

1. General. For the current UMR study on EOF loading condition, the web crippling capacity was considered without degradation of the web strength due to bending. Therefore, the percent-of-solid-web-strength, *PSW*, could be recorded directly without any adjustments for significant bending.

The primary measure of the effect of circular web openings on EOF web crippling capacity is the failure load, $(P_n)_{test}$, of the test specimens (Table III). The parameters associated with the circular web openings were used to measure the effect of the web crippling capacity. A previous study by Langan, LaBoube, and Yu (1994) and the parameters $\alpha$, *a/h*, and *h/t* were considered in determining the effects of EOF web crippling capacity.

2. Effect of $\alpha$ on Web Crippling Capacity. In the process of evaluating the test results of both the current UMR study and the Langan, LaBoube, and Yu (1994) investigation, a notable trend was observed within the test results. As the value of $\alpha$ increased from 0 to 1.5 (combined studies), the web crippling capacity, *PSW*, increased. Data points from the current UMR study are graphically illustrated in Figure 10 to show the increasing *PSW* associated with the increasing $\alpha$ values. The range of $\alpha$ values for this study were from 0.0 to 1.0.

3. Effect of *a/h* on Web Crippling Capacity. Another notable trend that was determined to effect the web crippling capacity was the parameter *a/h*. It was noted that as *a/h* increased the *PSW* distinctively decreased. Therefore, it was concluded that *a/h* is inversely proportional to the *PSW*. Figure 11 shows the inverse relationship of decreasing *PSW* corresponding to increasing *a/h* ratio's. The range of *a/h* values for this investigation is from 0.266 to 0.812.

## F. EVALUATION OF LANGAN, LABOUBE, AND YU REDUCTION FACTOR EQUATION

1. General. In the evaluation of the current test results, it was determined that the same parameters, $\alpha$ and *a/h*, incorporated in the Langan, LaBoube, and Yu (1994) reduction factor equation (Eq. 7), were the controlling parameters effecting the EOF web crippling capacity. Therefore, the Langan, LaBoube, and Yu reduction factor equation

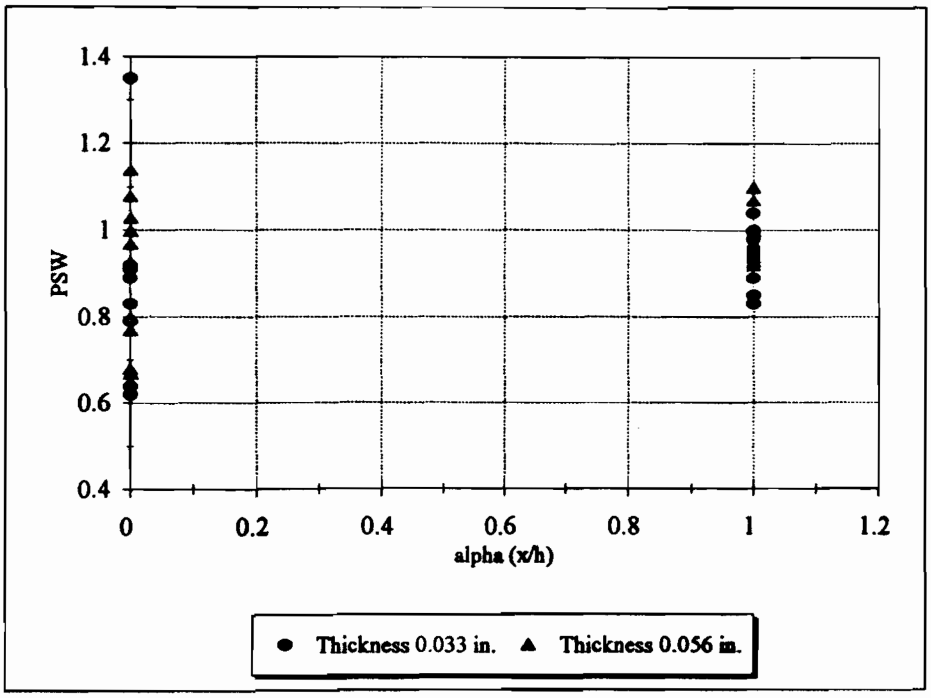



**Figure 10** Graphic Illustration of α (*x/h*) vs. *PSW* for Current UMR Study

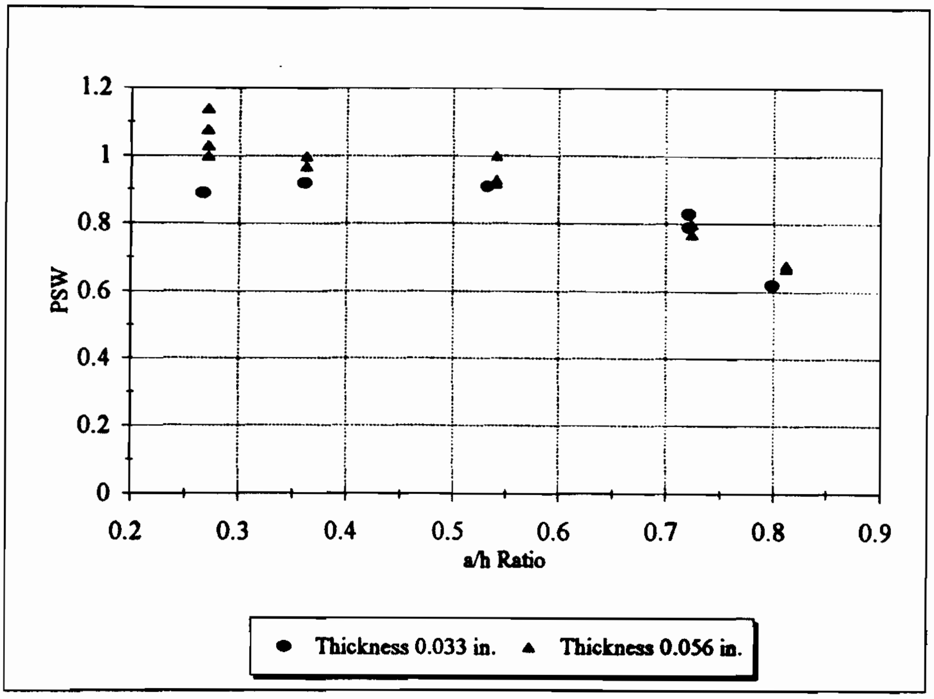



**Figure 11** Graphic Illustration of *a/h* vs. *PSW* for Current UMR Study

**Table III** Unreinforced EOF Test Results

| Specimen Number | L (in.) | N (in.) | α | (P ) (lbs.) | PSW | Limit State | Reduction Factor | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Langan RF | Current RF |
| EOF-C8-16-0-0-1 | 27.16 | 1 | ----- | 756.25 | 1.04 | WEB CRIPPLING | 1.08 | 1.01 |
| EOF-C8-16-0-0-2 | 27.16 | 1 | ----- | 725.00 | 1.00 | WEB CRIPPLING | 1.08 | 1.01 |
| EOF-C8-16-0-0-3 | 27.16 | 1 | ----- | 725.00 | 1.00 | WEB CRIPPLING | 1.08 | 1.01 |
| EOF-C8-16-0-0-4 | 27.16 | 1 | ----- | 706.25 | 0.97 | WEB CRIPPLING | 1.08 | 1.01 |
| EOF-C8-16-0-2-1 | 27.16 | 1 | 0 | 787.50 | 1.08 | WEB CRIPPLING | 0.91 | 0.92 |
| EOF-C8-16-0-2-2 | 27.16 | 1 | 0 | 831.25 | 1.14 | WEB CRIPPLING | 0.91 | 0.92 |
| EOF-C8-16-0-2-3 | 27.16 | 1 | 0 | 750.00 | 1.03 | WEB CRIPPLING | 0.91 | 0.92 |
| EOF-C8-16-0-2-4 | 27.16 | 1 | 0 | 725.00 | 1.00 | WEB CRIPPLING | 0.91 | 0.92 |
| EOF-C8-16-1-2-1 | 27.16 | 1 | 1 | 725.00 | 1.00 | WEB CRIPPLING | 1.00 | 1.01 |
| EOF-C8-16-0-4-1 | 27.16 | 1 | 0 | 668.75 | 0.92 | WEB CRIPPLING | 0.74 | 0.84 |
| EOF-C8-16-0-4-2 | 27.16 | 1 | 0 | 743.75 | 1.00 | WEB CRIPPLING | 0.74 | 0.84 |

**Table III** Unreinforced EOF Test Results (cont'd)

| Specimen Number | L (in.) | N (in.) | α | (P ) (lbs.) | PSW | Limit State | Reduction Factor | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Langan RF | Current RF |
| EOF-C8-16-0-4-3 | 27.16 | 1 | 0 | 675.00 | 0.93 | WEB CRIPPLING | 0.74 | 0.84 |
| EOF-C8-16-1-4-1 | 27.78 | 1 | 1 | 781.25 | 1.07 | WEB CRIPPLING | 0.86 | 0.92 |
| EOF-C8-16-1-4-2 | 27.78 | 1 | 1 | 800.00 | 1.10 | WEB CRIPPLING | 0.86 | 0.92 |
| EOF-C8-16-0-6-1 | 27.16 | 1 | 0 | 487.50 | 0.67 | WEB CRIPPLING | 0.57 | 0.75 |
| EOF-C8-16-0-6-2 | 27.16 | 1 | 0 | 493.75 | 0.68 | WEB CRIPPLING | 0.57 | 0.75 |
| EOF-C8-16-1-6-1 | 31.78 | 1 | 1 | 668.75 | 0.92 | WEB CRIPPLING | 0.69 | 0.83 |
| EOF-C8-16-1-6-2 | 31.78 | 1 | 1 | 725.00 | 1.00 | WEB CRIPPLING | 0.69 | 0.83 |
| | | | | | | | | |
| EOF-C8-20-0-0-1 | 27.53 | 1 | ----- | 306.25 | 1.04 | WEB CRIPPLING | 1.00 | 1.01 |
| EOF-C8-20-0-0-2 | 27.53 | 1 | ----- | 281.25 | 0.96 | WEB CRIPPLING | 1.00 | 1.01 |
| EOF-C8-20-0-2-1 | 27.53 | 1 | 0 | 262.50 | 0.89 | WEB CRIPPLING | 0.91 | 0.93 |

**Table III** Unreinforced EOF Test Results (cont'd)

| Specimen Number | L (in.) | N (in.) | α | (P ) (lbs.) | PSW | Limit State | Reduction Factor | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Langan RF | Current RF |
| EOF-C8-20-0-2-2 | 27.53 | 1 | 0 | 262.50 | 0.89 | WEB CRIPPLING | 0.91 | 0.93 |
| EOF-C8-20-1-2-1 | 27.53 | 1 | 1 | 275.00 | 0.94 | WEB CRIPPLING | 1.00 | 1.01 |
| EOF-C8-20-1-2-2 | 27.53 | 1 | 1 | 262.50 | 0.89 | WEB CRIPPLING | 1.00 | 1.01 |
| EOF-C8-20-0-4-1 | 27.53 | 1 | 0 | 268.75 | 0.91 | WEB CRIPPLING | 0.74 | 0.84 |
| EOF-C8-20-0-4-2 | 27.53 | 1 | 0 | 268.75 | 0.91 | WEB CRIPPLING | 0.74 | 0.84 |
| EOF-C8-20-1-4-1 | 28.02 | 1 | 1 | 306.25 | 1.04 | WEB CRIPPLING | 0.86 | 0.92 |
| EOF-C8-20-1-4-2 | 28.02 | 1 | 1 | 293.75 | 1.00 | WEB CRIPPLING | 0.86 | 0.92 |
| EOF-C8-20-0-6-1 | 27.53 | 1 | 0 | 181.25 | 0.62 | WEB CRIPPLING | 0.58 | 0.75 |
| EOF-C8-20-0-6-2 | 27.53 | 1 | 0 | 187.50 | 0.64 | WEB CRIPPLING | 0.58 | 0.75 |
| EOF-C8-20-1-6-1 | 32.02 | 1 | 1 | 250.00 | 0.85 | WEB CRIPPLING | 0.70 | 0.84 |
| EOF-C8-20-1-6-2 | 32.02 | 1 | 1 | 243.75 | 0.83 | WEB CRIPPLING | 0.70 | 0.84 |

**Table III** Unreinforced EOF Test Results (cont'd)

| Specimen Number | L (in.) | N (in.) | α | (P ) (lbs.) | PSW | Limit State | Reduction Factor | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Langan RF | Current RF |
| EOF-C6-16-0-0-1 | 21.59 | 1 | ----- | 937.50 | 1.08 | WEB CRIPPLING | 1.08 | 1.01 |
| EOF-C6-16-0-0-2 | 21.59 | 1 | ----- | 868.75 | 1.00 | WEB CRIPPLING | 1.08 | 1.01 |
| EOF-C6-16-0-2-1 | 21.59 | 1 | 0 | 868.75 | 1.00 | WEB CRIPPLING | 0.85 | 0.89 |
| EOF-C6-16-0-2-2 | 21.59 | 1 | 0 | 843.75 | 0.97 | WEB CRIPPLING | 0.85 | 0.89 |
| EOF-C6-16-1-2-1 | 21.59 | 1 | 1 | 837.50 | 0.96 | WEB CRIPPLING | 0.97 | 0.98 |
| EOF-C6-16-1-2-2 | 21.59 | 1 | 1 | 831.25 | 0.96 | WEB CRIPPLING | 0.97 | 0.98 |
| EOF-C6-16-0-4-1 | 21.59 | 1 | 0 | 668.75 | 0.77 | WEB CRIPPLING | 0.62 | 0.78 |
| EOF-C6-16-0-4-2 | 21.59 | 1 | 0 | 693.75 | 0.80 | WEB CRIPPLING | 0.62 | 0.78 |
| EOF-C6-16-1-4-1 | 24.06 | 1 | 1 | 806.25 | 0.93 | WEB CRIPPLING | 0.74 | 0.86 |
| EOF-C6-16-1-4-2 | 24.06 | 1 | 1 | 818.75 | 0.94 | WEB CRIPPLING | 0.74 | 0.86 |
| | | | | | | | | |

**Table III** Unreinforced EOF Test Results (cont'd)

| Specimen Number | L (in.) | N (in.) | α | (P ) (lbs.) | PSW | Limit State | Reduction Factor | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Langan RF | Current RF |
| EOF-C6-20-0-0-1 | 21.66 | 1 | ----- | 300.00 | 1.00 | WEB CRIPPLING | 1.00 | 1.01 |
| EOF-C6-20-0-0-3 | 21.66 | 1 | ----- | 300.00 | 1.00 | WEB CRIPPLING | 1.00 | 1.01 |
| EOF-C6-20-0-2-1 | 21.66 | 1 | 0 | 406.25 | 1.35 | WEB CRIPPLING | 0.85 | 0.89 |
| EOF-C6-20-0-2-2 | 21.66 | 1 | 0 | 275.00 | 0.92 | WEB CRIPPLING | 0.85 | 0.89 |
| EOF-C6-20-1-2-1 | 21.66 | 1 | 1 | 300.00 | 1.00 | WEB CRIPPLING | 0.97 | 0.98 |
| EOF-C6-20-1-2-2 | 21.66 | 1 | 1 | 281.25 | 0.94 | WEB CRIPPLING | 0.97 | 0.98 |
| EOF-C6-20-0-4-1 | 21.66 | 1 | 0 | 250.00 | 0.83 | WEB CRIPPLING | 0.63 | 0.78 |
| EOF-C6-20-0-4-3 | 21.66 | 1 | 0 | 237.50 | 0.79 | WEB CRIPPLING | 0.63 | 0.78 |
| EOF-C6-20-1-4-1 | 24.10 | 1 | 1 | 293.75 | 0.98 | WEB CRIPPLING | 0.75 | 0.86 |
| EOF-C6-20-1-4-2 | 24.10 | 1 | 1 | 287.50 | 0.96 | WEB CRIPPLING | 0.75 | 0.86 |

(Eq. 7) was compared to the current findings. However, this comparison discovered that Equation 7 was conservative at high *a/h* ratio's.

2. Effect of Langan, LaBoube, and Yu RF Equation on High *a/h* Values. Figure 12 graphically illustrates *PSW/Eq.7* vs. *a/h* for the combined test results of the combined Langan, LaBoube, and Yu (1994) study and the current UMR study. It can be noted that at *a/h* values greater than 0.5, the corresponding values of *PSW/Eq. 7* become considerably greater than 1.0. Therefore, as a result of this finding the Langan, LaBoube, and Yu reduction factor equation (Eq. 7) is considered to be conservative for *a/h* ratio's greater than 0.5.

Furthermore, Figure 12 illustrates that at *a/h* ratio's greater than 0.5, there were no tests conducted during the Langan (1994) investigation. Therefore, the current UMR study test results are beyond the range of the *a/h* values for the Langan (1994) investigation. Hence, a new reduction factor equation was developed.

3. Effect of Langan, LaBoube, and Yu RF Equation on *h/t* Ratio. Further consideration was given to the effects of *h/t* on the web crippling capacity and the validity of the Langan, LaBoube, and Yu (1994) reduction factor equation (Eq. 7). Figure 13 graphically illustrates the relationship of *PSW/Eq. 7* vs. *h/t* ratio. The current findings show that the Langan, LaBoube, and Yu (1994) reduction factor equation (Eq. 7) should consider the effects of the cross-sectional parameter of *h/t*. Figure 13 illustrates that for *h/t* values greater than 100, the corresponding *PSW/Eq. 7* values are considerably greater than 1.0. Therefore, the effect of *h/t* should be considered in a new reduction factor equation.

4. <u>Summary of The Effect of α, *a/h*, and *h/t* on Web Crippling Capacity</u>. The web opening parameters of α and *a/h* provide a distinct correlation with *PSW*. The cross-sectional parameter of *h/t* provides some correlation with *PSW* and will be considered as a third possible variable effecting the EOF web crippling capacity.

Therefore, two reduction factor equations were developed in order to determine which variables estimate the web crippling capacity most adequately. The first reduction factor equation was developed such that *a/h* and α are the independent variables and *PSW* is the dependent variable. A second reduction factor equation was developed such that *a/h*, α, and *h/t* are the independent variables and *PSW* is again the dependant variable. A statistical comparison was conducted between the two equations to determine which is most adequate in estimating the reduced web crippling capacity.

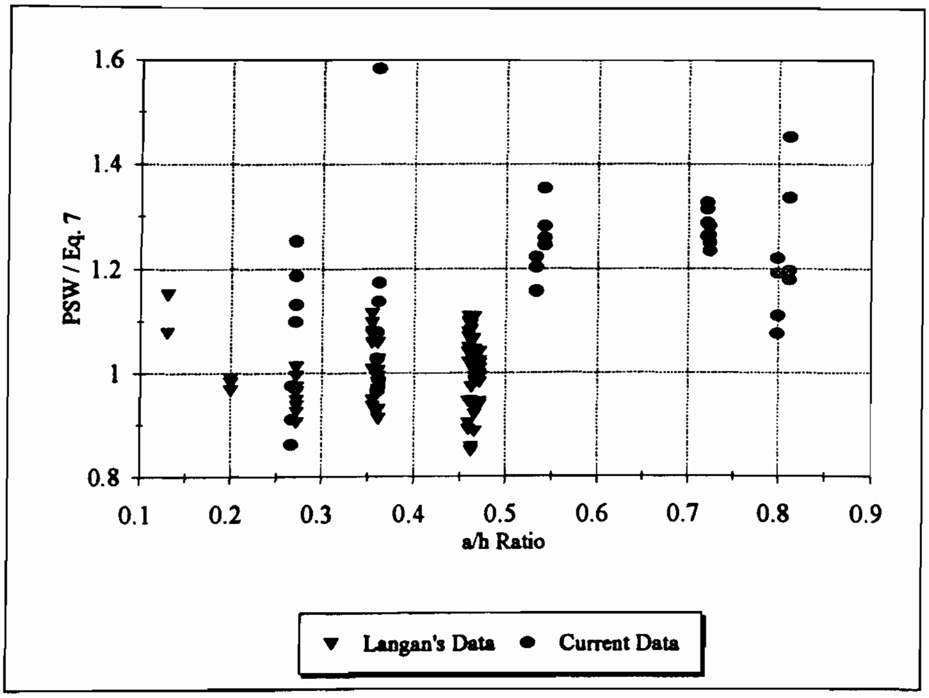



**Figure 12.** Combined Graphical Illustration of *PSW/Eq. 7* vs. *a/h* for Langan, LaBoube, and Yu (1994) and Current UMR Studies.

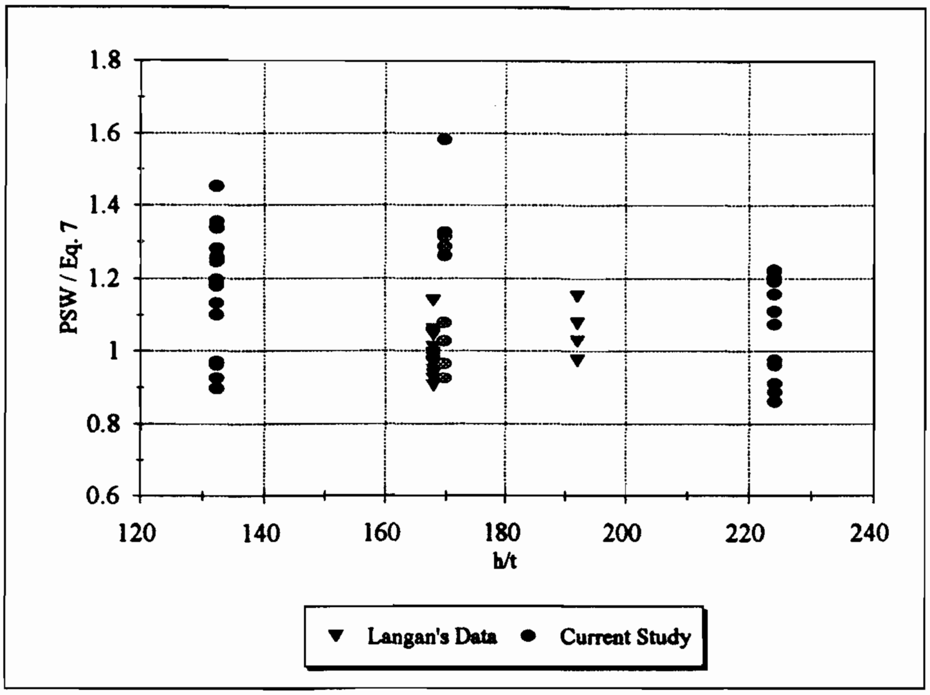



**Figure 13.** Combined Graphical Illustration of *PSW/Eq. 7* vs. *h/t* for Langan(1994) and Current UMR Studies.

G. DEVELOPMENT OF REDUCTION FACTOR EQUATIONS

1. General. In order to incorporate a wider range of parameter values and to consider the effect of *h/t* on the EOF web crippling capacity, a new reduction factor equation must be developed. The reduction factor equation developed by Langan, LaBoube and Yu (1994), Equation 7, is valid for *a/h* values up to 0.5. For *a/h* values greater than 0.5, reduction factor Equation 7 becomes overly conservative and therefore, a new reduction factor equation needs to be developed.

Furthermore, the cross-sectional parameter, *h/t*, was incorporated into the reduction factor equation to estimate its contribution to the reduction in EOF web crippling capacity. Therefore, a second reduction factor equation was developed to consider the *h/t* effect. This section will present and compare the reduction factor equations developed during this investigation.

2. Reduction Factor Equation with $\alpha$ and *a/h* as Independent Variables. In order to develop a reduction factor equation, a bivariate linear regression was performed on 120 test results comprised from the study by Langan, LaBoube, and Yu (1994) and the current UMR study using the statistical analysis software "Kwikstat". The first equation was developed with $\alpha$ and *a/h* as the independent variables and *PSW* as the dependent variable. The resulting equation, with a maximum limit of 100 percent was found to be:

$$RF = 101.2 - 32.45\frac{a}{h} + 8.34\alpha \leq 100\% \tag{18}$$

or,

$$RF = 1.01 - 0.325\frac{a}{h} + 0.0834\alpha \leq 1.00 \tag{19}$$

A *PSW* value of 100 percent signifies that no strength reduction is required.

It can be seen in Figure 14, *PSW/Eq. 19* vs. *a/h* converges upon a value of unity. For the data shown in Figure 14, the *PSW/Eq. 19* ratio has a mean value of 0.995, and a coefficient-of-variation equal to 0.102. A comparison between the statistical values for Equation 19 and the statistical values using Equation 7 is given in Table IV. Table IV shows that the statistical values for Equation 19 are less than those for Equation 7.

3. Reduction Factor Equation with $\alpha$, *a/h*, and *h/t* as Independent Variables. To consider the effect of *h/t*, a statistical analysis of the 120 test results was performed. The resulting equation was developed with $\alpha$, *a/h*, and *h/t* as the independent variables and *PSW* as the dependent variable. The resulting equation was found to be:

$$RF = 96.36 - 33.46\frac{a}{h} + 9.31\alpha + 0.044\frac{h}{t} \leq 100\% \tag{20}$$

or,

$$RF = 0.964 - 0.335\frac{a}{h} + 0.093\alpha + 0.0004\frac{h}{t} \leq 1.00 \tag{21}$$

A *PSW* value of 100 percent signifies no strength reduction is required.

It can be seen by Figure 15, that for *PSW/Eq. 21* vs. *a/h,* the data points also fall within an acceptable range of ±20 percent. However, the statistical values produced using Eq. 21 are less accurate than those using Eq. 19. Equation 21 results in a mean value equal to 1.06, and a coefficient of variation of 0.101. Again, these values are less than those given by the Langan, LaBoube, and Yu (1994) Equation 7, but are greater than those given by Equation 19. A comparison of all three statistical analyses is given in Table IV.

A comparison of *PSW/Eq. 19* vs. *h/t* and *PSW/Eq. 21* vs. *h/t* is illustrated in Figures 16 and 17, respectively. It can be seen that in Figures 16 and 17 the data points fall within an acceptable range about unity of ±20 percent. This illustrates that h/t does not contribute significantly to the reduction of web crippling strength.

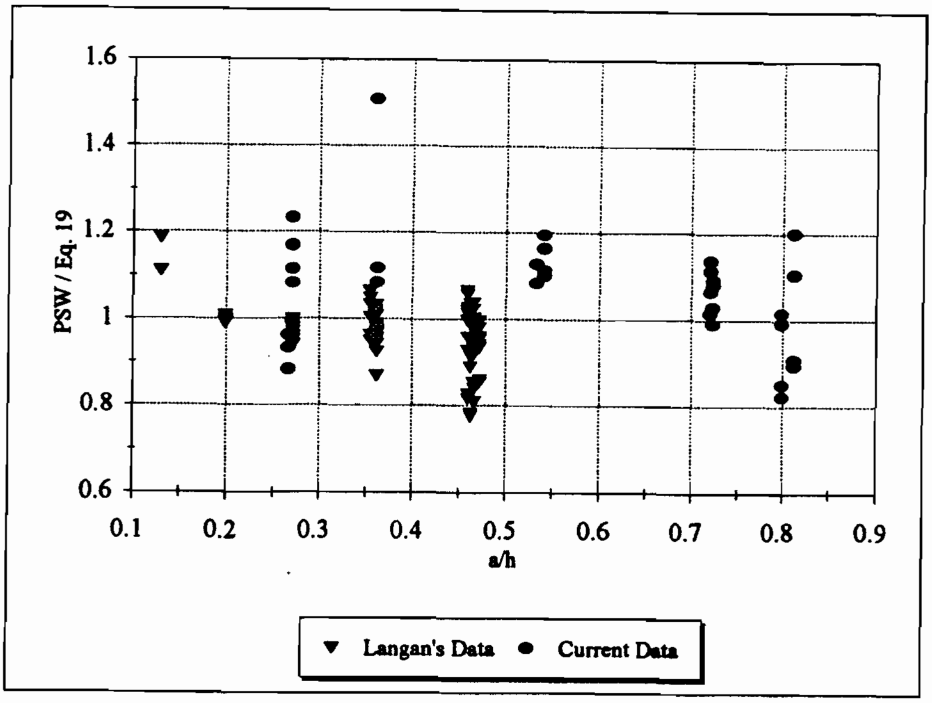



**Figure 14** Combined *PSW/Eq. 19* vs. *a/h* of Langan, LaBoube, and Yu (1994) and Current UMR Studies.

**Table IV** Statistical Analysis and Comparison of Reduction Factor Equations

| | Langan Study (1994) (Eq. 7, Fig. 12) | Current Study (Eq. 20, Fig. 14) | Current Study (Eq. 21, Fig. 15) |
|---|---|---|---|
| STATISTICS FOR PSW/RF vs. a/h | | | |
| MEAN | 1.02 | 0.995 | 1.06 |
| STANDARD DEVIATION | 0.132 | 0.102 | 0.107 |
| COEFFICIENT OF VARIATION | 0.128 | 0.102 | 0.101 |

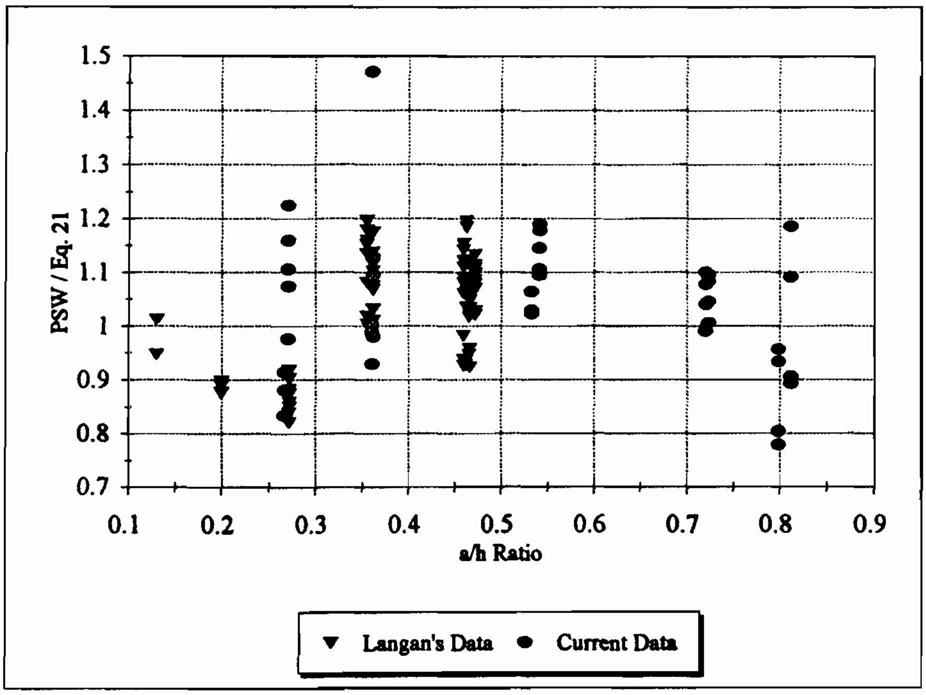



**Figure 15** Combined *PSW/Eq. 21* vs. *a/h* of Langan, LaBoube, and Yu (1994) and Current UMR Studies.

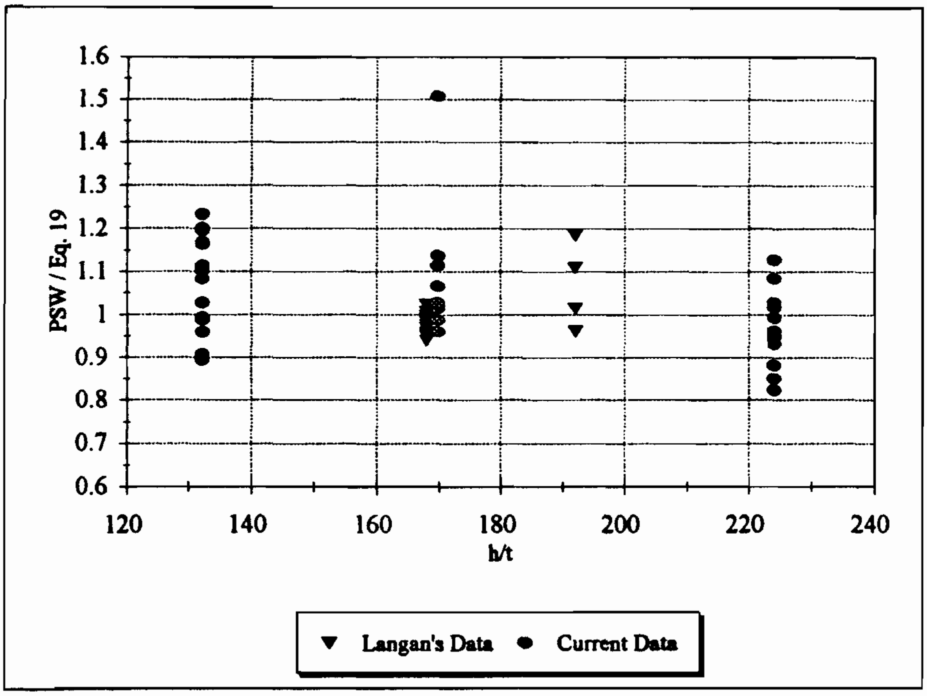



**Figure 16** Combined *PSW/Eq. 19* vs. *h/t* of Langan, LaBoube, and Yu (1994) and Current UMR Studies.

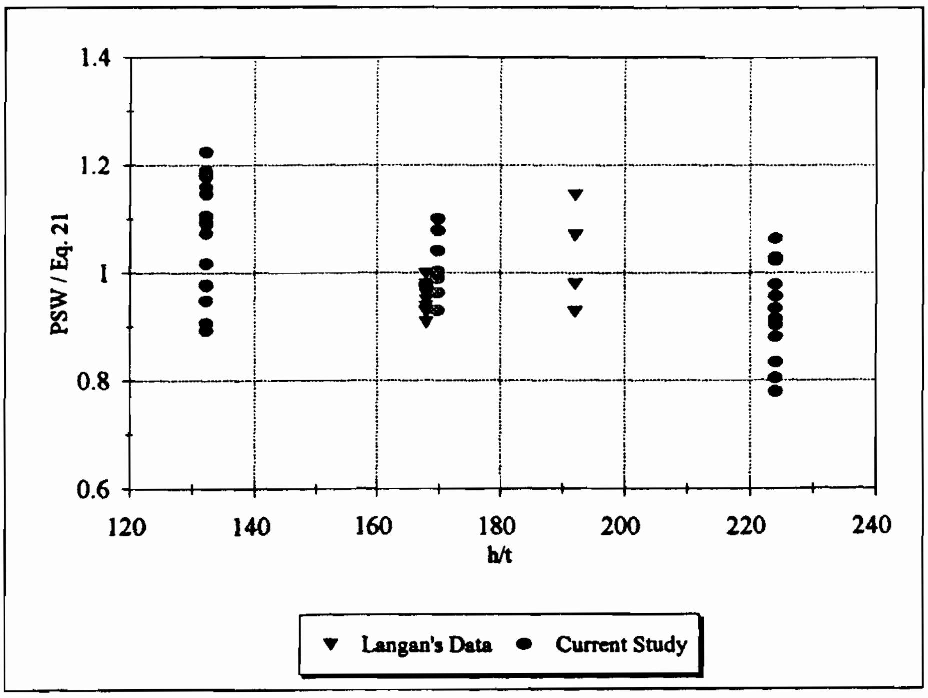



**Figure 17** Combined *PSW/Eq. 21* vs. *h/t* of Langan, LaBoube, and Yu (1994) and Current UMR Studies.

H. <u>DESIGN RECOMMENDATIONS</u>

1. <u>Reduction Factor Equation</u>. The statistical comparison given in Table IV was used as the measure of the effectiveness of the reduction factor equations developed in this study and by Langan, LaBoube, and Yu (1994). Based on the statistical analysis, Equation 19 is recommended to be used as a reduction factor for the AISI Specification (1986) solid web Equations 13 thru 16 for web crippling capacity.

2. <u>Limitations of Reduction Factor Equation</u>. The AISI ASD Specification (1986) allowable web crippling capacity and the AISI LRFD Specification (1991a) nominal web crippling capacity for sections with web openings can be obtained by applying Equation 19

to Equations 13 thru 16. This can be accomplished by multiplying the values produced by Equations 13 thru 16 by the reduction factor Equation 19.

The use of the reduction factor equation gives the web crippling capacity of sections with web openings. Equation 19 is only applicable to specimens that meet the ranges of applicability. The limiting factors that control the applicability of Equation 19 are as follows: 1. the range of parameters for the test specimens given in Tables I-A through V-A in the Appendix, 2. the imposed limits on the existing Specification provisions for web crippling, 3. the industry imposed limits, and 4. engineering judgement.

The current AISI Specification (1986; 1991a) provisions provide the following limits applied to Equations 13 through 16:

(1) The maximum *h/t* value that is allowed is 200 even though tests in this study were conducted on specimens with *h/t* values as large as 224. No minimum h/t value is enforced.

(2) All *R/t* values must be less than or equal to 6.0 for Equations 13 thru 16 to be valid. The range of *R/t* values used for the current study was 3.336 to 5.256.

(3) All *N/t* values less than or equal to 210 are valid for use of Equation 19, because this is the maximum limit for Equations 13 thru 16. The range of *N/t* values used in the current study was 17.794 to 30.581 therefore, due to the significant difference between the AISI maximum limit and the current study limit, the newly developed reduction factor equation is only valid for a maximum *N/t* value of 31.

(4) All *N/h* values less than or equal to 3.5 are valid for the use of Equation 19, because this is the maximum limit for Equations 13 thru 16.

(5) All θ values must be between the 45 to 90 degrees for Equation 19 to be valid. This range is imposed for Equations 13 thru 16.

Industry standard imposes a maximum *a/h* limit of 0.5 for pre-punched holes. However, the current study has broadened these limits to *a/h* values greater 0.5. Equation 19 is valid for *a/h* values from zero to 0.812.

The value of α has a lower limit of zero because any opening located above or below an EOF load or reaction plate must provide web reinforcement. There is no maximum limit for α because as α increases the maximum limit of 100 percent for the reduction factor will be achieved and therefore, no reduction in web capacity is necessary.

The yield strength, $F_y$, range that was used in the current study was 47.0 to 56.8 ksi. However, the Langan, LaBoube, and Yu (1994) data that was used in the current study used values up to 93 ksi. Therefore, Equation 19 is valid for $F_y$ values up to 93 ksi. For cross-sections with $F_y$ greater than 66.5 ksi, a value of 66.5 ksi must be used for Equations 13 thru 16 to be valid.

Even though the current study addressed only circular shaped web openings, there is no requirement on the shape of web opening that can be used. Also, although this study addressed only the end-one-flange loading condition, a companion UMR study investigated the interior-one-flange loading condition (Deshmukh, 1996).

# IV. CONCLUSIONS

A total of 55 EOF web crippling strength tests were conducted on single web sections with circular web openings. Analysis of the tests results provide two reduction factor equations for the degradation of web capacity due to the web openings. Of the two reduction factor equations developed (Eqs. 19 and 20) Equation 19 provided the best statistical results. Equation 19 was also compared to the reduction factor equation (Eq. 7) developed by Langan, LaBoube, and Yu (1994) which resulted in Equation 19 again providing the best statistical analysis results. To determine the web crippling capacity for sections with web openings, the reduction factor equation may be applied to the AISI Specification web crippling equations (Eq. 13 thru 16). The design parameters must satisfy the limits of applicability given in Section III.H.2.

The reduction factor equation (Eq. 19) is a function of the $\alpha$ and $a/h$ values of the design situation in question. A range of $\alpha$ and $a/h$ has been identified in which no web crippling capacity reduction is necessary. The incorporation of the reduction factor equation can easily be implemented into standard practice to ensure that the reduced web crippling capacity be taken into consideration. The application of the reduction factor equation ensures that adequate strength and serviceability is achieved for sections with web openings. Limit states such as shear, flexure, combined bending and web crippling, etc... should be checked independently of the web crippling limit state.

# V. FUTURE RESEARCH

Future studies 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 end-one-flange loading condition. Also, only single web sections with the web hole located at mid-height of the section were considered. Future studies may include:

1. Two-flange loading condition
2. Different shapes of single web sections other than C-sections
3. Multiple web sections
4. Closely spaced holes or holes of different shapes
5. Holes not located at mid-height of the web

**Table I-A.** Cross-Sectional Properties for End-One-Flange Test Specimens

| Specimen | D (in) | R (in) | t (in) | h (in) | B (in) | $d_f$ (in) | a (in) | $F_y$ (in) | h/t | a/h | R/t | N/t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EOF-C8-16-0-0-1 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | solid | 56.8 | 132.1 | ---- | 3.918 | 17.889 |
| EOF-C8-16-0-0-2 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | solid | 56.8 | 132.1 | ---- | 3.918 | 17.889 |
| EOF-C8-16-0-0-3 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | solid | 56.8 | 132.1 | ---- | 3.918 | 17.889 |
| EOF-C8-16-0-0-4 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | solid | 56.8 | 132.1 | ---- | 3.918 | 17.889 |
| EOF-C8-16-0-2-1 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 2 | 56.8 | 132.1 | 0.271 | 3.918 | 17.889 |
| EOF-C8-16-0-2-2 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 2 | 56.8 | 132.1 | 0.271 | 3.918 | 17.889 |
| EOF-C8-16-0-2-3 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 2 | 56.8 | 132.1 | 0.271 | 3.918 | 17.889 |
| EOF-C8-16-0-2-4 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 2 | 56.8 | 132.1 | 0.271 | 3.918 | 17.889 |
| EOF-C8-16-1-2-1 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 2 | 56.8 | 132.1 | 0.271 | 3.918 | 17.889 |
| EOF-C8-16-1-2-2 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 2 | 56.8 | 132.1 | 0.271 | 3.918 | 17.889 |
| EOF-C8-16-0-4-1 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 4 | 56.8 | 132.1 | 0.541 | 3.918 | 17.889 |
| EOF-C8-16-0-4-2 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 4 | 56.8 | 132.1 | 0.541 | 3.918 | 17.889 |

**Table II-A.** Cross-Sectional Properties for End-One-Flange Test Specimens

| Specimen | D (in) | R (in) | t (in) | h (in) | B (in) | $d_f$ (in) | a (in) | $F_y$ (in) | h/t | a/h | R/t | N/t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EOF-C8-16-0-4-3 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 4 | 56.8 | 132.1 | 0.541 | 3.918 | 17.889 |
| EOF-C8-16-1-4-1 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 4 | 56.8 | 132.1 | 0.541 | 3.918 | 17.889 |
| EOF-C8-16-1-4-2 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 4 | 56.8 | 132.1 | 0.541 | 3.918 | 17.889 |
| EOF-C8-16-0-6-1 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 6 | 56.8 | 132.1 | 0.812 | 3.918 | 17.889 |
| EOF-C8-16-0-6-2 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 6 | 56.8 | 132.1 | 0.812 | 3.918 | 17.889 |
| EOF-C8-16-1-6-1 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 6 | 56.8 | 132.1 | 0.812 | 3.918 | 17.889 |
| EOF-C8-16-1-6-2 | 7.938 | 0.219 | 0.056 | 7.388 | 1.625 | 0.438 | 6 | 56.8 | 132.1 | 0.812 | 3.918 | 17.889 |
| EOF-C8-20-0-0-1 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | solid | 47 | 224.1 | ---- | 5.134 | 29.851 |
| EOF-C8-20-0-0-2 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | solid | 47 | 224.1 | ---- | 5.134 | 29.851 |
| EOF-C8-20-0-2-1 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 2 | 47 | 224.1 | 0.266 | 5.134 | 29.851 |
| EOF-C8-20-0-2-2 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 2 | 47 | 224.1 | 0.266 | 5.134 | 29.851 |
| EOF-C8-20-1-2-1 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 2 | 47 | 224.1 | 0.266 | 5.134 | 29.851 |

**Table III-A.** Cross-Sectional Properties for End-One-Flange Test Specimens

| Specimen | D (in) | R (in) | t (in) | h (in) | B (in) | $d_f$ (in) | a (in) | $F_y$ (in) | h/t | a/h | R/t | N/t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EOF-C8-20-1-2-2 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 2 | 47 | 224.1 | 0.266 | 5.134 | 29.851 |
| EOF-C8-20-0-4-1 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 4 | 47 | 224.1 | 0.533 | 5.134 | 29.851 |
| EOF-C8-20-0-4-2 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 4 | 47 | 224.1 | 0.533 | 5.134 | 29.851 |
| EOF-C8-20-1-4-1 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 4 | 47 | 224.1 | 0.533 | 5.134 | 29.851 |
| EOF-C8-20-1-4-2 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 4 | 47 | 224.1 | 0.533 | 5.134 | 29.851 |
| EOF-C8-20-0-6-1 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 6 | 47 | 224.1 | 0.799 | 5.134 | 29.851 |
| EOF-C8-20-0-6-2 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 6 | 47 | 224.1 | 0.799 | 5.134 | 29.851 |
| EOF-C8-20-1-6-1 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 6 | 47 | 224.1 | 0.799 | 5.134 | 29.851 |
| EOF-C8-20-1-6-2 | 7.920 | 0.172 | 0.034 | 7.509 | 1.650 | 0.500 | 6 | 47 | 224.1 | 0.799 | 5.134 | 29.851 |

**Table IV-A.** Cross-Sectional Properties for End-One-Flange Test Specimens

| **Specimen** | **D (in)** | **R (in)** | **t (in)** | **h (in)** | **B (in)** | **$d_f$ (in)** | **a (in)** | **$F_y$ (in)** | **h/t** | **a/h** | **R/t** | **N/t** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EOF-C6-16-0-0-1 | 6.017 | 0.188 | 0.056 | 7.388 | 1.625 | 0.438 | solid | 56.8 | 98.39 | ---- | 3.336 | 17.794 |
| EOF-C6-16-0-0-2 | 6.017 | 0.188 | 0.056 | 7.388 | 1.625 | 0.438 | solid | 56.8 | 98.39 | ---- | 3.336 | 17 794 |
| EOF-C6-16-0-2-1 | 6.017 | 0.188 | 0.056 | 7.388 | 1.625 | 0.438 | 2 | 56.8 | 98.39 | 0.362 | 3.336 | 17.794 |
| EOF-C6-16-0-2-2 | 6.017 | 0.188 | 0.056 | 7.388 | 1.625 | 0.438 | 2 | 56.8 | 98.39 | 0.362 | 3.336 | 17.794 |
| EOF-C6-16-1-2-1 | 6.017 | 0.188 | 0.056 | 7.388 | 1.625 | 0.438 | 2 | 56.8 | 98.39 | 0.362 | 3.336 | 17.794 |
| EOF-C6-16-1-2-2 | 6.017 | 0.188 | 0.056 | 7.388 | 1.625 | 0.438 | 2 | 56.8 | 98.39 | 0.362 | 3.336 | 17.794 |
| EOF-C6-16-0-4-1 | 6.017 | 0.188 | 0.056 | 7.388 | 1.625 | 0.438 | 4 | 56.8 | 98.39 | 0.362 | 3.336 | 17.794 |
| EOF-C6-16-0-4-2 | 6.017 | 0.188 | 0.033 | 7.509 | 1.625 | 0.438 | 4 | 56.8 | 98.39 | 0.723 | 3.336 | 17.794 |
| EOF-C6-16-1-4-1 | 6.017 | 0.188 | 0.033 | 7.509 | 1.625 | 0.438 | 4 | 56.8 | 98.39 | 0.723 | 3.336 | 17.794 |
| EOF-C6-16-1-4-2 | 6.017 | 0.188 | 0.033 | 7.509 | 1.625 | 0.438 | 4 | 56.8 | 98.39 | 0.723 | 3.336 | 17.794 |
| EOF-C6-20-0-0-1 | 5.961 | 0.172 | 0.033 | 7.509 | 1.625 | 0.438 | solid | 50.5 | 169.8 | ---- | 5.256 | 30.581 |
| EOF-C6-20-0-0-2 | 5.961 | 0.172 | 0.033 | 7.509 | 1.625 | 0.438 | solid | 50.5 | 169.8 | ---- | 5.256 | 30.581 |

**Table V-A.** Cross-Sectional Properties for End-One-Flange Test Specimens

| Specimen | D (in) | R (in) | t (in) | h (in) | B (in) | $d_f$ (in) | a (in) | $F_y$ (in) | h/t | a/h | R/t | N/t |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EOF-C6-20-0-0-3 | 5.961 | 0.172 | 0.033 | 5.552 | 1.625 | 0.438 | solid | 50.5 | 169.78 | ---- | 3.336 | 17.794 |
| EOF-C6-20-0-2-1 | 5.961 | 0.172 | 0.033 | 5.552 | 1.625 | 0.438 | 2 | 50.5 | 169.78 | 0.360 | 3.336 | 17 794 |
| EOF-C6-20-0-2-2 | 5.961 | 0.172 | 0.033 | 5.552 | 1.625 | 0.438 | 2 | 50.5 | 169.78 | 0.360 | 3.336 | 17.794 |
| EOF-C6-20-1-2-1 | 5.961 | 0.172 | 0.033 | 5.552 | 1.625 | 0.438 | 2 | 50.5 | 169.78 | 0.360 | 3.336 | 17.794 |
| EOF-C6-20-1-2-2 | 5.961 | 0.172 | 0.033 | 5.552 | 1.625 | 0.438 | 2 | 50.5 | 169.78 | 0.360 | 3.336 | 17.794 |
| EOF-C6-20-0-4-1 | 5.961 | 0.172 | 0.033 | 5.552 | 1.625 | 0.438 | 4 | 50.5 | 169.78 | 0.720 | 3.336 | 17.794 |
| EOF-C6-20-0-4-2 | 5.961 | 0.172 | 0.033 | 5.552 | 1.625 | 0.438 | 4 | 50.5 | 169.78 | 0.720 | 3.336 | 17.794 |
| EOF-C6-20-0-4-3 | 5.961 | 0.172 | 0.033 | 5.552 | 1.625 | 0.438 | 4 | 50.5 | 169.78 | 0.720 | 3.336 | 17.794 |
| EOF-C6-20-1-4-1 | 5.961 | 0.172 | 0.033 | 5.552 | 1.625 | 0.438 | 4 | 50.5 | 169.78 | 0.720 | 3.336 | 17.794 |
| EOF-C6-20-1-4-2 | 5.961 | 0.172 | 0.033 | 5.552 | 1.625 | 0.438 | 4 | 50.5 | 169.78 | 0.720 | 3.336 | 17.794 |

# BIBLIOGRAPHY

American Iron and Steel Institute, AISI, (1986), "Cold-Formed Steel Design Manual: Specification for the Design of Cold-Formed Steel Structural Members", August 19, 1986, 1989 Adendum.

American Iron and Steel Institute, AISI, (1991a), "Load and Resistance Factor Design Specification fo Cold-Formed Steel Design".

American Institute of Steel Construciton, AISC, (1990), "Steel Design Guide Series: Steel and Composite Beams with Web Openings".

Chan, P.W., and R.G. Redwood, (1974), "Stresses in Beams with Circular Eccentric Web Holes", Journal of the Structural Division, Vol. 100, No. ST1, January 1974, Americna Society of Civil Engineers.

Deshmukh, S. U., "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," A thesis presented to the faculty of the University of Missouri-Rolla in partial fulfillment of the requirements for the degree Master Science in Civil Engineering.

Hetrakul, N., and W.W. Yu, (1978), "Structural Behavior of Beam Webs Subjected to Web Crippling and a Combination of Web Crippling and Bending", Final Report, Civil Engineering Study 78-4, University of Missouri-Rolla, June 1978.

LaBoube, R.A., (1990a), "Design Guidelines for Web Elements with Web Openings", Civil Engineerning Department, University of Missouri-Rolla, July 16, 1990.

Langan, J.E., R.A. LaBoube, and W.W. Yu, (1994), "Structural Behavior of Perforated Web Elements of Cold-Formed Steel Flexural Members Subjected to web Crippling and a Combination of Web Crippling and Bending", PhD Dissertation, University of Missouri-Rolla

Narayanan, R., and F.Y. Chow, (1984), "Ultimate Capacity of Uniaxially Compressed Perforated Plates", contained in publication titled. "Thin-Walled Structures" Vol.2 No. 3, Elsevier Science Publishers Ltd., Great Britain.

Redwood, R.G., H. Baranda, and M.J. Daly, (1978), "Tests of Thin-webbed Beams with Unreinforced Holes", Journal of the Structural Division, Vol. 104, No. ST3, March 1978, American Society of Civil Engineers.

Redwood, R.G., and M. Uenoya, (1979), "Critical Loads for Webs with Holes", Journal of the Structural Division, Vol105, No, ST10, October 1979, American Society of Civil Engineers.

Redwood, R.G., and S.C. Shrivastava, (1980), "Design Recommendations for Steel Beams with Web Holes", Canadian Journal of Civil Engineering, 7: No. 4, pp. 642-650, December 1980.

Santaputra, C., and W.W. Yu, (1986), "Design of Automotive Structural Components Using High Strength Sheet Steels (and) Web Crippling of Cold-Formed Steel Beams", Eighth Progress Report, Civil Engineering Study 86-1, University of Missouri-Rolla, August 1986.

Santaputra, C., M.B. Parks, and Yu, (1986), "Web-Crippling Strength of Cold-Formed Steel Beams", Journal of the Structural Division, Vol. 115, Bo. 10, October 1989, American Society of Civil Engineers.

Sivakumaran, K.S., and K.M. Zielonka, (1989), "Web Crippling Strength of Thin-Walled Steel Members with Web Opeings", contained in publication titled, "Thin-Walled Structures", Elsevier Science Publishers Ltd., Great Britain.

Stiemer, S.F., and H.G.L. Prion, (1990), "Plastic Buckling Capacity of Square Shear Plates with Circular Perforations", Annual Technical Session, Structural Stability research Council, pp. 231-240.

Winter, G., and R.H.J. Pian, (1946), "Crushing Strength of Thin Steel Webs", Cornell bulletin 35, pt. 1, April 1946.

Yu, W.W., and C.S. Davis, (1973), "Cold-Formed Steel Members with Perforated Elements", Journal of the Structural Division, Vol 99, No. ST10, October 1973, American Society of Civil Engineers.

Yu, W.W., (1991), Cold-Formed Steel Design: 2nd Ed., John Wiley and Sons, Inc.

Zetlin, L., (1955), "Elastic Instability of Flat Plates Subjected to Partial Edge Loads", Journal of the Structural Division, Vol. 81, September 1955, American Society of Civil Engineers