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BENDING AND SHEAR BEHAVIOR OF WEB ELEMENTS WITH OPENINGS

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Abstract

Cold-formed steel C-sections are frequently used as wall studs and floor joists in both commercial and residential construction. To facilitate installation of ancillary systems such as electrical wiring and plumbing, the C-section is manufactured with a web opening. Although the opening offers construction advantages, it may degrade the structural integrity of the member. To quantify the degrading effect of a web opening, a study has been conducted at the University of Missouri-Rolla (UMR). The UMR study included the loading conditions of bending, shear, web crippling and the combinations thereof. This paper summarizes the results of an experimental study of the behavior of combined bending and shear. A total of 68 beam specimens, having varying magnitudes of bending moment and shear force have been tested. Based on the findings of this study, it is concluded that the interaction equation employed by the AISI Specification will provide an adequate strength prediction, provided that the individual shear capacity is modified to account for the influence of the web opening. The bending capacity must recognize the strength at the section being evaluated.

Introduction

Cold-formed steel flexural members are the mainstay of the light-steel framing industry in the United States. Light-steel framing has become the preferred structural system in commercial wall and facia systems, and is beginning to make major inroads in the residential framing market. Cold-formed steel members are used as wall studs, floor joists, and components for roof trusses.

For both commercial and residential applications, the mass produced cold-formed steel C-section is typically produced with a standard web punchout pattern. These punchouts, or web openings, typically range in size from 1-1/2 in. (3.81 cm) by 4 in. (10.16 cm) to 3/4 in. (1.91) by 2 in. (5.08 cm); located at mid-depth of the web; and spaced longitudinally 24 in. (61 cm) on center (Fig 1).

Because the current design specifications (Specification 1986, 1991) do not explicitly address web punchouts in flexural members, a comprehensive study was initiated at the University of Missouri- Rolla (UMR) in 1990. This study, co-funded by the American Iron and Steel Institute and Metal/Lath Steel Framing Association, specifically addressed the limit states of bending, shear, web crippling, and combinations thereof. This paper will summarize the findings of the bending study and shear study, and will give specifics pertaining to the combined bending and shear study.

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UMR Bending Study

Based on an experimental and analytical study, Shan (1994) determined that the local buckling characteristics of a flexural member were only slightly influenced by the presence of a web opening. This is due primarily to the web punchout being centered at mid-depth of the cross section, a region of only minor bending stress.

To ensure no loss of structural efficiency, Shan (1994) recommended that, with in the limits of the UMR study, the flexural capacity of a section containing a punchout could be defined by using the following equation:

$$M_n = S_{xe} F_y \qquad (1)$$

where F_y is the yield stress of the steel sheet, and S_{xe} is the effective section modulus computed at F_y. When evaluating S_{xe}, the effective width approach is to be employed. For the compression flange and edge stiffener, the effective widths are determined per the relevant AISI Specification provisions. However, the effective compression portion of the web is computed assuming the web element above of the punchout to be an unstiffened compression element under uniform stress F_y. The applicable plate buckling coefficient, k, shall be taken as 0.43.

UMR Shear Study

For loading conditions that impose a transverse shear force on a region of the web, Shan (1994) discovered that the presence of a web punchout would result in a measurable decrease in the structural performance of the web.

Based on the findings from an experimental and analytical study (Shan, 1994) of the behavior of web elements of cross sections with web openings subjected to transverse shear force, the nominal shear strength can be adequately determined by applying a strength reduction factor to strength calculations for a cross section devoid of web punchouts. Shan (1994) developed both linear and non-linear reduction factors, that when applied to the nominal shear strength determined by the present AISI design provisions yielded reliable design strengths. Both the linear and non-linear strength reduction factors, q_s, are as follows:

1. $a/h \leq 0.383$
   $$q_s = 1.711 - 3.611\,(a/h) \leq 1.0 \qquad (2)$$

   $0.383 < a/h \leq 1.0$
   $$q_s = 0.456 - 0.377\,(a/h) \qquad (3)$$

or

$$2.\quad q_s = 1.506 * 10^{[-1.33(a/h)]} \leq 1.0 \qquad (4)$$

where a is the depth of web opening and h is the flat width of the web.

UMR Combined Bending and Shear Study

There was no literature discovered that reported on the design of web elements with punchouts subjected to combined loading of bending and shear. The current AISI Specification, in Section C3.3, addresses the ultimate strength of web elements without openings under a load combination of bending and shear. For beams with unreinforced webs, the applied moment, M, and applied shear, V, shall satisfy the following interaction equation:

$$(M/M_a)^2 + (V/V_a)^2 \leq 1.0 \qquad (5)$$

where M_a is the allowable moment when bending along exists, and V_a is the allowable shear force when shear alone exists.

The purpose of this phase of the research was to investigate the behavior of a single web with openings when subjected to a combined shear force and bending moment. The interaction between shear forces and bending moments on the ultimate capacity of the web elements with openings was experimentally investigated. The test results are compared with Eq. 5, the interaction equation of the AISI Specification for a solid web cross section.

The experimental investigation and the evaluation of the test results will be presented and discussed. The following discussion will cover the fabrication of test specimens, test procedure, test results, and analysis of the results. Based on the findings of this study, design recommendations for the interaction relationship have been presented herein.

Experimental Study. To determine the effects of web openings on the member strength, an experimental investigation was conducted to determine the interaction between bending moment and shear force, and the influence of the interaction on the strength of unreinforced beam webs having openings. The ratio of web opening depth to web depth, a/h, was determined to have a significant effect on the ultimate shear capacity of web element with web openings. This ratio was also given particular consideration in the analysis of the interaction between bending moment and shear force.

Sixty-eight beam tests were conducted in this study. Beam specimens having three different web opening sizes [4 x 1.5 in. (10.16 x 3.81 cm), 4 x 0.75 in. (10.16 x 1.91 cm), and 2 x 0.75 in. (5.08 x 1.91 cm)] located at the mid-height of the web were tested. The dimensions of each test specimen and its web openings are given by Shan (1994). For the combination of bending and shear behavior, the location of the web opening, i.e., the distance x' as shown in Fig. 2, was also investigated.

The beam test specimens had the following range of geometric and material properties:

$h/t = 34.43$ to 98.23, $w/t = 19$ to 36, $a/h = 0.352$ to 0.740, $t = 0.032$ to 0.071 in. (0.81 to 1.81 mm), and $F_y = 33.70$ to 81.36 ksi (233 to 561 MPa).

Preparation of Beam Specimens. Two common industry standard C-sections (2.5 (6.35 cm) and 3.625 (9.21 cm) inches deep) were tested for various thicknesses of C-sections. The test specimen cross-section is shown in Fig. 3.

Each beam specimen was fabricated by cutting to the required length. To prevent lateral-torsional buckling of each C-section, the sections were interconnected by aluminum angles attached to the flanges using self-drilling screws (Fig. 3).

Testing of Specimens. Table 1 lists the tensile test data for thickness, yield strength (F_y), ultimate tensile strength (F_u) and percent elongation in 2 inches (5.08 cm) gage length.

Each specimen was tested as a simply supported beam subjected to a concentrated load at midspan (Fig 2).

Test Results. A total of 68 tests were completed, 30 tests experienced combined bending and shear, 20 tests failed by pure bending and 18 tests focused on pure shear.

The test results of V_t and M_t are listed in Table 2. For each test specimens, the failure shear load (V_t) was 1/4 of the maximum midspan load and the bending moment (M_t) was computed on the basis of V_t.

Evaluation of Test Data. To study the correlation between the bending and shear behavior, two analysis methods were considered. The nominal shear strengths and bending moments were computed as follows:

(i) Based on the 1986 AISI Specification equations, the unmodified nominal shear strength, V_n, and moment capacity ,M_n, were calculated and are listed in Table 3.

(ii) Using Eqs. 2 and 3 for the linear shear reduction factor, Eq. 4 for the non-linear shear reduction factor, and the effective net section modulus approach, Eq. 1, the modified nominal shear strengths and moment capacities, $(V_n)_{m1}$, $(V_n)_{m2}$ and $(M_n)_m$, were evaluated and are given in Table 3.

The ratios, V_t/V_n, $V_t/(V_n)_{m1}$, $V_t/(V_n)_{m2}$, M_t/M_n and $M_t/(M_n)_m$, were also computed and are shown on Figures 5 through 9.

Comparison of Test Results. For the test specimens that failed by the combined bending and shear behavior, the type of failure mode is indicated in Fig. 4. The failure pattern is defined by a bending failure at midspan and a diagonal shear failure around the corners of the web opening. These two failure patterns generally occurred simultaneously as the ultimate load was achieved.

Based on the above analysis of shear ratios and moment ratios, three interaction relationships were examined. The values of V_t/V_n versus M_t/M_n are shown graphically by Fig. 5. Also shown in Fig. 5 is the unit circle which represents the present AISI design approach for combined bending and shear. As indicated by Fig. 5, the AISI Specification, which is for solid webs, does not provide a good relationship between bending and shear for webs with openings.

Figure 6 is a plot of the relationship between $V_t/(V_t)_{m1}$ and $M_t/(M_n)_m$ while Fig. 7 shows the relationship between $V_t/(V_t)_{m2}$ and $M_t/(M_n)_m$. These two figures present better correlation between bending moment and shear force when compared with the AISI design approach.

Based on a plot of $V_t/(V_n)_{m1}$ and M_t/M_n, and $V_t/(V_n)_{m2}$ and M_t/M_n, Figs. 8 and 9 also demonstrate good interaction between bending moment and shear force for web elements with openings. Figures 8 and 9 consider the shear reduction factor only. Figures 8 and 9 are more appropriate comparisons because at the location of maximum moment, the web did not have an opening.

Summary and Design Recommendations

Summary. The intent of this investigation was to study the behavior of C-shaped members with elliptical web openings subjected to combined bending moment and shear force. Based on 68 beam specimen tests, the current AISI Specification interaction equation adequately predicts the web capacity if the nominal shear and bending strengths are appropriately modified to account for the web opening.

Design Recommendations. Based on the findings of this study, the following design recommendations are suggested:

The AISI Specification interaction equation can be used to predict the strength of a beam web with an opening by using the modified nominal shear strength and bending moment.

$$(M/M_n)^2 + (V/V_{n,m})^2 \leq 1.0 \tag{6}$$

where M = Applied moment
M_n = Nominal moment capacity at the section being investigated
V = Applied shear force
$V_{n,m}$ = Modified shear strength using either the linear or non-linear shear reduction factor

Appendix. - References

Specification for the Design of Cold-Formed Steel Structural Members (1986), American Iron and Steel Institute, Washington, D.C.

Load and Resistance Factor Design Specification for Cold-Formed Steel Structural Members (1991), American Iron and Steel Institute, Washington, D. C.

Shan, M. Y. (1994), "Behavior of Web Elements With Openings Subjected to Bending, Shear and the Combination of Bending and Shear", Ph.D. dissertation, Department of Civil

Engineering, University of Missouri-Rolla, Rolla, MO.

Appendix. - Notation

a = Depth of web opening;
h = Depth of flat portion of web;
t = Base thickness of steel;
w = Flat width of flange;
q_s = Shear reduction factor;
F_y = Design yield stress;
M = Applied moment;
M_a = Allowable design moment;
M_n = Nominal moment capacity at the section being investigated;
S_{xe} = Effective section modulus;
V = Applied shear force;
V_a = Allowable shear force;
$V_{n,m}$ = Modified shear strength using either the linear or non-linear shear reduction factor

TABLE 1 MATERIAL PROPERTIES FOR COMBINED BENDING AND SHEAR TEST SPECIMENS

Specimen No.	Thickness (in.)	F_y (ksi)	F_u (ksi)	Elongation (%)
BS-3-14	0.067	47.88	54.68	41.9
BSB-3-14-1,2	0.077	63.72	78.42	23.0
BSB-3-14-3,4	0.071	81.36	104.28	21.9
BSS-3-14-1,2	0.077	63.72	78.42	23.0
BSS-3-14-3,4	0.071	81.36	104.28	21.9
BS-3-18	0.045	52.75	63.65	41.3
BSB-3-18-1,2	0.044	46.92	60.32	31.0
BSB-3-18-3,4	0.044	53.13	70.16	24.0
BSS-3-18-1,2	0.044	46.92	60.32	31.0
BS-3-20	0.033	58.65	69.18	40.0
BSB-3-20-1,2	0.044	46.82	60.31	31.0
BSB-3-20-3,4,5	0.036	63.71	78.95	29.2
BS-2-16	0.055	55.30	64.75	36.9
BSB-2-16-1	0.062	37.23	48.86	38.0
BSB-2-16-2,3	0.059	53.59	74.74	39.1
BSS-2-16	0.059	53.59	74.74	39.1
BS-2-20	0.032	55.33	68.10	39.2
BSB-2-20-1,2	0.039	33.70	48.02	44.0
BSB-2-20-3,4	0.033	67.15	71.50	35.4
BSS-2-20-1,2	0.039	33.70	48.02	44.0
BSS-2-20-3,4,5,6,7,	0.033	67.15	71.50	35.4

Notes: 1. Specimen Designation: BS-2-16-1A
BS: Combined Bending and Shear; BSB: Combined Bending and Shear for Pure Bending behavior; BSS: Combined Bending and Shear for Pure Shear behavior; 2 = Nominal Depth; 16 = Gage No.; 1 = Test No.
2. 1 in. = 25.4 mm; 1 ksi = 6.9 MPa.

TABLE 2 EXPERIMENTAL DATA FOR TEST SPECIMENS

Specimen No. (in.)	Span Length	h/t	a/h	V_t (lbs)	M_t (k-in)
BS-3-14-1A	40.0	48.41	0.462	1283	21.78
BS-3-14-2A	40.0	48.41	0.462	1288	21.89
BS-3-14-1B	40.0	48.41	0.462	1320	22.42
BS-3-14-2B	40.0	48.41	0.462	1325	22.53
BS-3-14-1C	40.0	48.41	0.462	1345	22.84
BS-3-14-2C	40.0	48.41	0.462	1350	22.95
BSB-3-14-1	150.0	41.77	0.466	925	75.17
BSB-3-14-2	150.0	41.80	0.466	885	72.01
BSB-3-14-3	150.0	44.78	0.472	1078	86.99
BSB-3-14-4	150.0	44.75	0.472	1065	85.68
BSS-3-14-1	34.8	41.79	0.466	2406	18.21
BSS-3-14-2	34.8	41.79	0.466	2750	21.06
BSS-3-14-3	34.8	41.79	0.466	2556	9.91
BSS-3-14-4	26.5	44.77	0.472	2760	12.03
BS-3-18-1A	40.0	72.61	0.459	650	11.05
BS-3-18-2A	40.0	72.61	0.459	650	11.05
BS-3-18-1B	40.0	72.61	0.459	713	12.11
BS-3-18-2B	40.0	72.61	0.459	638	10.84
BS-3-18-1C	40.0	72.61	0.459	745	12.65
BS-3-18-2C	40.0	72.61	0.459	745	12.65
BSB-3-18-1	150.0	74.99	0.455	338	29.32
BSB-3-18-2	150.0	73.68	0.463	343	29.70
BSB-3-18-3	150.0	73.17	0.466	400	34.15
BSB-3-18-4	150.0	73.25	0.465	378	32.39
BSS-3-18-1	27.5	74.34	0.459	1125	6.90
BSS-3-18-2	29.5	74.34	0.459	929	6.16
BS-3-20-1A	40.0	98.23	0.463	425	7.23
BS-3-20-2A	40.0	98.23	0.463	458	7.76
BS-3-20-1B	40.0	98.23	0.463	475	8.08

Note: 1 in. = 25.4 mm; 1 lb. = 4.45 N.

TABLE 2 (CONTINUED) EXPERIMENTAL DATA FOR TEST SPECIMENS

Specimen No. (in.)	Span Length	h/t	a/h	V_t (lbs)	M_t (k-in)
BS-3-20-2B	40.0	98.23	0.463	463	7.86
BS-3-20-1C	40.0	98.23	0.463	483	8.18
BS-3-20-2C	40.0	98.23	0.463	508	8.61
BSB-3-20-1	150.0	74.42	0.458	338	29.31
BSB-3-20-2	150.0	74.48	0.458	358	30.78
BSB-3-20-3	150.0	89.50	0.466	300	26.35
BSB-3-20-4	150.0	89.50	0.466	275	24.40
BSB-3-20-5	150.0	89.26	0.467	335	28.88
BS-2-16-1A	40.0	38.68	0.353	645	10.94
BS-2-16-2A	40.0	38.68	0.353	650	11.05
BS-2-16-1B	40.0	38.68	0.353	688	11.69
BS-2-16-2B	40.0	38.68	0.353	658	11.16
BS-2-16-1C	40.0	38.68	0.353	658	11.16
BS-2-16-2C	40.0	38.68	0.353	675	11.48
BSB-2-16-1	150.0	33.43	0.362	260	23.37
BSB-2-16-2	150.0	34.37	0.740	338	29.17
BSB-2-16-3	150.0	34.48	0.737	340	29.47
BSS-2-16-1	19.1	34.43	0.739	800	2.82
BSS-2-16-2	19.1	34.43	0.739	778	3.05
BSS-2-16-3	19.1	34.43	0.739	775	3.51
BSS-2-16-4	19.1	34.43	0.739	775	4.30
BSS-2-16-5	19.1	34.43	0.739	756	2.66
BS-2-20-1A	40.0	66.67	0.352	320	5.42
BS-2-20-2A	40.0	66.67	0.352	320	5.42
BS-2-20-1B	40.0	66.67	0.352	313	5.31
BS-2-20-2B	40.0	66.67	0.352	325	5.53
BS-2-20-1C	40.0	66.67	0.352	330	5.42
BS-2-20-2C	40.0	66.67	0.352	338	5.74

Note: 1 in. = 25.4 mm; 1 lb. = 4.45 N.

TABLE 2 (CONTINUED) EXPERIMENTAL DATA FOR TEST SPECIMENS

Specimen No.	Span Length (in.)	h/t	a/h	V_t (lbs)	M_t (k-in)
BSB-2-20-1	150.0	53.92	0.362	115	11.85
BSB-2-20-2	150.0	54.46	0.357	115	11.95
BSB-2-20-3	150.0	61.96	0.734	150	14.65
BSB-2-20-4	150.0	62.03	0.733	160	15.33
BSS-2-20-1	19.2	62.00	0.734	338	1.19
BSS-2-20-2	19.2	62.00	0.734	341	1.34
BSS-2-20-3	19.2	62.00	0.734	328	1.49
BSS-2-20-4	19.2	62.00	0.734	325	1.81
BSS-2-20-5	19.2	62.00	0.734	344	1.56
BSS-2-20-6	22.1	54.19	0.355	550	2.78
BSS-2-20-7	22.1	54.19	0.355	438	2.21

Notes: V_t = Tested Shear Strengths
M_t = Tested Moment Capacities
1 in. = 25.4 mm; 1 lb = 4.45 N; 1 in.-k = 113 KN-mm

TABLE 3 COMPUTED NOMINAL SHEAR STRENGTHS AND BENDING MOMENTS

Specimen No.	a/h	V_n (lbs)	$(V_n)_{m1}$ (lbs)	$(V_n)_{m2}$ (lbs)	M_n (k-in)	$(M_n)_m$ (k-in)
BS-3-14-1A	0.462	5963	1681	2182	26.39	25.27
BS-3-14-2A	0.462	5963	1681	2182	26.44	27.25
BS-3-14-1B	0.462	5963	1681	2182	26.44	27.64
BS-3-14-2B	0.462	5963	1681	2182	26.54	27.64
BS-3-14-1C	0.462	5963	1681	2182	26.20	25.12
BS-3-14-2C	0.462	5963	1681	2182	26.44	25.36
BSB-3-14-1	0.466	9166	2569	2323	82.30	81.02
BSB-3-14-2	0.466	9166	2569	2323	81.02	72.02
BSB-3-14-3	0.472	11524	3204	2868	89.50	86.42
BSB-3-14-4	0.472	11524	3204	2868	88.68	82.41
BSS-3-14-1	0.466	9213	2583	2335	40.83	40.28
BSS-3-14-2	0.466	9213	2583	2335	40.83	40.28
BSS-3-14-3	0.466	9213	2583	2335	44.55	42.40
BSS-3-14-4	0.472	11524	3204	2868	40.83	40.28
BS-3-18-1A	0.459	3738	1058	968	17.64	16.10
BS-3-18-2A	0.459	3738	1058	968	17.64	16.60
BS-3-18-1B	0.459	3738	1058	968	17.32	15.68
BS-3-18-2B	0.459	3738	1058	968	17.37	16.45
BS-3-18-1C	0.459	3738	1058	968	17.42	16.43
BS-3-18-2C	0.459	3738	1058	968	17.79	16.06
BSB-3-18-1	0.455	3371	959	884	33.93	32.29
BSB-3-18-2	0.463	3371	949	862	33.93	32.26
BSB-3-18-3	0.466	3580	1004	907	34.85	31.88
BSB-3-18-4	0.465	3580	1005	910	35.07	31.33
BSS-3-18-1	0.459	3371	954	873	16.97	16.30
BSS-3-18-2	0.459	3371	954	873	16.97	16.30
BS-3-20-1A	0.463	1586	446	406	13.19	9.58
BS-3-20-2A	0.463	1586	446	406	13.24	9.95
BS-3-20-1B	0.463	1586	446	406	13.48	9.85
BS-3-20-2B	0.463	1586	446	406	13.36	9.72
BS-3-20-1C	0.463	1586	446	406	13.13	9.81

Note: 1 in. = 25.4 mm; 1 lb. = 4.45 N.

TABLE 3 (CONTINUED) COMPUTED NOMINAL SHEAR STRENGTHS AND BENDING MOMENTS

Specimen No.	a/h	V_n (lbs)	$(V_n)_{m1}$ (lbs)	$(V_n)_{m2}$ (lbs)	M_n (k-in)	$(M_n)_m$ (k-in)
BS-3-20-2C	0.463	1586	446	406	13.36	9.72
BSB-3-20-1	0.458	3371	955	876	33.84	30.79
BSB-3-20-2	0.458	3371	955	876	33.46	32.44
BSB-3-20-3	0.466	2062	578	523	31.86	27.64
BSB-3-20-4	0.466	2062	578	523	31.73	27.68
BSB-3-20-5	0.467	2062	577	521	31.60	27.52
BS-2-16-1A	0.353	3788	1586	1935	15.54	15.17
BS-2-16-2A	0.353	3788	1586	1935	15.54	15.16
BS-2-16-1B	0.353	3788	1586	1935	15.37	14.85
BS-2-16-2B	0.353	3788	1586	1935	15.37	14.92
BS-2-16-1C	0.353	3788	1586	1935	15.37	14.85
BS-2-16-2C	0.353	3788	1586	1935	15.43	14.92
BSB-2-16-1	0.362	2745	1059	1364	22.35	22.05
BSB-2-16-2	0.740	3731	660	583	29.90	26.87
BSB-2-16-3	0.737	3731	665	588	30.23	27.30
BSS-2-16-1	0.739	3732	662	585	15.04	13.65
BSS-2-16-2	0.739	3732	662	585	15.04	13.65
BSS-2-16-3	0.739	3732	662	585	15.04	13.65
BSS-2-16-4	0.739	3732	662	585	15.04	13.65
BSS-2-16-5	0.739	3732	662	585	15.04	13.65
BS-2-20-1A	0.352	1934	817	991	7.36	6.25
BS-2-20-2A	0.352	1934	817	991	7.47	6.03
BS-2-20-1B	0.352	1934	817	991	7.41	6.20
BS-2-20-2B	0.352	1934	817	991	7.36	5.98
BS-2-20-1C	0.352	1934	817	991	7.41	6.25
BS-2-20-2C	0.352	1934	817	991	7.41	6.07
BSB-2-20-1	0.362	1614	623	802	12.51	11.97

Note: 1 in. = 25.4 mm; 1 lb. = 4.45 N.

TABLE 3 (CONTINUED) COMPUTED NOMINAL SHEAR STRENGTHS AND BENDING MOMENTS

Specimen No.	a/h	V_n (lbs)	$(V_n)_{m1}$ (lbs)	$(V_n)_{m2}$ (lbs)	M_n (k-in)	$(M_n)_m$ (k-in)
BSB-2-20-2	0.357	1614	652	815	12.04	11.45
BSB-2-20-3	0.734	2264	406	360	17.19	13.52
BSB-2-20-4	0.733	2264	407	361	17.19	13.50
BSS-2-20-1	0.734	2264	406	360	8.60	6.76
BSS-2-20-2	0.734	2264	406	360	8.60	6.76
BSS-2-20-3	0.734	2264	406	360	8.60	6.76
BSS-2-20-4	0.734	2264	406	360	8.60	6.76
BSS-2-20-5	0.734	2264	406	360	8.60	6.76
BSS-2-20-6	0.355	1614	664	820	2.78	5.93
BSS-2-20-7	0.355	1614	664	820	2.21	5.93

Notes: V_n = Nominal Shear Strength Based on the 1986 AISI Specification
$(V_n)_{m1}$ = Shear Strength Based on Eqs.3 and 4 for Reduction Factor
$(V_n)_{m2}$ = Shear Strength Based on Eq. 5 for Reduction Factor
M_n = Nominal Moment Capacity Based on the 1986 AISI Specification
$(M_n)_m$ = Moment Capacity Based on the Effective Net Section Approach, Eq. 1
1 in. = 25.4 mm.; 1 lb. = 4.45 N.

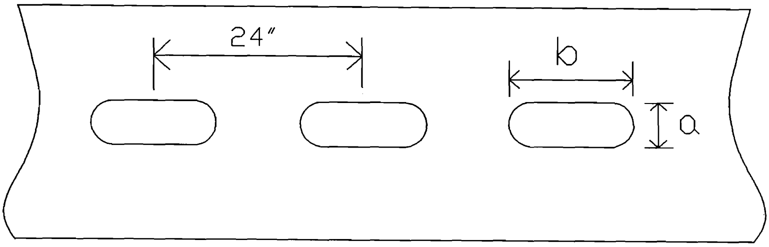

Figure 1. Web Opening Configuration

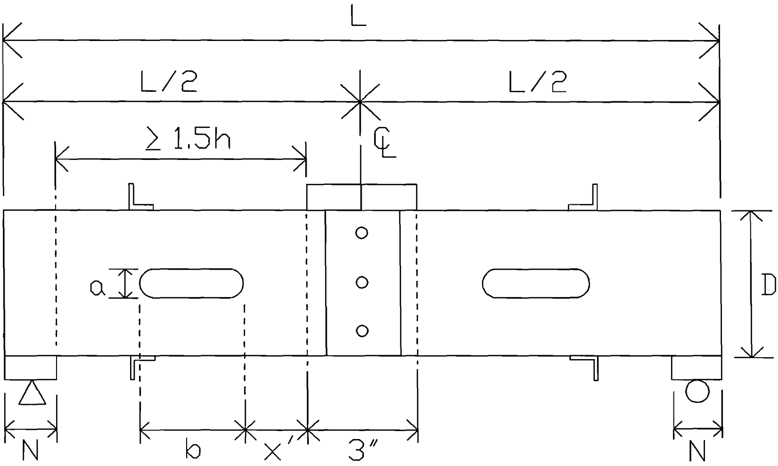

Figure 2. Test Setup for Combined Bending and Shear Test Specimens

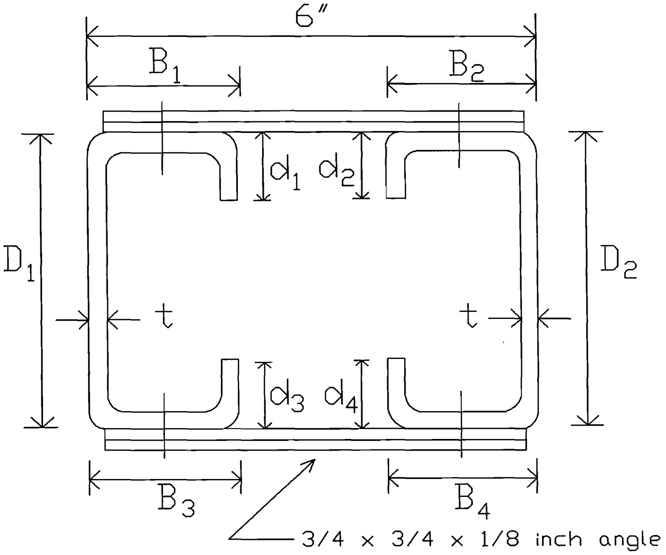

Figure 3. Typical Cross Section of Test Specimen

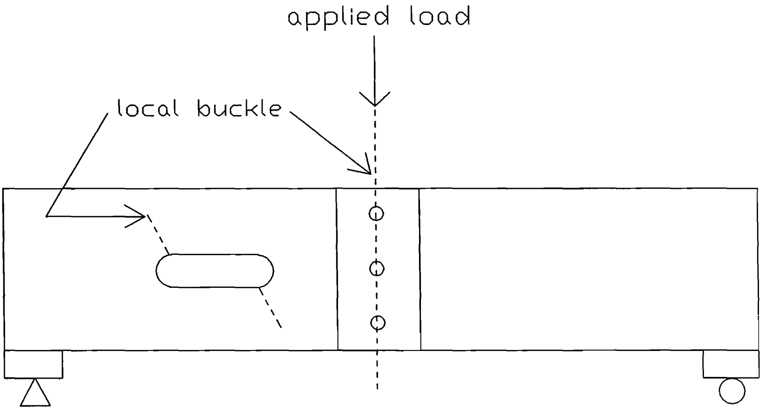

Figure 4. Typical Failure Mode Combined Bending and Shear

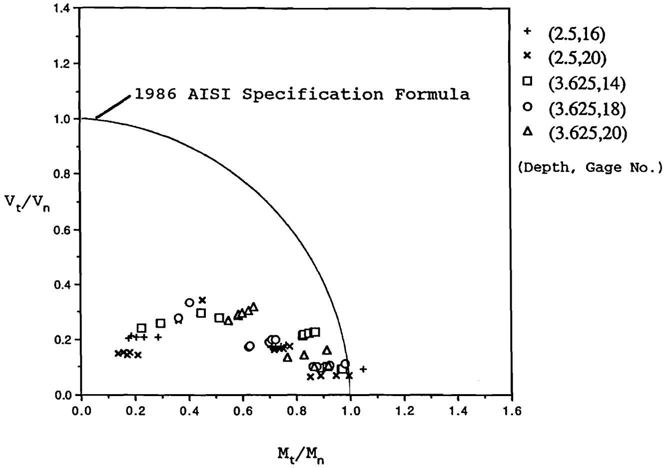

Figure 5. Interaction Diagram for V_t/V_n and M_t/M_n Based on 1986 AISI Specification for Solid Webs

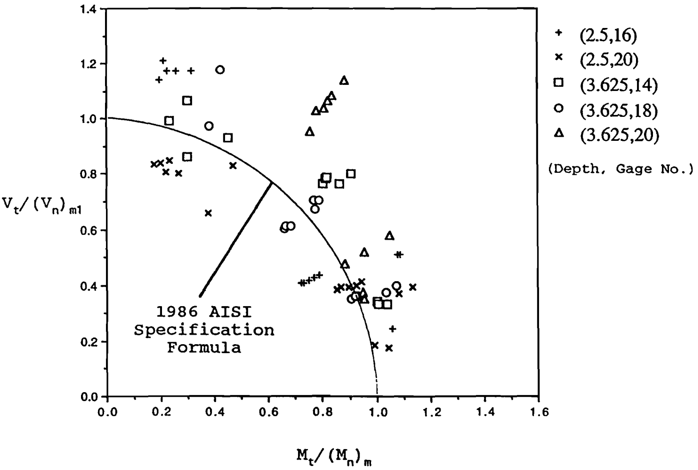

Figure 6. Interaction Diagram for $V_t/(V_n)_{m1}$ and $M_t/(M_n)_m$ Based on the Shear Reduction Factor and Effective Net Section Approach

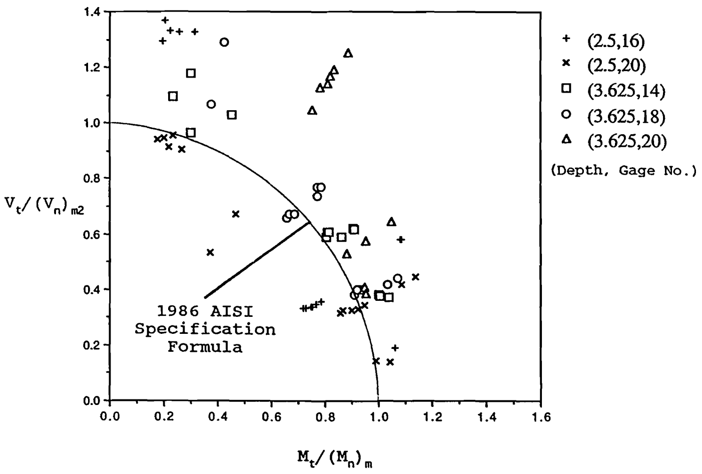

Figure 7. Interaction Diagram for $V_t/(V_n)_{m2}$ and $M_t/(M_n)_m$ Based on the Shear Reduction Factor and Effective Net Section Approach

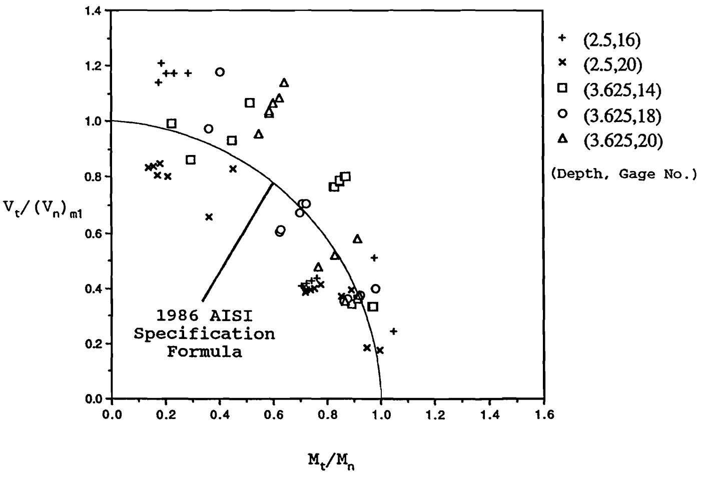

Figure 8. Interaction Diagram for $V_t/(V_n)_{m1}$ and M_t/M_n Based on the Shear Reduction Factor Only

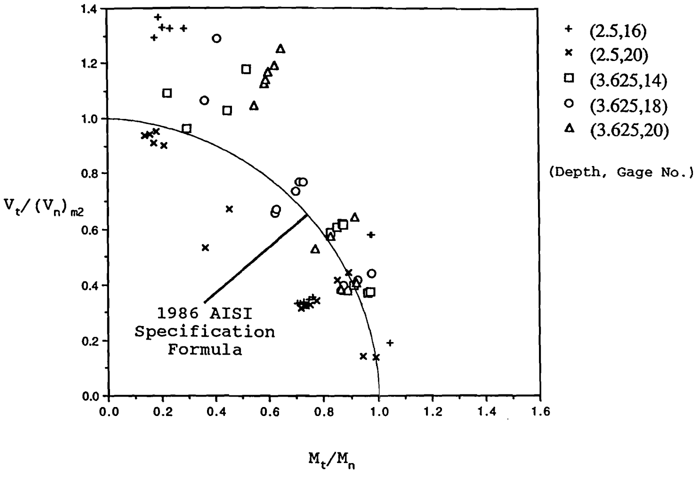

Figure 9. Interaction Diagram for $V_t/(V_n)_{m2}$ and M_t/M_n Based on the Shear Reduction Factor Only