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Behavior of web elements with openings subjected to linearly varying shear

Matthew R. Eiler

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

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

Civil Engineering Study 97-5
Cold-Formed Steel Series

Final Report

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PREFACE

An experimental investigation of the shear buckling limit state was conducted on single web, cold-formed steel flexural members with web openings. The purpose of the investigation was to develop a better understanding of the behavior of web elements having a web opening, and to propose appropriate design recommendations based on the observed behavior. The present AISI ASD and LRFD specifications do not contain design provisions for webs with openings, thus the findings of this study will aid in enhancing the shear design provisions.

The test specimens, constructed from C-sections, were subjected to linearly varying shear resulting from the application of a uniform load. Test data from this investigation was combined with previous test data which was based on test specimens subjected to a constant shear. Three hole geometries, rectangular with corner fillets, circular, and diamond, were represented by the available test data. All openings were centered at mid-depth of the web.

Based on the findings of this study, it was concluded that the slenderness ratio of the web element above or below the opening was dominant parameter influencing the shear behavior. It was also discovered that the distribution of the shear across the opening affected the shear capacity of the web.

Based on the findings and conclusions obtained from the experimental investigations, a design expression was developed. The design expression recognizes the reduction in shear capacity of a web when an opening is present in the web.

This report is based on a thesis presented to the faculty of the University of Missouri-Rolla in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering.

The report was prepared for the AISI Committee on Specifications for the Design of Cold-Formed Steel Structural Members. The investigation was sponsored by the American Iron and Steel Institute (AISI). The technical guidance provided by the AISI Stud Design; Perforated Elements Subcommittee is acknowledged. The Subcommittee members are: E. R. Estes, Jr. (Chairman), F. M. Bolio, R. E. Brown, C. R. Clauer, E. R. diGirolamo, L. Hernandez, W. Guiher, J. Klaiman, R. A. LaBoube, R. Madsen, J. P. Matsen, W. R. Midgley, T. H. Miller, K. T. Niu, T. B. Pekoz, C. W. Pinkham, G. S. Ralph, V. Sagan, R. J. Schrader, R. M. Schuster, T. W. Trestain, S. Walker, R. Zadeh. Thanks are also extended to D. F. Boring, R. B. Haws, H. Chen, K. C. Slaughter, and S. P.Bridgewater, AISI staff.

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I. INTRODUCTION

A. GENERAL

Cold-formed steel has been used in light-industrial construction for many years and has become economically viable in residential construction due to increases in the cost of wood during the past decade. In addition to economic benefits, cold-formed steel has many advantages over other building materials. Some of the engineering advantages include its high strength-to-weight ratio, consistent cross-sectional properties, economy in transportation, and easy erection and installation. Other advantages of cold-formed steel are that it is recyclable, rot proof, termite proof, and non-combustible.

Typical applications for cold-formed steel members in both commercial and residential construction include exterior wall framing studs and floor joists. The use of pre-punched holes in these members to allow for installation of utilities and bracing requirements has been common industry practice. Since the size and position of these holes are standardized, it is often necessary to enlarge the existing holes or create new holes. Although structural elements containing web holes are widely employed, only a small amount of information is available for the design and analysis of the web element.

The first design standard for cold-formed steel members was the "Specification for the Design of Light Gage Steel Structural Members" which was published by the American Iron and Steel Institute (AISI) in 1946 (1). The specification has been revised several times and each subsequent edition incorporates the findings of research studies and industry experience. The current AISI Specifications do not have complete design provisions for webs having holes or punchouts and therefore the load-carrying capacity of flexural members with web holes must be either determined experimentally or by a rational analysis.

B. PURPOSE OF INVESTIGATION

The main purpose of this experimental investigation was to study the structural behavior of cold-formed steel web elements with holes subjected to shear. Both constant shear and linear variation in shear were considered in the study. The research has developed new design equations which are based on modifications of current design equations in the AISI Specification.

C. SCOPE OF INVESTIGATION

This study consisted of experimental and analytical investigations of the structural behavior of cold-formed steel C-sections with web holes subjected to either a constant shear or a linearly varying shear.

Available literature and research reports relating to beam members with web holes and current cold-formed steel design specification have been studied. A summary of the literature review and current design criteria is given in Section II.

The shear behavior of web elements with holes is discussed in Section III. This section contains the experimental test setup and test procedure for each beam specimen. Parameter ranges for the current investigation and the other pertinent data are given. The experimental results and comparisons of tested and theoretical values computed by using the AISI LRFD Specification are presented. Shear reduction factors for C-section members with web holes are developed and compared with reduction factors reported in the literature. Finally, a summary and design recommendations are presented.

Section IV includes conclusions and Section V includes topics for further study.

II. REVIEW OF LITERATURE

A. GENERAL

A survey of literature was conducted to review previous works relative to the ultimate strength of cold-formed steel sections with web openings subjected to shear. Design recommendations of the most recent studies are summarized.

B. INVESTIGATION OF SHEAR BEHAVIOR IN PLATES AND PLATE GIRDERS

A review of the research work involving the effects of openings on the behavior of thin-walled elements in steel structures was performed by Shanmugam (2). This paper summarizes pertinent research performed on plate elements with holes subjected to either uniaxial compression, biaxial compression or shear loading. The stated research includes stiffened plates, shear webs and cold-formed steel sections.

The effect of centrally located circular holes in square plates subjected to shear was studied by Rockey et al. (3) using the finite element method. It was found that the critical shear buckling coefficient is reduced by the presence of openings. Relationships for the reduction of the shear buckling coefficients were developed based on the ratio of hole diameter to the plate width and the plate support conditions.

Based on 366 tests on steel and aluminum girders subjected primarily to shear, Hoglund (4) summarized comparisons and presented modified design methods for the shear buckling resistance of plate girders with web holes.

Procedures for determining the strength of steel and composite beams with web openings are presented in a supplemental reference guide to the AISC Manual of Steel Construction (5). The procedures contained in this guide are based on research reports and recognized engineering principles. The equations presented for shear strength may be used to calculate the maximum shear strength of steel and composite members constructed with compact steel sections containing rectangular or circular web openings.

C. INVESTIGATION OF SHEAR BEHAVIOR IN COLD-FORMED STEEL WEB ELEMENTS

1. Solid Webs. Prior to 1978 there was no experimental work conducted on cold-formed steel webs subjected primarily to shear. The AISI design criteria for shear had been adopted from the AISC Specification for the sake of uniformity (6). LaBoube (6) investigated the validity of the theoretical equations, and the acceptance of the AISC equations in the AISI provisions for solid web elements in shear are based on this study.

2. Webs with Holes. The exact analysis and the design of web elements with holes are complex with the load-carrying capacity of the members usually governed by the buckling behavior and the postbuckling strength of the component elements (7).

The first tests performed on cold-formed steel web elements with holes subjected primarily to shear were conducted at the University of Missouri-Rolla (UMR) by Shan (8) in 1994. In this investigation, a total of 26 beam specimens ranging in depth from 2.5 to 12 inches were tested. The web holes were rectangular with filleted corners (elliptical) having a dimension of 0.75 x 4.0 inch or 1.5 x 4.0 inch. The beams were tested as simply supported with a point load at mid-span (constant shear). Both reinforced and unreinforced webs were included in the study.

Shan found that the major parameter influencing the shear strength was the ratio of the depth of hole to the flat depth of the web, a/h. It was also determined that the flat depth of the web to the thickness, h/t, influenced the shear strength to a lesser extent. Based on the experimental data, Shan developed both a linear reduction factor and a non-linear reduction factor which emphasized the parameter a/h. These shear perforation reduction factors, q_s, are as follows:

Linear shear reduction factor:

when $a/h \leq 0.383$

$$q_s = 1.711 - 3.661(a/h) \leq 1.000 \tag{1}$$

when $0.383 < a/h \leq 1.000$

$$q_s = 0.456 - 0.377(a/h) \tag{2}$$

Non-linear shear reduction factor:

$$q_s = 1.506 \cdot 10^{[-1.33(a/h)]} \leq 1.000 \tag{3}$$

These reduction factors were developed by defining $q_s = P_{u(test)}/V_n$ and plotting q_s versus a/h for the test data, where $P_{u(test)}$ was the test shear per web element and V_n was the calculated nominal shear resistance per web element in accordance with Section C3.2 of the 1991 AISI LRFD Specification (9).

Schuster (10), at the University of Waterloo, tested 13 beam specimens with web holes. In this test program the depth of the hole was varied from 1.5 to 6 inches and elliptical, diamond, and circular shaped geometries were considered (Fig. 1). The depths of the webs used in the test program were 8 inches for specimens with elliptical holes, 6 inches for

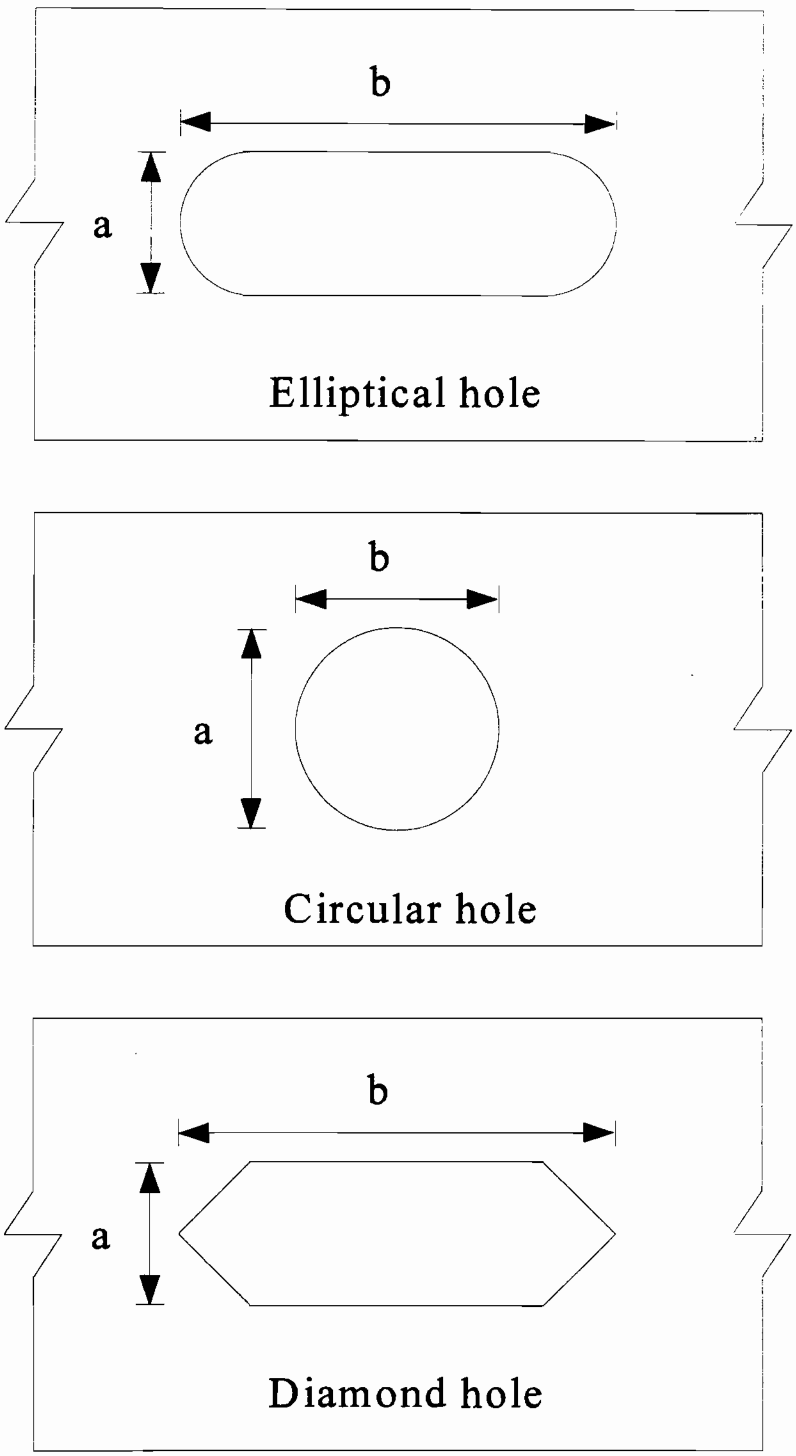

Figure 1 Hole Geometries and Dimensions

specimens with diamond shaped holes, and 3.625 inches for specimens with circular holes. The beams were tested as simply supported with a point load at mid-span (constant shear). The University of Waterloo test data was combined with the Shan data and analyzed. A reduction factor involving the slenderness ratio of the web element above or below the opening, c/t, was developed. This c/t ratio had been observed by Redwood (11) as having an important influence on the behavior of hot rolled beam members with holes. Based on the available data, Schuster proposed the following expression for q_s:

$$q_s = \frac{(c/t)}{60} \tag{4}$$

Where c is the flat web distance above or below the opening:

$$c = \frac{h}{2} - \frac{a}{2} \tag{5}$$

D. CURRENT DESIGN CRITERIA

The current AISI cold-formed steel design criteria does not contain provisions for webs with openings subjected to shear. The design strength for solid web elements subjected to shear alone can be estimated by applying the equations from Section C3.2 of the 1991 Edition of the AISI LRFD Specification (9). These nominal equations also serve as the basis for the shear strength equations given in the AISI ASD Specification (12). The shear force at any section shall not exceed the nominal shear, V_n, calculated as follows:

(a). For $h/t \leq [(E\,k_v)/F_y]^{0.5}$:

$$V_n = 0.557\, F_y\, h\, t \tag{6}$$

(b). For $[(E\,k_v) / F_y]^{0.5} < h/t \leq 1.415\,[(E\,k_v) / F_y]^{0.5}$:

$$V_n = 0.64\ t^2 \sqrt{k_v\ F_y\ E} \tag{7}$$

(c). For $h/t > 1.415\,[(E\,k_v) / F_y]^{0.5}$:

$$V_n = 0.905\ E\ k_v\ t^3/h \tag{8}$$

where

V_n = Nominal shear strength of beam

t = Web thickness

h = Depth of the flat portion of the web measured along the plane of the web

k_v = Shear buckling coefficient determined as follows:

1. For unreinforced webs, $k_v = 5.34$

2. For beam webs with transverse stiffeners satisfying the requirements of Section B6

when $a'/h \leq 1.0$

$$k_v = 4.00 + \frac{5.34}{(a'/h)^2} \tag{9}$$

when $a'/h > 1.0$

$$k_v = 5.34 + \frac{4.00}{(a'/h)^2} \tag{10}$$

where

a′ = the shear panel length for unreinforced web element
= distance between transverse stiffeners for reinforced web elements.

III. SHEAR BEHAVIOR OF WEB ELEMENTS WITH OPENINGS

A. GENERAL

The purpose of this research has been to investigate the behavior of a single web with openings when subjected to a linearly varying shear force produced by a uniform load. UMR tests were performed on C-shaped members with elliptical or circular web openings. This data was combined with data from previous research by Shan (8) and Schuster (10) conducted on C-shaped members with web openings subjected to a constant shear force. The results have been analyzed and evaluated to develop a load reduction factor for the shear behavior of C-section members with web openings located at mid-height of the web.

This section is concerned with the test procedure, test results, and the analysis of the results for this study. The analysis was broken into two parts, the analysis of the behavior of beams with web openings subjected to a varying shear under a uniform load, and the analysis of the combined data. The results of the investigation are summarized, and design equations have been developed based on the combined data and are presented herein.

B. EXPERIMENTAL STUDY

The objective for this experimental investigation was to determine the strength of a beam with a web hole subjected primarily to shear, and to develop shear reduction equations applicable for design. The shear strength for beams with web holes was determined experimentally and compared to the computed shear strength of beam webs as determined by the theoretical equations given by the AISI Specification (9) for solid webs. Parameters evaluated in determining the reduction of shear strength of a solid web due to the presence of a hole were the slenderness ratio of the web, h/t, the ratio of web hole depth to the depth of web, a/h, and the ratio of the web depth above or below the hole to the thickness, c/t. These parameters have been found in previous research studies to have some effect on the shear strength of webs with holes. In addition to these parameters, the ratio of the shear at each edge of the hole, V1/V2, and the geometry of the hole, b/a, have been evaluated. The experimental results are also compared to shear reduction equations derived from previous research.

A total of 46 beam specimens were completed in this study. The 26 beam specimens with 3.625 inch depths had 4 x 1.5 inch standard web holes located at mid-height of the web. For the 6 inch deep specimens, 10 specimens had 4 x 1.5 inch standard web holes and 10 specimens had 4 inch diameter circular web holes located at mid-height of the web.

The range of parameters considered in the beam test specimens performed in this test program are given as follows:

$c/t = 15.6$ to 36.6

$c_1/t = 15.6$ to 43.5

$h/t = 58.5$ to 172.7

$a/h = 0.268$ to 0.702

$V1/V2 = 1.21$ to 3.00

$F_y = 42$ to 57 ksi

1. <u>Preparation of Beam Specimens.</u> Industry standard C-sections (3.625 and 6 inches deep) with various thicknesses were tested. The cross-section dimensions, thickness, and geometric parameters of the C-sections are recorded in Table I. When thin steel beam members with web holes are subjected to a uniform load, three failure modes may occur:

bending, shear, or web crippling. The influence of bending was minimized by using members with short span lengths. A span length, L, of 25 inches was used for the 3.625 inch deep specimens, and a span length of 50 inches was used for the 6 inch deep specimens.

TABLE I DIMENSIONS OF TEST SPECIMENS

	Cross-Section Dimensions			Hole Geometry	
Specimen No.	Thickness, t (in.)	Depth, h (in.)	Radius (in.)	a (in.)	b (in.)
C3-16	0.055	3.63	0.188	1.5	4.0
C3-18	0.043	3.63	0.172	1.5	4.0
C3-20	0.033	3.63	0.203	1.5	4.0
C6-16	0.056	6.00	0.203	1.5	4.0
C6-20	0.033	5.95	0.125	4.0	4.0

Notes: 1. See Figure 2 for the symbols used for the hole geometry.
2. See Figure 3 for the symbols used for cross-section dimensions.

To prevent web crippling from occurring at the end reactions, stiffeners were placed vertically at the end of each member and attached with self-drilling screws. The screws were located below mid-height of the web to minimize the stiffener effect on the shear strength.

Each test specimen consisted of two C-sections connected together to form a box-beam. A 0.5 inch thick by 6 inch wide piece of plywood was attached to the top flange of each C-section with self-drilling screws at approximately 6 inch spacing along the length of the specimen. The bottom flanges were connected together using 3/4 x 3/4 x 1/8 inch aluminum angles and self-drilling screws. To provide additional lateral support for the 6 inch specimens, diagonal braces were connected to the end stiffeners. For fabrication details, see Figures 2 and 3.

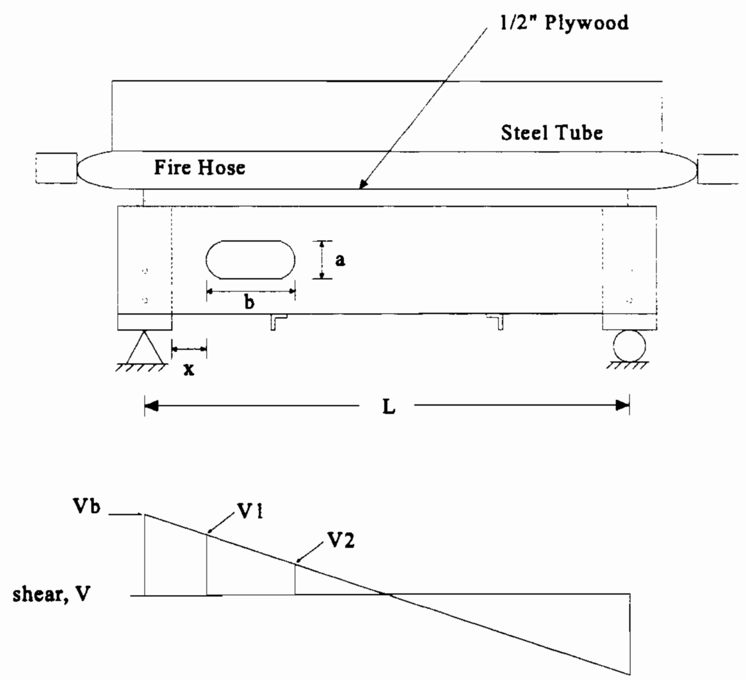

Figure 2 Test Setup for Shear Test Specimens

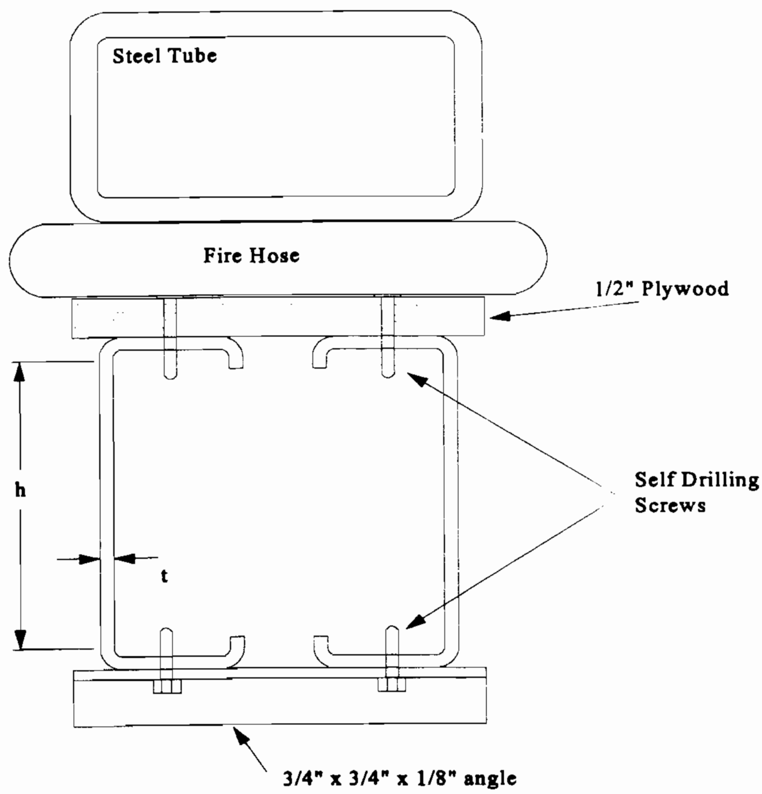

Figure 3 Cross Section of Shear Test Specimens

To achieve a uniform load it was necessary to use a flexible material that would deform with the specimen. The use of a fire hose partially filled with water provided the flexibility needed to distribute the load uniformly along the length of the specimen. However, the fire hose could not be placed directly on top of the flanges of the C-sections. Therefore, plywood was used to stabilize the top flanges of the C-sections and to distribute the load from the fire hose to the specimens. The use of plywood is validated since typical wall and floor systems consist of a plywood sheathing or other load transferring sheathing. Based on pilot tests, it was found that the plywood had minimal effect on the shear capacity of the specimens. This was verified by testing a specimen with 2 inch strips of plywood spaced with a 1/4 inch gap so that the plywood was not continuous along the length of the specimen and comparing the ultimate capacity with that of a specimen with continuous plywood along the length. The ultimate capacity of the specimen with continuous plywood was 125 pounds greater than the specimen with strips of plywood. However, the percent difference between the two specimens was only 2.7 % and was within the limits of experimental error.

2. Testing of Specimens

a. Tensile Coupon Tests. The material properties of the steel were established by standard tensile coupon specimens cut from the web element of the section. The coupons were tested in a 150,000 pound Tinius-Olsen universal testing machine which was linked to the computer software package Labtech Notebook. The average material property values obtained for each material from the coupon tests were used in the analysis of the data. Table II lists the tensile test data for thickness, yield strength (F_y), ultimate tensile strength (F_u) and percent elongation in 2 inches gage length.

TABLE II MATERIAL PROPERTIES FOR SHEAR TEST SPECIMENS

Specimen No.	Thickness (in.)	F_y (ksi)	F_u (ksi)	Elongation (%)
C3-16	0.055	55.5	68.5	32.5
C3-18	0.043	43.0	62.0	42.5
C3-20	0.033	42.5	57.5	25.5
C6-16	0.056	56.8	69.4	40.8
C6-20	0.033	50.5	55.3	38.2

b. <u>Testing of Beam Specimens.</u> All test specimens were tested in a Tinius-Olsen universal testing machine as simple supported beams subjected to a uniform load. Rollers and 3 inch bearing plates were placed at each end of the beam. A 4 inch diameter fire hose partially filled with water and clamped at each end was placed on top of the plywood. A 4 x 6 x 1/4 inch steel tube was placed on top of the fire hose to distribute the load from the testing machine to the hose. Support was provided to the six inch specimens to prevent lateral movement by extending the plywood between the supports of the testing machine. The load was increased gradually until the beam reached failure and could no longer bear additional load.

Figure 4 shows a completed beam specimen in the testing apparatus with applied load. For each cross-section, the distance of the web hole from the bearing plate, x, (Figure 2) was increased by one inch increments.

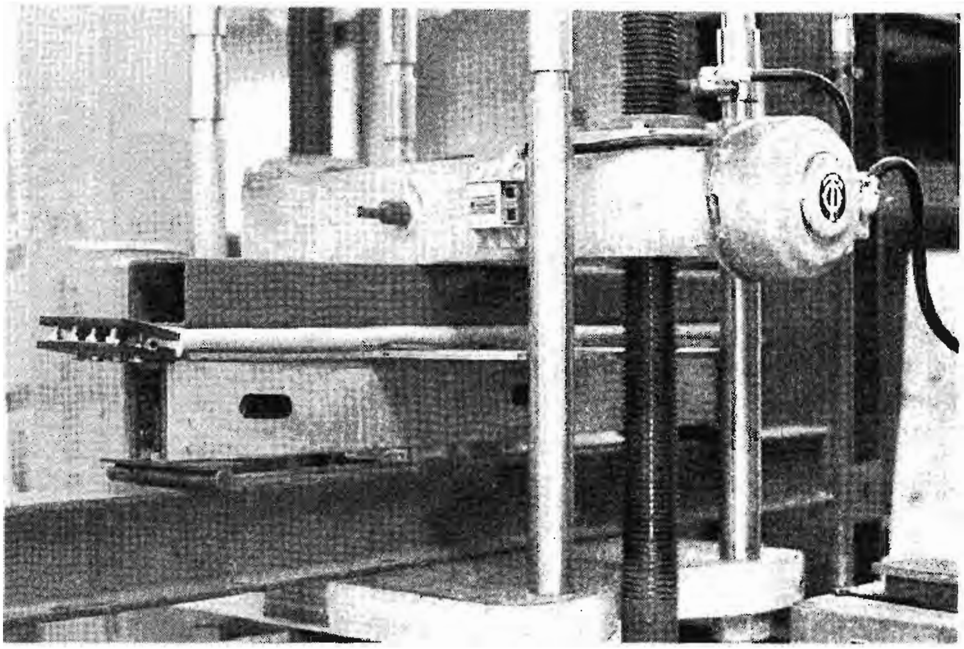

Figure 4 Beam Test Specimen with Applied Load

3. Test Results. Forty-six tests of beams with web holes were conducted in this experimental investigation. Table III lists the test results.

TABLE III EVALUATION OF SHEAR TEST DATA

Specimen No.	V1 (lbs)	V2 (lbs)	V1/V2	V_b (lbs)	V_n (lbs)	V_b/V_n
C3-18-0-1	1287	819	1.57	1463	3155	0.47
C3-18-0-2	1276	812	1.57	1450	3155	0.47
C3-18-1-1	1135	681	1.67	1419	3155	0.46
C3-18-1-2	1195	717	1.67	1494	3155	0.48
C3-18-2-1	1107	615	1.80	1538	3155	0.49
C3-18-2-2	1067	593	1.80	1481	3155	0.48
C3-18-3-1	960	480	2.00	1500	3155	0.48
C3-18-3-2	996	498	2.00	1556	3155	0.50

TABLE III (CONTINUED) EVALUATION OF SHEAR TEST DATA

Specimen No.	V1 (lbs)	V2 (lbs)	V1/V2	V_b (lbs)	V_n (lbs)	V_b/V_n
C3-18-4-1	903	387	2.33	1613	3155	0.52
C3-18-4-2	879	377	2.33	1569	3155	0.50
C3-18-5-1	762	254	3.00	1588	3155	0.51
C3-20-0-1	897	571	1.57	1019	1561	0.65
C3-20-0-2	913	581	1.57	1038	1561	0.66
C3-20-1-1	830	498	1.67	1038	1561	0.66
C3-20-1-2	810	486	1.67	1013	1561	0.65
C3-20-2-1	698	388	1.80	969	1561	0.62
C3-20-2-2	684	380	1.80	950	1561	0.61
C3-20-3-1	588	294	2.00	919	1561	0.59
C3-16-0-1	2178	1386	1.57	2475	5699	0.43
C3-16-1-2	2130	1278	1.67	2663	5699	0.47
C3-16-2-1	2016	1120	1.80	2800	5699	0.49
C3-16-2-2	1926	1070	1.80	2675	5699	0.47
C3-16-3-1	1832	916	2.00	2863	5699	0.50
C3-16-3-2	1776	888	2.00	2775	5699	0.49
C6-16-0-1	3901	3237	1.21	4150	4476	0.93
C6-16-0-2	3836	3183	1.21	4081	4476	0.91
C6-16-1-1	3763	3094	1.22	4181	4476	0.93
C6-16-1-2	3780	3108	1.22	4200	4476	0.94
C6-16-2-1	3488	2839	1.23	4056	4476	0.91
C6-16-2-2	3601	2931	1.23	4188	4476	0.94
C6-16-3-1	3270	2632	1.24	3988	4476	0.89
C6-16-3-2	3075	2475	1.24	3750	4476	0.84
C6-16-3-3	3034	2442	1.24	3700	4476	0.83

TABLE III (CONTINUED) EVALUATION OF SHEAR TEST DATA

Specimen No.	V1 (lbs)	V2 (lbs)	V1/V2	V_b (lbs)	V_n (lbs)	V_b/V_n
C6-16-4-1	3120	2480	1.26	4000	4476	0.89
C6-20-0-1	1011	839	1.21	1075	899	1.20
C6-20-0-2	940	780	1.21	1000	899	1.11
C6-20-1-1	849	698	1.22	944	899	1.05
C6-20-1-2	917	754	1.22	1019	899	1.13
C6-20-2-1	849	691	1.23	988	899	1.10
C6-20-2-2	790	643	1.23	919	899	1.02
C6-20-3-1	779	627	1.24	950	899	1.06
C6-20-3-2	789	635	1.24	963	899	1.07
C6-20-4-1	746	593	1.26	956	899	1.06
C6-20-5-1	689	540	1.28	931	899	1.04

The maximum distance of the hole from the bearing, x, (Figure 2) for each specimen, was determined by observing the failure mode. At increased x values, a combined failure mode would develop. Initially a shear buckle formed at the location of V1. With increased load, at the mid-span side of the hole, V2 location, instead of a shear buckle developing, a crease would develop and continue up to the top of the web above the end bearing stiffener. A similar failure mode has been found to occur in aluminum plate girders without intermediate stiffeners when subjected to a uniform load or closely spaced point loads (3). This failure mode had not been seen in the previous research by Shan or Schuster. This mode was attributed to the loading situation, the load was transferred from the plywood to the flanges producing slight bending of the flanges which caused the web to deflect out of plane and thus create an overall web buckling failure mode. Also, the previous studies of Shan and Schuster loaded the specimens through stiffeners at mid-span, whereas this study did not use stiffeners in the clear span of the specimen (Figure 2). The shear failure load for each web was recorded for the shear force at the reaction, V_b. The shear force at each vertical edge of the hole, V1 and V2 (Figure 2) was computed assuming the beam to be simple span with a uniform load. Table III gives the value of V_b, V1, and V2 for each test specimen. The uniform load was the load indicated by the test machine divided by the span length, L, for each web.

4. Evaluation of Test Data. For solid web elements subjected to shear only, the nominal strength can be estimated by Equations 6 through 8. Based on these equations, the nominal shear strength, V_n, of each test specimen web was calculated and is listed in Table III.

a. Current Investigation (Eiler Data). The ratios of V_b/V_n (Table III) show the reduction of the shear strength of a C-section with a web hole. Shear buckles occur diagonally as a result of the principal compressive stresses (Figure 5). The capacity of a compression element is affected by the slenderness ratio of the element. For solid webs subjected to shear, the shear buckling behavior is influenced by the depth-to-thickness ratio (slenderness ratio) of the web, h/t. However, for webs with openings, the h/t parameter does not take into account the size of the hole and the boundary conditions of the compression portion of the web. Therefore, a parameter that includes the size of the hole must be considered in the development of reduction factor equations. Previous investigations have found the ratio of the web opening depth to web depth, a/h, to influence the shear buckling strength of beam webs with holes. This parameter considers the size of the hole but does not include the thickness (or slenderness) of the web element and does not completely reflect the buckling behavior of beam webs with holes. Therefore, a parameter must be identified which includes both the size of the hole and the slenderness of the compression element. The ratio of the distance above or below the hole to the web thickness, c/t, addresses both of these requirements. Previous research indicated that the shear strength of a beam web is influenced by the slenderness ratio of the web element above or below the hole, c/t. The parameter c/t was plotted verse the ratio of V_t/V_n and good correlation was found except for the specimens with circular holes (Figure 6). It was concluded that the parameter c/t does not adequately account for the location of the shear buckle at the edge of a circular hole and therefore the definition of c was adjusted for a circular hole.

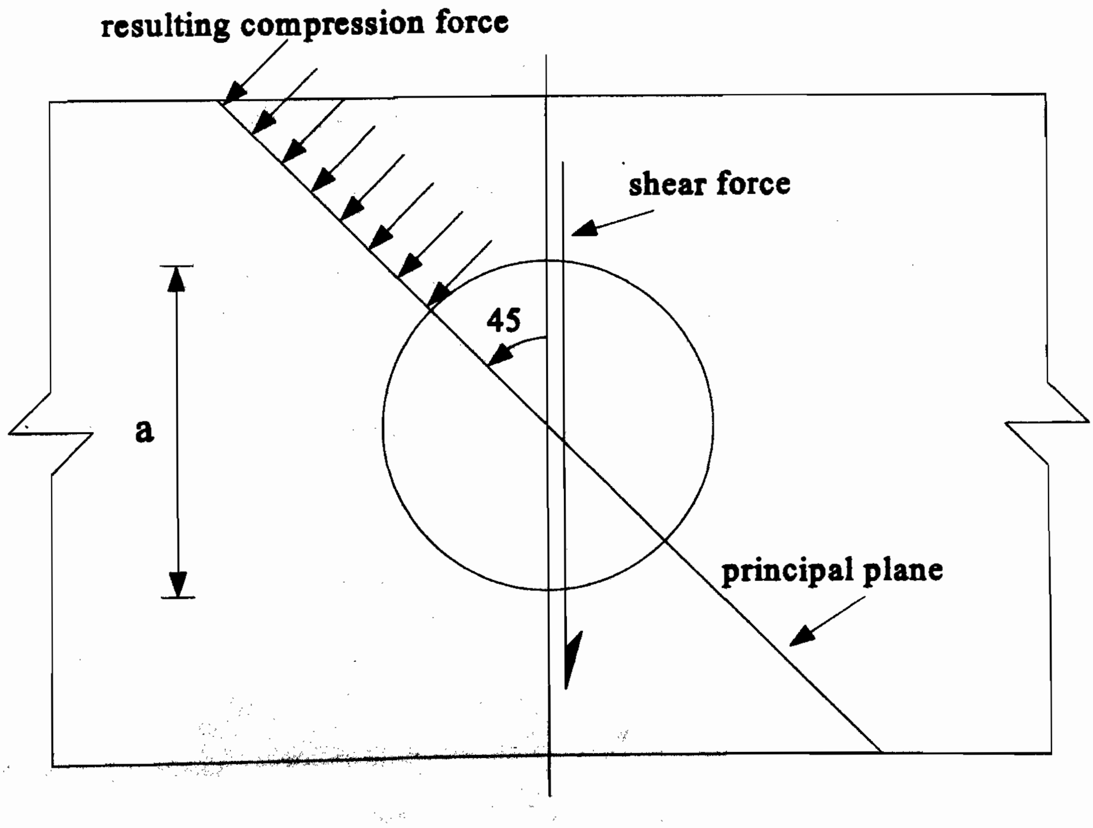

Figure 5 Resulting Compression Force due to Shear

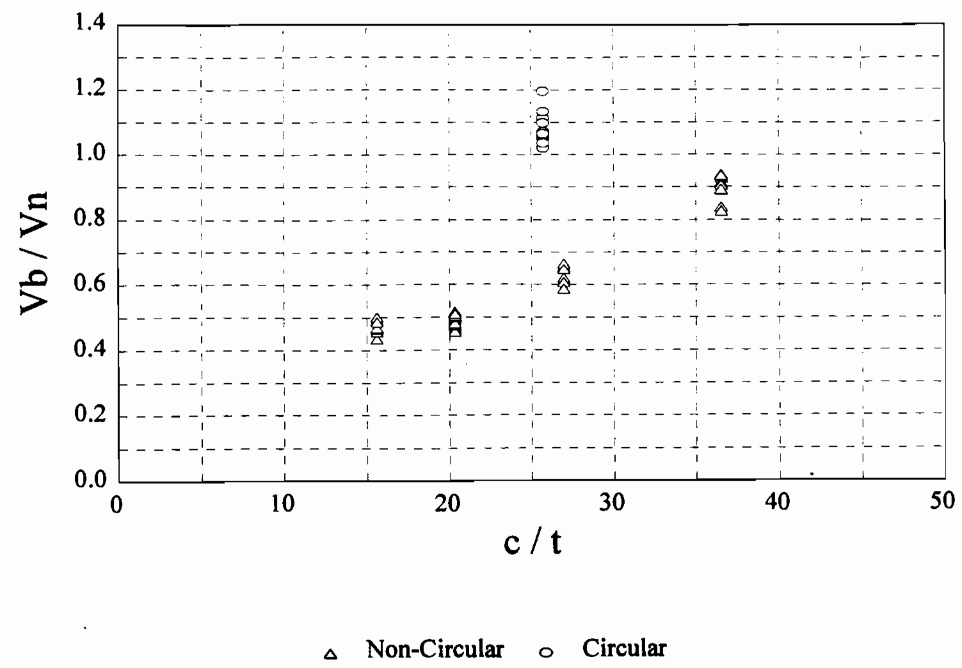

Figure 6 V_b/V_n vs. c/t (Eiler Data)

A new definition of c, based on a typical shear failure occurring at a 45 degree angle, was adopted. This angle represents the location of the shear compression stresses acting on the principal plane. For a circular hole at mid-height of the web, the shear failure will occur at approximately a 45 degree angle through the hole (Figure 7). This was observed during the test program, Figure 8. The vertical distance from the point of the shear buckle at the edge of the hole to the corner radius at the flat of the web defines a new c value, c_1. The following equation defines c_1 for a circular hole at mid-height of a web:

$$c_1 = \frac{h}{2} - \frac{a \cdot \cos 45^\circ}{2} = \frac{h}{2} - \frac{a}{2.828} \qquad (11)$$

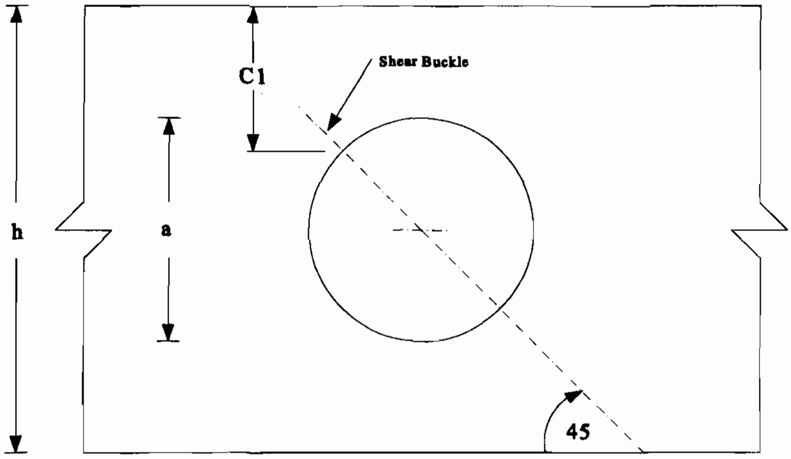

Figure 7 Location of Shear Buckle (Circular Hole)

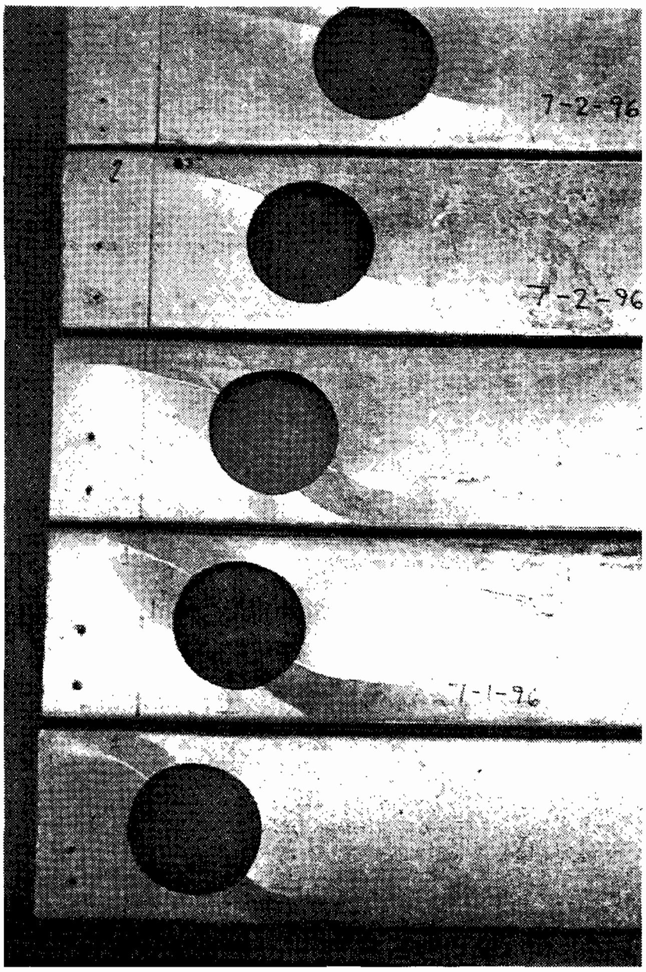

Figure 8 Failed Beam Test Specimens (6" with Circular Hole)

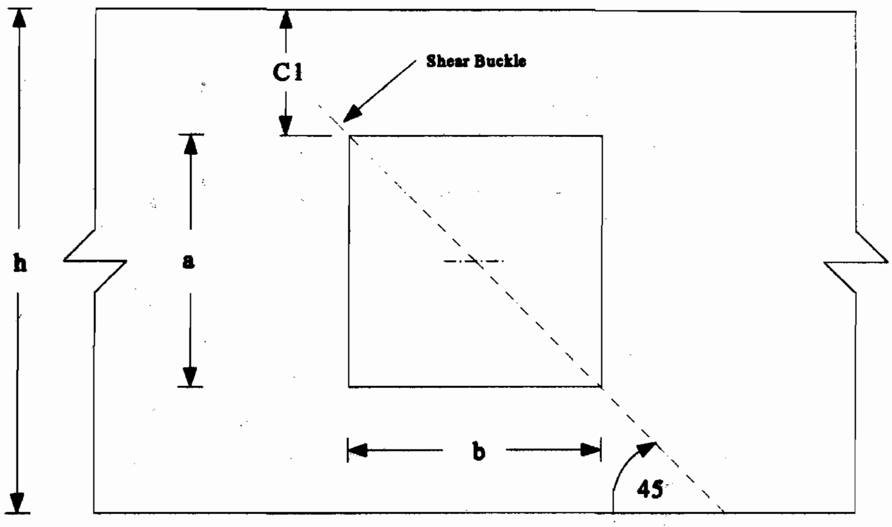

Figure 9 Location of Shear Buckle (Square Hole)

For a square hole at mid-height of the web, the shear failure will also occur at a 45 degree angle through the hole (Figure 9). The vertical distance from the point of shear buckle at the corner of the hole to the corner radius at the flat of the web defines the c_1 value. The following equation defines c_1 for a square hole at mid-height of a web:

$$c_1 = \frac{h}{2} - \frac{a}{2} \qquad (12)$$

Equation 12 is the same definition of c that was used by the Schuster analysis.

For a rectangular hole with b/a > 1.0 located at mid-height of the web, the failure will occur at the corners due to local stress concentrations. The failure still occurs along the diagonal from each corner (Figure 10). The standard punchouts (elliptical holes) with b/a > 1.0 will behave in a similar manner (Figure 11). This failure pattern was observed in the test program, Figures 12 and 13.

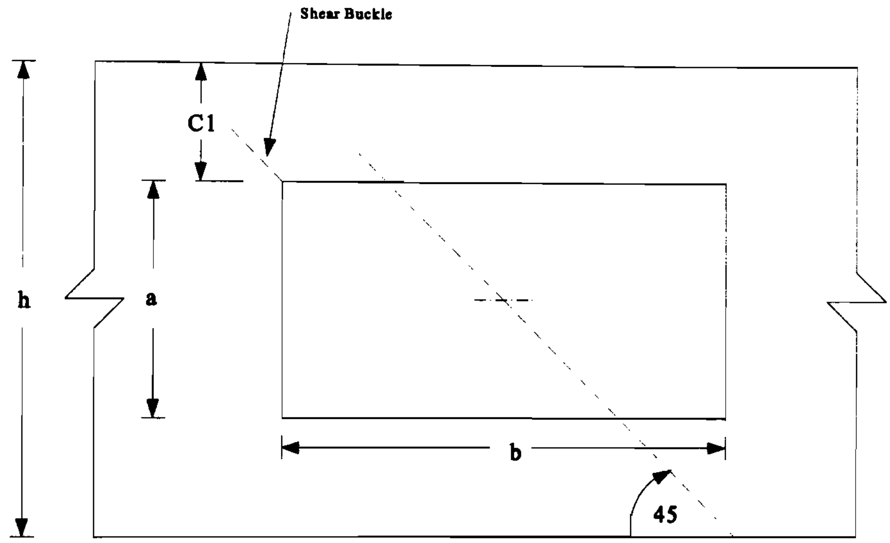

Figure 10 Location of Shear Buckle (Rectangular Hole)

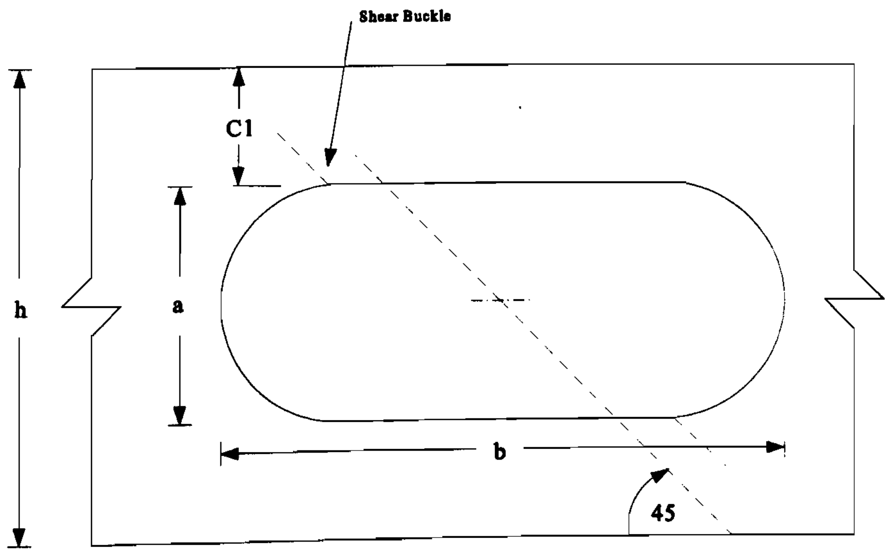

Figure 11 Location of Shear Buckle (Elliptical Hole)

Figure 12 Failed Beam Test Specimens (3.625" with Elliptical Hole)

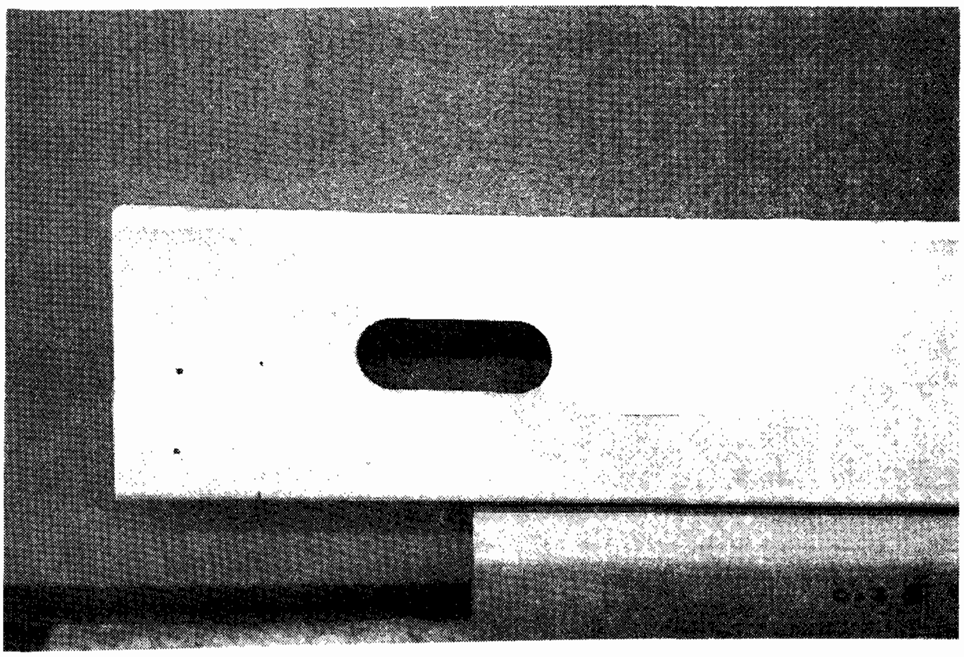

Figure 13 Failed Beam Test Specimen (6" with Elliptical Hole)

Based on the observed failure modes, two definitions of c_l were used for the evaluation of the test data: Equation 11 was used for circular holes and Equation 12 was used for all other hole geometries. Figure 14 shows the distribution of the test results for the linearly varying shear test specimens when c_l is defined by either Equation 11 or Equation 12.

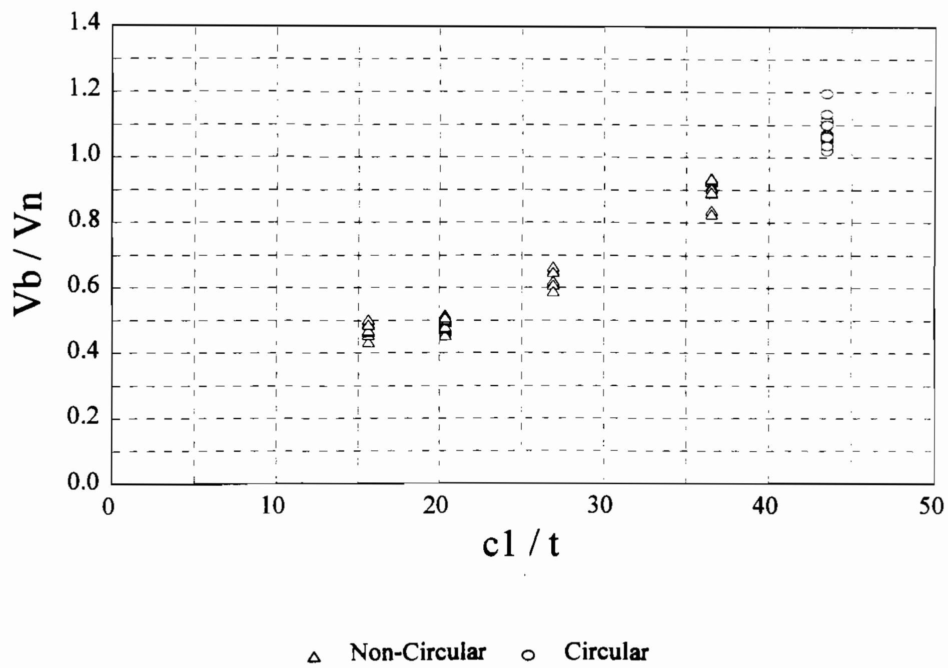

Figure 14 V_b/V_n vs. c_l/t (Eiler Data)

b. <u>Combined Test Data.</u> A total of eighty-five tests of beams with web holes were evaluated (46-Eiler, 13-Schuster, 26-Shan). Table IV lists the range of parameters for all data. The a/h and h/t parameters did not show a strong influence on the tested load capacity, as is graphically shown in Figures 15 and 16.

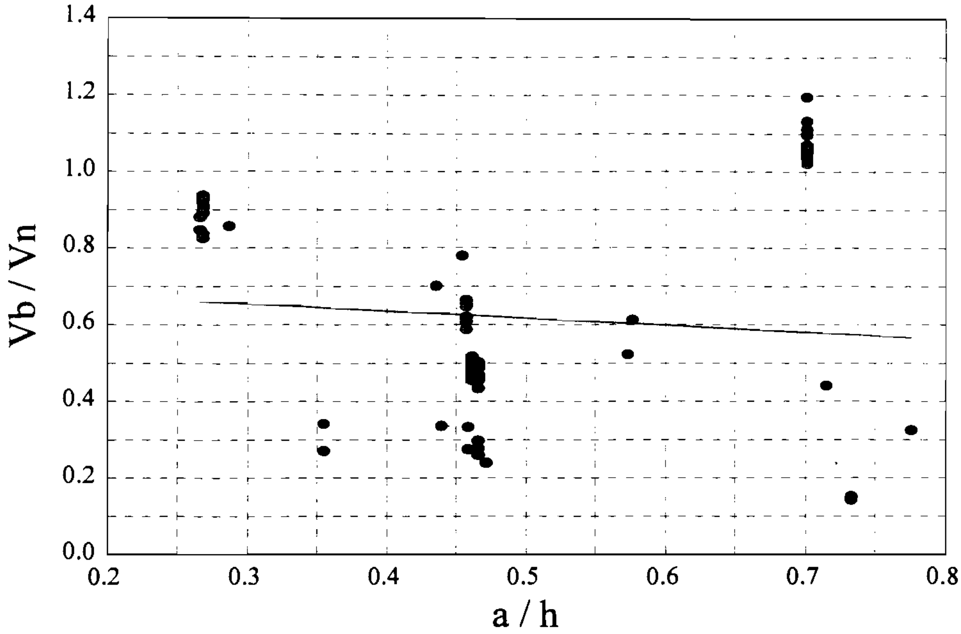

Figure 15 V_b/V_n vs. a/h (Combined Data)

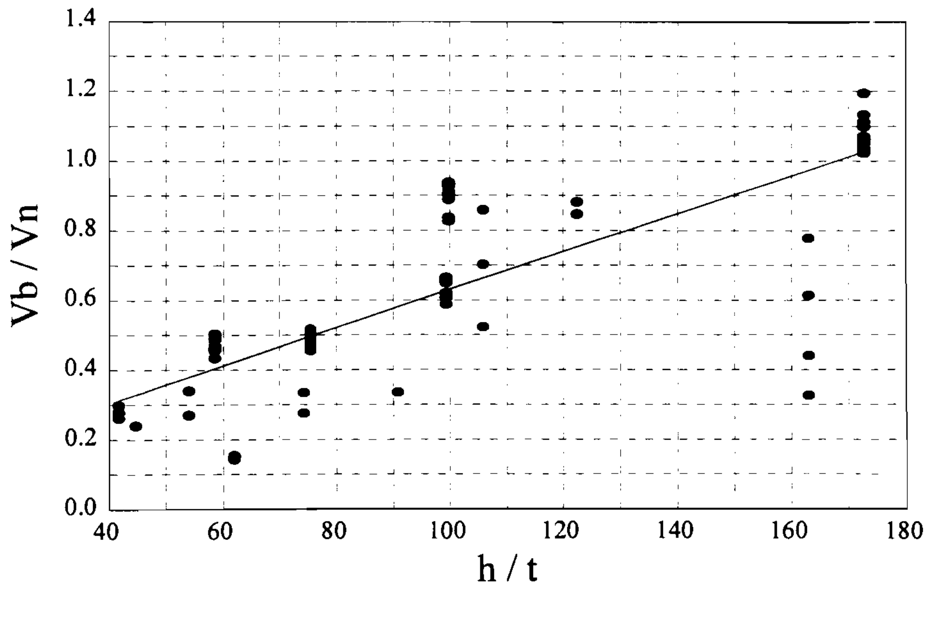

Figure 16 V_b/V_n vs. h/t (Combined Data)

TABLE IV PARAMETER RANGES OF SHEAR TEST DATA

Parameter	Eiler Data	Shan & Schuster Data
c/t	15.6 to 36.6	8.3 to 91.6
c_1/t	15.6 to 43.5	8.3 to 91.6
h/t	58.5 to 172.7	41.8 to 210.4
a/h	0.268 to 0.702	0.130 to 0.776
V1/V2	1.21 to 3.00	1.00
F_y (ksi)	42 to 57	34 to 81

The c_1/t parameter was found to be the dominant parameter effecting the behavior of webs with holes. Similar to the trend presented by Figure 6, the specimens with circular holes in the Schuster data also plotted above the general trend of the specimens with non-circular holes (Figure 17). There were three specimens with circular holes tested in the

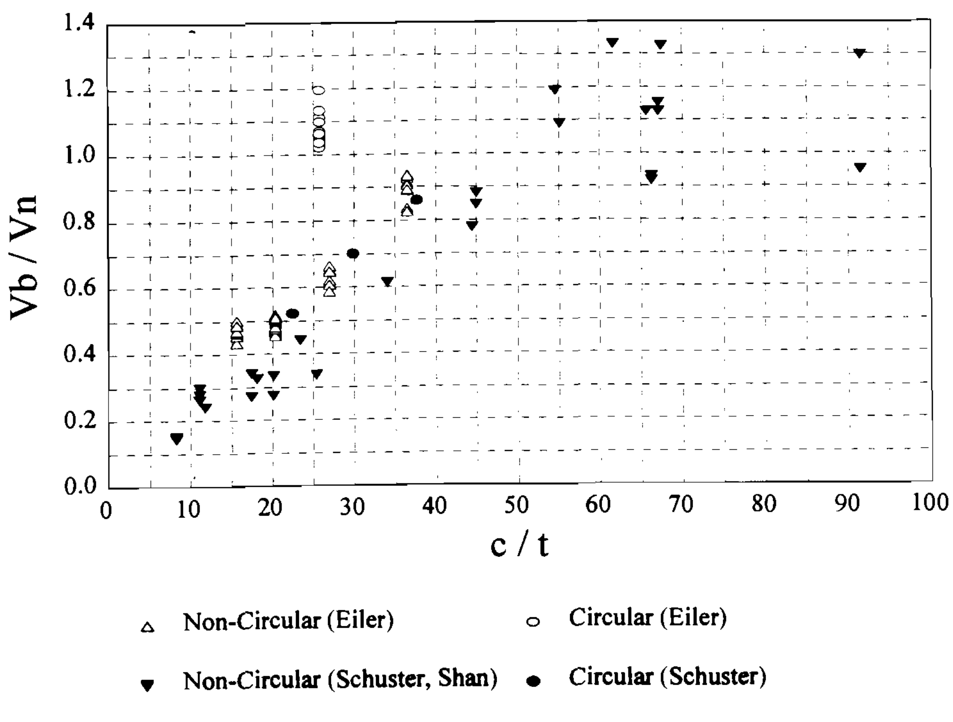

Figure 17 V_b/V_n vs. c/t (Combined Data)

Schuster investigation and each of these data points plot above the general trend of the remaining constant shear data (Schuster, Shan), Figure 17. Also, the specimens with a $c_l/t > 54$ had no reduction in capacity due to the presence of a hole, i.e., $V_b/V_n \geq 1.0$.

The definitions of c_l (Eq. 11 and Eq. 12) account for the location of the shear buckle at the edge of the hole. Figure 18 shows an improved distribution for the test results when the ratio of c_l/t is considered.

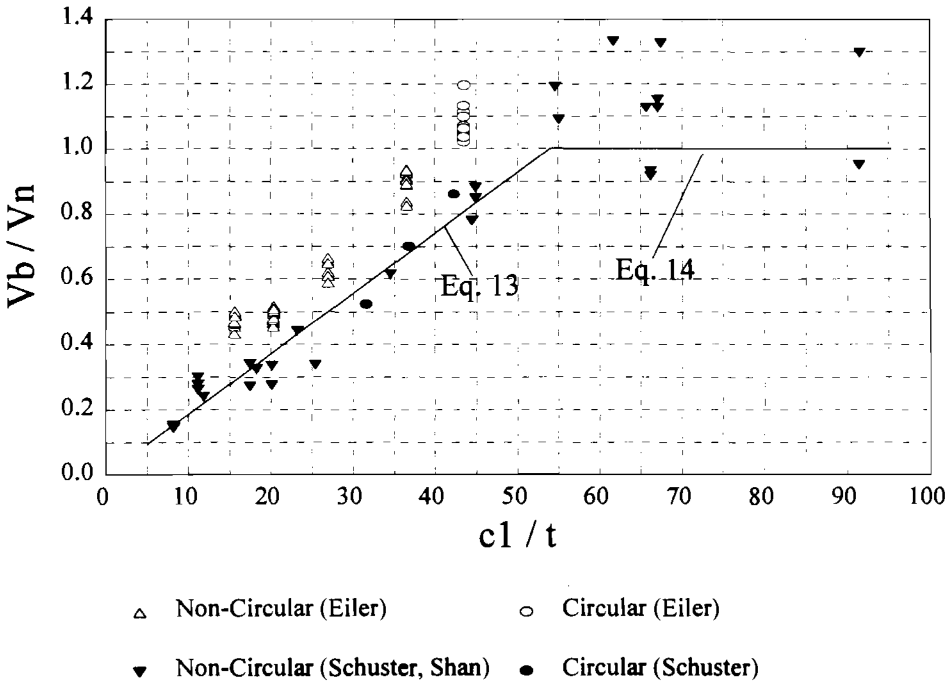

Figure 18 V_b/V_n vs. c_l/t (Combined Data)

5. Development of Reduction Factors. The influence of a web hole on the ultimate shear strength is not accounted for by the current AISI Specification (9,12). The reduction of shear strength due to web holes can be estimated by applying a reduction factor to the nominal shear strength of the web.

Based on Figure 18 the following shear strength reduction factor, q_{s1} ($q_{s1} = V_b/V_n$), was developed:

For $5 < c_1/t \leq 54$

$$q_{sl} = \frac{(c_1/t)}{54} \tag{13}$$

For $c_1/t > 54$

$$q_{sl} = 1.0 \tag{14}$$

Where:

For circular holes,

$$c_1 = \frac{h}{2} - \frac{a}{2.83} \tag{15}$$

For all other holes,

$$c_1 = \frac{h}{2} - \frac{a}{2} \tag{16}$$

Using Equations 13 and 14, the nominal shear strength can be computed as:

$$V_{nq} = q_{sl} \cdot V_n \tag{17}$$

Where V_n is given by the nominal shear strength equations for a solid web in Section C3.2 of the AISI Specification (Equations 6, 7, and 8).

The general trend of the linearly varying shear data (Eiler) also plotted above the general trend of the constant shear data, (Figure 18). This is due to the slope of the shear diagram, i.e., the difference in the shear at each side of the hole. During a test, a shear buckle would first occur at the edge of the hole with the larger shear force, V1, without any noticeable buckle occurring at the edge of the hole with the smaller shear force, V2. As additional load was applied, a second shear buckle would occur at the V2 edge of the hole. From this trend, it was concluded that the slope of the shear diagram for the uniformly loaded specimens must be taken into account in the shear reduction factor. For test specimens having a linearly varying shear diagram, Equation 17 consistently underestimated the tested shear capacity. This is graphically depicted by Figure 19 which shows for specimens having either non-circular (Eiler) or circular (Eiler) holes, the ratio of $V_b/q_{s1}V_n$ is greater than unity.

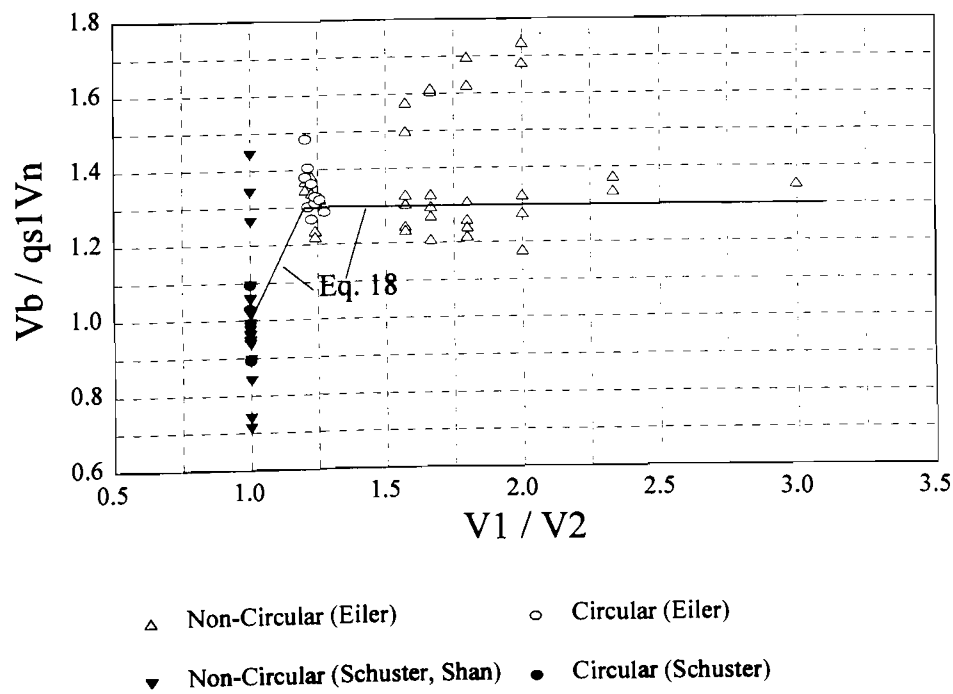

Figure 19 $V_b/q_{s1}V_n$ vs. V1/V2 (Combined Data)

Based on the distribution of data shown on Figure 19, the following shear strength factor, q_{s2} ($q_{s2} = V_b/(V_n \cdot q_{s1})$), was developed:

For $V1/V2 \geq 1.0$

$$q_{s2} = 1.5 \cdot (V1/V2) - 0.5 \leq 1.3 \qquad (18)$$

Based on the above analysis of the test results, Equations 13, 14, and 18 can be used to modify the current AISI design criteria for web design. The equations are limited to the parameters considered in the test program (Table IV).

6. Comparison of Test Results. The statistical results of Equations 13, 14, and 18 are compared with Schuster's reduction factor (Eq. 4) for the Eiler data and the combined data (Shan, Schuster, Eiler) in Table V. The combined statistical data is limited to 69 data points with $5 \leq c_l/t \leq 54$. Figures 20 and 21 summarize the results in a graphical form.

TABLE V COMPARISON OF STATISTICAL ANALYSIS

	Eiler Data		Combined Data	
	Eq. 4	**Eqs. 13,14,18**	Eq. 4	**Eqs. 13,14,18**
Mean	1.743	**1.052**	1.548	**1.037**
Standard Deviation	0.446	**0.106**	0.472	**0.130**
Coefficient of Variation	0.256	**0.101**	0.305	**0.125**

Notes: 1. Eiler data based on 46 tests
2. Combined data based on 69 tests with $5 \leq c_l/t \leq 54$

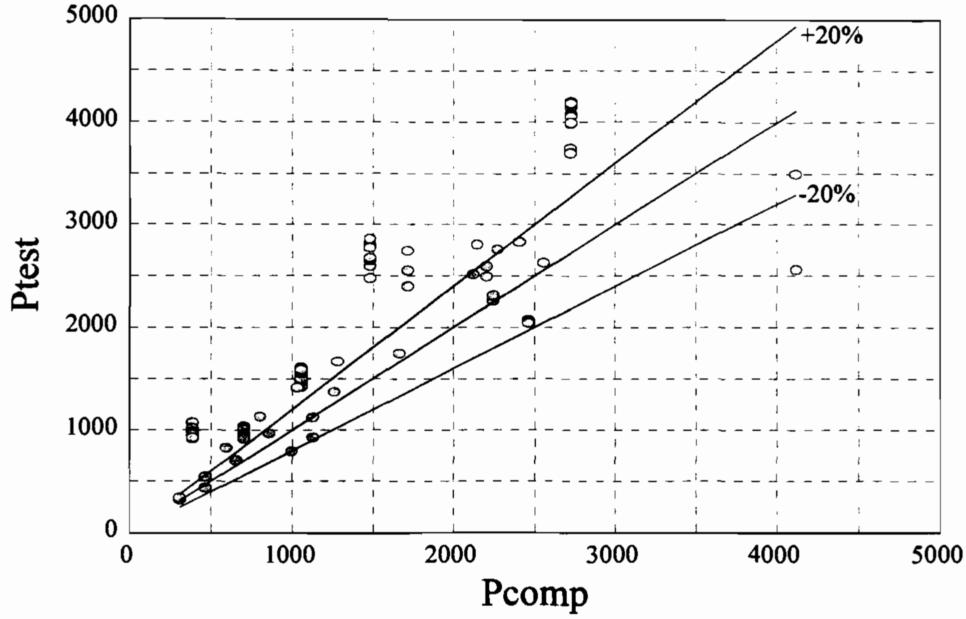

Figure 20 P_{test} vs. P_{comp} using Equation 4 (Schuster)

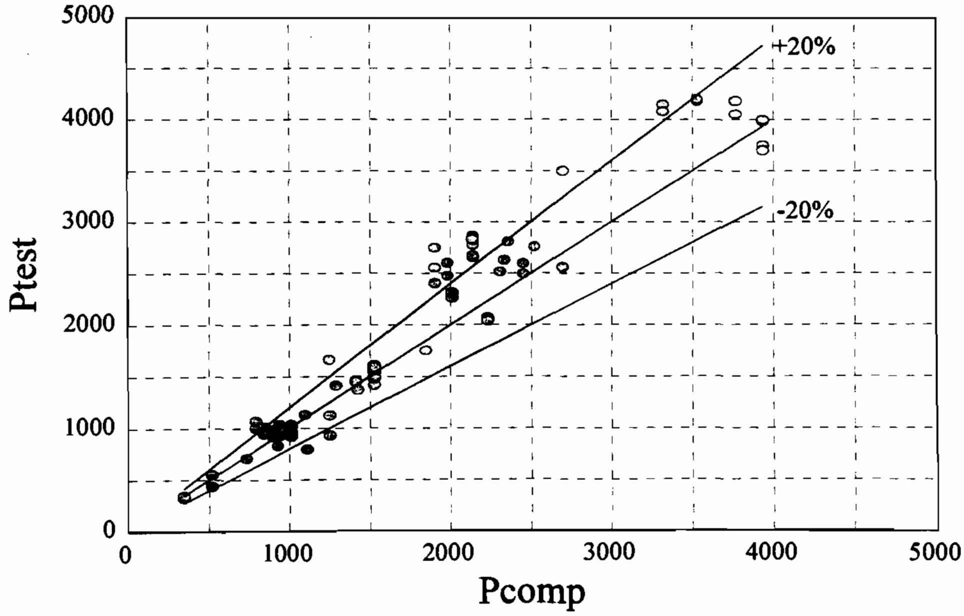

Figure 21 P_{test} vs. P_{comp} using Equations 13, 14, 18 (Eiler)

C. SUMMARY AND DESIGN RECOMMENDATIONS

1. Summary. An investigation was conducted to study the behavior of C-shaped members with web holes at mid-height subjected to a shear failure load. Based on 46 beam specimen tests (current investigation) subjected to a linearly varying shear and 39 beam specimen tests (previous investigations) subjected to a constant shear, shear reduction equations were developed that enable determination of the strength of a web element with a hole at mid-height. The c_1/t ratio, which includes the effect of the hole geometry, was found to be the primary parameter contributing to the reduction of the capacity for a web element with a hole. A secondary parameter influencing the shear buckling capacity was the variation in shear across the web hole, V1/V2.

2. Design Recommendations. Based on this investigation, the following design recommendations for the shear capacity of a beam member with a web hole at mid-height are proposed:

a. The web hole reduces the shear buckling load and therefore the current AISI design equations may be modified by a linear shear reduction factor to account for the effect of the presence of a web hole. The behavior of stress concentrations at the edge of the hole is effected by the geometry of the hole and can be accounted for by the following definition of c_1:

$$c_1 = \frac{h}{2} - \frac{a}{2.83} \qquad \text{For circular holes} \qquad (19)$$

$$c_1 = \frac{h}{2} - \frac{a}{2} \qquad \text{For all other holes} \qquad (20)$$

b. The shear strength reduction factor, q_{s1}, can be expressed as:

When $5 \leq c_1/t \leq 54$:

$$q_{s1} = \frac{(c_1/t)}{54} \tag{21}$$

When $c_1/t > 54$:

$$q_{s1} = 1.0, \quad q_{s2} = 1.0 \tag{22}$$

c. The slope of the shear diagram effects the shear capacity of webs with holes and can be accounted for by the ratio of the shear force at each edge of the hole, V1/V2. The influence of the shear forces is expressed by the following:

When $V1/V2 \geq 1.0$ and $c_1/t \leq 54$:

$$q_{s2} = 1.5 \cdot (V1/V2) - 0.5 \leq 1.3 \tag{23}$$

d. Therefore, the shear capacity for a web member with a hole can be obtained from the products of the shear reduction factors (q_{s1} and q_{s2}) and nominal shear strength (V_n):

$$V_{n1} = q_{s1} \cdot q_{s2} \cdot V_n \tag{24}$$

IV. CONCLUSIONS

A total of eighty-five tests of beams with a web hole subjected primarily to shear were evaluated. Analysis of the test results provide reduction factor equations for the degradation of the web shear capacity due to web holes. To determine the shear capacity for sections with web holes, the reduction factor as defined by the product of q_{s1} and q_{s2} (Eqs. 21 thru 23) may be applied to the AISI Specification shear equations (Eqs. 6 thru 8). The design parameters must satisfy the limits of applicability given in Table IV.

The shear reduction is a function of the slenderness ratio of the compression element above or below the web hole, c_l/t, and the ratio of the shear force at each edge of the web hole, V1/V2. A range of c_l/t has been identified in which no shear capacity reduction is necessary, $c_l/t \leq 54$. The incorporation of the reduction factor equations can easily be implemented into standard practice to ensure that the reduced shear capacity be taken into consideration. The application of the reduction factor equations ensures that adequate strength is achieved for sections with web holes.

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 beam webs with holes when subjected to a linearly varying shear force produced by a uniform load. Also, only single web sections with the web opening at mid-height of the section were considered. Future studies may include:

1. Single web sections other than C-sections
2. Closely spaced holes
3. Holes not located at mid-height of the web
4. Different support conditions (track sections)
5. Required reinforcement to increase the shear capacity of web elements with holes

APPENDIX

Constant Shear Data

Shan Data
(constant shear)

Specimen No.	Type of Opening	F_y (ksi)	t (in)	h (in)	a (in)	b (in)	V_{test} (lbs)	V_n (lbs)
SU-4-7	Elliptical	81.4	0.071	3.18	1.50	4.0	2760	11524
SU-6-3	Elliptical	67.2	0.033	2.05	1.50	4.0	338	2264
SU-6-4	Elliptical	67.2	0.033	2.05	1.50	4.0	341	2264
SU-6-5	Elliptical	67.2	0.033	2.05	1.50	4.0	328	2264
SU-6-6	Elliptical	67.2	0.033	2.05	1.50	4.0	325	2264
SU-6-7	Elliptical	67.2	0.033	2.05	1.50	4.0	344	2264
SU-8-8	Elliptical	33.7	0.039	2.11	0.75	2.0	550	1614
SU-8-9	Elliptical	33.7	0.039	2..11	0.75	2.0	438	1614
SU-9-10	Elliptical	46.9	0.044	3.27	1.50	4.0	1125	3371
SU-9-11	Elliptical	46.9	0.044	3.27	1.50	4.0	929	3371
SU-10-5	Elliptical	63.7	0.077	3.22	1.50	4.0	2406	9213
SU-10-6	Elliptical	63.7	0.077	3.22	1.50	4.0	2750	9213
SU-10-7	Elliptical	63.7	0.077	3.22	1.50	4.0	2556	9213
SR-12-1	Elliptical	49.1	0.055	11.57	1.50	4.0	2563	2700
SR-12-2	Elliptical	49.1	0.055	11.57	1.50	4.0	3500	2700
SR-13-1	Elliptical	72.3	0.045	7.54	1.50	4.0	2263	2010
SR-13-2	Elliptical	72.3	0.045	7.54	1.50	4.0	2313	2010
SR-14-1	Elliptical	47.2	0.046	5.64	1.50	4.0	2494	2943
SR-14-2	Elliptical	47.2	0.046	5.64	1.50	4.0	2594	2943
SR-15-1	Elliptical	22.0	0.046	7.60	1.50	4.0	2075	2230
SR-15-2	Elliptical	22.0	0.046	7.60	1.50	4.0	2044	2230

Note: Refer to Fig. 1 for the Type of Opening.

Shan, M.Y., R. A. LaBoube, and W. W. Yu, "Behavior of Web Elements with Openings Subjected to Bending, Shear, and the Combination of Bending and Shear", Final Report, Civil Engineering Study 94-2, University of Missouri-Rolla, May 1994.

Schuster Data
(constant shear)

Specimen No.	Type of Opening	F_y (ksi)	t (in)	h (in)	a (in)	b (in)	V_{test} (lbs)	V_n (lbs)
B200R-40	Elliptical	38.4	0.047	7.71	1.50	4.01	2630	2336
B200R-65	Elliptical	38.4	0.047	7.71	2.52	4.49	2518	2311
B200R-90	Elliptical	38.4	0.047	7.71	3.50	6.14	1749	2245
B200R-115	Elliptical	38.4	0.047	7.71	4.45	6.50	1371	2234
B200R-140	Elliptical	38.4	0.047	7.71	5.51	7.52	971	2201
B200R-150	Elliptical	38.4	0.047	7.71	5.98	8.62	708	2176
C200R-40	Diamond	47.6	0.046	7.71	1.50	4.60	2832	2138
C200R-65	Diamond	49.0	0.048	7.71	2.52	4.60	2810	2362
C150R-40	Diamond	50.2	0.035	5.79	1.50	4.60	1664	1250
C90R-40	Diamond	48.7	0.037	3.40	1.50	4.60	794	2361
R90R-25	Circular	41.2	0.032	3.43	0.98	0.98	1416	1648
R90R-40	Circular	41.2	0.032	3.43	1.50	1.50	1135	1617
R90R-50	Circular	41.2	0.032	3.43	1.97	1.97	832	1590

Note: Refer to Fig. 1 for the Type of Opening.

Schuster, R. M., "Research into Cold Formed Steel Perforated C-Sections in Shear", Progress Report No.1 of Phase I of CSSBI / IRAP Project, University of Waterloo, Waterloo, Ontario Canada, May 1995.

BIBLIOGRAPHY

1. "Specification for the Design of Light Gage Steel Structural Members", American Iron and Steel Institute, April, 1946, New York, NY.

2. Shanmugam, N. E., "Openings in Thin-Walled Steel Structures", Bicentenary Conference on Thin-Walled Structures, University of Strathclyde, Glasgow, Scotland, December 1996.

3. Rockey, K. C., R. G. Anderson, and Y. K. Cheung, "The Behavior of Square Shear Webs Having a Circular Hole", presented at the Symposium on Thin-Walled Structures, University College of Swansea, 1967.

4. Hoglund, T., "Shear Buckling Resistance of Steel and Aluminum Plate Girders", Bicentenary Conference on Thin-Walled Structures, University of Strathclyde, Glasgow, Scotland, December 1996.

5. "Steel and Composite Beams with Web Openings", Steel Design Guide Series, American Institute of Steel Construction, 2nd printing, September 1991.

6. LaBoube, R. A., and W. W. Yu, "Structural Behavior of Beam Webs Subjected Primarily to Shear", Final Report, Civil Engineering Study 78-2, University of Missouri-Rolla, June 1978

7. Yu, W. W., Cold-Formed Steel Design, Second Edition, John Wiley & Sons, Inc., New York, 1991.

8. Shan, M.Y., R. A. LaBoube, and W. W. Yu, "Behavior of Web Elements with Openings Subjected to Bending, Shear, and the Combination of Bending and Shear", Final Report, Civil Engineering Study 94-2, University of Missouri-Rolla, May 1994.

9. "Load and Resistance Factor Design Specification for Cold-Formed Steel Structural Members", American Iron and Steel Institute, March 16, 1991.

10. Schuster, R. M., "Research into Cold Formed Steel Perforated C-Sections in Shear", Progress Report No.1 of Phase I of CSSBI / IRAP Project, University of Waterloo, Waterloo, Ontario Canada, May 1995.

11. Redwood, R. G., Baranda, H., and Daly, M. J., " Tests of Thin-Walled Beams with Unreinforced Holes", Journal of the Structural Division, ASCE Proceedings, Vol. 104, No. STR, March 1978.

12. "Specification For the Design of Cold-Formed Steel Structural Members", American Iron and Steel Institute, August 19, 1986, with December 11, 1989 Addendum.