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Shear and combined bending and shear behavior of web elements with openings

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INTRODUCTION

The purpose of this phase of the research project has been to investigate the behavior of a single web with web openings when subjected to either a constant shear force or a combined shear force and bending.

The literature indicates that the main parameter that appears to effect the shear capacity is the ratio of web opening depth to web depth, a/h. Thus, the objective for this phase of the investigation was to experimentally determine the shear strength, and compare the tested shear strength with the computed shear strength as given by the AISI Specification for solid webs. The experimental results are also compared to a shear reduction equation derived by Davis and Yu (3) for circular holes with certain limitations.

The interaction between shear forces and bending moments on the ultimate capacity of the web elements was experimentally investigated. The test results are compared with the interaction equations as given in the AISI Specification for solid webs.

This report summarizes the test procedure, the test results, and the evaluation of the results for this study. Based on the findings of this study, design equations have been developed and are presented herein.

TEST SPECIMENS

Three common industry standard C-sections (2.5, 3.625 and 12-in. deep) were tested for various thicknesses of each C-section. The cross-section dimensions, thicknesses and geometric parameters of each test specimen are recorded in Table 1 for the shear tests and Tables 6-1 through 6-5 for the combined bending and shear tests.

The material properties of the steel, for each test specimen, were established by standard tensile coupon specimens cut from the web of the section. Tables 2 and 7 list the tensile test data for thickness, yield strength, ultimate tensile strength and percent elongation in 2-in. gage length.

Each beam specimen was fabricated by cutting the C-sections to the required length. Specimens having three different web opening sizes [(0.75 x 2 inch, 0.75 x 4 inch, and 1.50 x 4 inch)] located at the mid-height of the web were tested. The dimensions of the web openings are listed in Tables 1, 6-1, 6-2, 6-3, 6-4, and 6-5 and shown in Fig. 2. For the combination of bending and shear, the location of the opening, as shown in Fig. 2, was also investigated.

TEST SETUP

In order to prevent lateral-torsional buckling, each test specimen consisted of two C-shaped beams connected together using 3/4 x 3/4 x 1/8 inch angles and self-drilling screws. For cross section details, see Figs. 2 and 3.

When thin steel members with web openings are subjected to concentrated loads or reactions, web crippling may occur. To preclude web crippling at midspan, two stiffeners were attached vertically to each web.

For the 12-in. deep section (Specimen No. SR-12), vertical stiffeners were also added to each web at the end support to prevent web crippling. To provide additional lateral support, two diagonal braces were connected to the angles as shown by Fig. 5. To preclude a bending failure, the strength was increased by a steel strip attached to the top and bottom flanges of each 12-in. C-section. These strips were attached by using self-drilling screws, spaced 1-in. on center.

Shown by Figs. 2 and 4, the test setup was the same for both shear tests and combined bending and shear tests. Each test specimen was subjected to a concentrated load at midspan (Figs. 2 and 4) until the maximum load of the member was obtained.

TEST PROCEDURE

All specimens were tested in a Tinius-Olsen universal testing machine as simple supported beams subjected to a concentrated load at midspan. The load was increased gradually until the beam reached failure and could no longer bear additional load.

TEST RESULTS

(1) Shear behavior

To date a total of twenty tests of beams with webs having punchouts were conducted in this experimental investigation of shear behavior. The shear strength of the beam webs was influenced primarily by the depth-to-thickness ratio of the web (h/t), and the ratio of web opening depth to web depth (a/h). For the twenty tests reported herein, the web depth-to-thickness ratios, h/t, ranges from 34.0 to 210.0 and the a/h ratios vary from 0.13 to 0.74. The shear failure load per web, V_t, is taken as 1/4 of the ultimate midspan load. Table 3 tabulates the test results.

(2) Combined bending and shear behavior

A total of 68 tests were conducted, 30 tests experienced combined bending and shear, 20 tests failed by pure bending and 18 tests focused on pure shear. The test results are listed in Tables 8-1 and 8-2. The failure load, V_t, is 1/4 of the the maximum midspan load. For the study of beams subjected to combined bending and shear, the web-to-thickness ratios, h/t, ranges from 34.0 to 98.0 and the a/h ratios vary from 0.35 to 0.74.

SHEAR CAPACITY CALCULATION

For solid web elements subjected to shear only, the design strength can be estimated by applying the equations from Section C3.2 of the 1991 Edition of the AISI LRFD Specification (2). These nominal equations also serve as the basis for the shear strength equations given in the AISI ASD Specification (1). The equations are as follows:

(a) For $h/t \le \sqrt{Ek_v/F_y}$:

$$V_n = 0.577F_y ht \quad \text{(Eq. 1)}$$

(b) For $\sqrt{Ek_v/F_y} < h/t \le 1.415\sqrt{Ek_v/F_y}$:

$$V_n = 0.64t^2\sqrt{k_v F_y E} \quad \text{(Eq. 2)}$$

(c) For $h/t > 1.415\sqrt{Ek_v/F_y}$:

$$V_n = 0.905Ek_v t^3/h \quad \text{(Eq. 3)}$$

where

V_n = Nominal shear strength of web

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

when $a/h \le 1.0$

$$k_v = 4.00+5.34/(a+h)^2$$

when $a/h > 1.0$

$$k_v = 5.34+4.00/(a+h)^2$$

where

a = the shear panel length for unreinforced web element

= distance between transverse stiffeners for reinforced web elements

The above equations are for a web element with no opening or punchout. Based on the above equations, the nominal shear strength, V_n, of each test specimen was calculated and is listed in Tables 4, 8-1, and 8-2.

EVALUATION OF TEST RESULTS

(1) Shear behavior

The influence of a web opening on the ultimate shear strength is not accounted for by the current AISI Specifications (1,2). Based on the AISI Specification for shear strength of the solid webs, the ratio of V_t/V_n (Table 4) shows the reduction of the shear strength of C-section with web openings.

Based on a plot of the test data, Fig. 6, and using a linear regression analysis, two straight lines were derived for a shear strength reduction factor q_s ($q_s=V_t/V_n$). Equations 4 and 5 are the linear relationships that define these two straight lines for elliptical holes:

when $a/h \le 0.35$:

$$q_s = 1.610-3.727(a/h) \le 1.0 \qquad \text{(Eq. 4)}$$

when $0.35 \le a/h \le 0.8$:

$$q_s = 0.443-0.361(a/h) \qquad \text{(Eq. 5)}$$

Based on twelve tests of I-beams Davis and Yu (3) derived Eq.

6 for web design when a circular hole was present at mid-depth in a web element.

$$q_s = 1.0-1.1(d/h) \qquad \text{(Eq. 6)}$$

where

d = the diameter of a circular hole

h = the clear distance between flanges measured along the plane of the web

Equation 6 is limited only to $a/h \leq 0.5$. The comparison between Eq. 6 and the test data of this study is indicated in Table 5 and shown in Fig. 6.

(2) Combined bending and shear behavior

To study the bending and shear behavior, two methods were applied to the analysis of the combined shear force and bending moment. The nominal shear strength and bending moment were computed as follows:

(i) Based on the 1986 AISI Specification V_n and M_n are listed in Table 9.

(ii) Based on the shear reduction factor (Eqs. 4 or 5) and the effective net section modulus approach as reported in Reference 5, $(V_n)_m$ and $(M_n)_m$ are given in Table 9.

The shear ratios (V_t/V_n and $V_t/(V_n)_m$) and moment ratios (M_t/M_n and $M_t/(M_n)_m$) were computed and shown in Table 9.

DISCUSSION OF TEST RESULTS

(1) Shear behavior

Because the maximum shear stress occurs at mid-depth, where web material is removed, and because an elliptical web opening creates a stress concentration at the corners of the opening, premature shear failures occurred in the diagonal direction at the location of the web openings. See Figure 7. For the configurations used in the tests, the major parameter that appears to influence the shear strength is a/h. This parameter (a/h) is emphasized in the development of the reduction factor, q_s, for evaluating shear strength. From the experimental results and the above analysis, the reduction, q_s, is given by Eqs. 4 and 5.

As shown by Fig. 6, when $a/h \le 0.23$, the q_s of the Davis and Yu is lower than that of Eq. 4. When $a/h \ge 0.23$, the situation is reversed. The lower q_s values given by Eqs. 4 and 5 are being attributed to the web opening size and shape. It should be noted that for the study of Davis and Yu, specimens had circular openings, while as for the tests reported herein, the web openings were elliptical.

(2) Combined bending and shear behavior

The type of failure mode was indicated in Fig. 7b. The failure pattern is defined by bending failure in the midspan and shear diagonal failure around the corners of the opening. These two failure modes almost took place simultaneously when the ultimate load was achieved.

The values of V_t/V_n and M_t/M_n (Table 9) are shown graphically by

Fig. 8. Also shown in Fig. 8 is the unit circle which represents the present AISI design approach for combined bending and shear. As indicated by Fig. 8, the AISI Specification does not provide a good relationship between bending and shear for webs with openings.

Figure 9 is a plot of the relationship between $V_t/(V_n)_m$ and $M_t/(M_n)_m$ (Table 9). It presents a good correlation between bending moment and shear force when compared with the AISI design approach.

Based on a plot of $V_t/(V_n)_m$ and M_t/M_n, Fig. 10 also demonstrates a good interaction between bending moment and shear force for web elements with openings. Figure 10 consideres the shear reduction factor only. Figure 10 is a more appropriate comparison because at the location of maximum moment, the web did not have an opening.

SUMMARY

An investigation was conducted to study the behavior of C-shaped members with elliptical web openings subjected to a either shear or combined bending and shear failure. For the shear strength, based on 20 beam specimen tests, modified equations were developed for design. For the combined bending and shear behavior, 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 modified or only the nominal shear strength are adjusted to account for the web opening.

REFERENCES

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3. Davis, C.S., and Yu, W.W., "Cold-Formed Steel Members with Perforated Elements", Journal of the Structural Division, ASCE, Vol. 99, No. ST10, Proc. Paper 10059, October 1973, pp. 2061-2077
4. "Structural Behavior of Beam Webs Subjected to A Combination of Bending And Shear", by R.A. LaBoube, and W.W. Yu, June 1978
5. Shan, M.Y., Batson, K.D., LaBoube, R.A., and Yu, W.W., "Flexural Behavior of Web Elements with Openings", Fourth Progress Report, Department of Civil Engineering, University of Missouri-Rolla, MO, January 15, 1992

TABLE 1
DIMENSIONS OF TEST SPECIMENS
SUBJECTED TO SHEAR

Beam Specimen No.	Cross-Section Dimenisions (inches)											Hole Geom. (in.)	
	Thick.	D1	D2	B1	B2	B3	B4	d1	d2	d3	d4	b	a
SU-4	0.071	3.65	3.63	1.63	1.64	1.63	1.63	0.54	0.51	0.49	0.52	4	1.50
SU-5	0.059	2.47	2.46	1.63	1.63	1.62	1.62	0.47	0.49	0.52	0.49	4	1.50
SU-6	0.033	2.42	2.43	1.63	1.64	1.63	1.62	0.42	0.42	0.50	0.50	4	1.50
SU-8	0.039	2.51	2.50	1.60	1.61	1.59	1.60	0.39	0.42	0.45	0.41	2	0.75
SU-9	0.044	3.70	3.65	1.56	1.57	1.57	1.58	0.57	0.57	0.56	0.50	4	1.50
SU-10	0.077	3.69	3.69	1.64	1.63	1.64	1.63	0.55	0.54	0.59	0.54	4	1.50
SR-12	0.055	12.02	11.97	1.57	1.57	1.57	1.57	0.46	0.57	0.55	0.48	4	1.50

Note:
1. See Fig. 1 for the symbols used for dimensions.
2. See Fig. 2 for the symbols used for the hole geometry.
3. SU: Single Unreinforced (Web)
4. SR: Single Reinforced (Web)

TABLE 2
MATERIAL PROPERTIES
FOR SHEAR TEST SPECIMENS

Specimen No.	Thickness (in.)	F_y (ksi)	F_u (ksi)	Elongation (%)
SU-4	0.071	81	104	22
SU-5	0.059	54	75	39
SU-6	0.033	67	72	35
SU-8	0.039	34	48	44
SU-9	0.044	47	60	31
SU-10	0.077	64	78	23
SR-12	0.055	49	57	32

Note:
1. SU: Single Unreinforced (Web)
2. SR: Single Reinforced (Web)

TABLE 3
EXPERIMENTAL DATA FOR SHEAR TEST SPECIMENS

Specimen no.	L(in.)	N(in.)	h/t	a/h	V_t(lbs)
SU-4-7	26.54	0	45	0.47	2760
SU-5-3	19.10	1.0	34	0.74	801
SU-5-4	19.10	1.0	34	0.74	778
SU-5-5	19.10	1.0	34	0.74	775
SU-5-6	19.10	1.0	34	0.74	775
SU-5-7	19.10	1.0	34	0.74	756
SU-6-3	19.16	1.0	62	0.73	338
SU-6-4	19.16	1.0	62	0.73	341
SU-6-5	19.16	1.0	62	0.73	328
SU-6-6	19.16	1.0	62	0.73	325
SU-6-7	19.16	3.0	62	0.73	344
SU-8-8	22.11	6.0	54	0.35	550
SU-8-9	22.11	6.0	54	0.35	438
SU-9-10	27.54	5.0	74	0.46	1125
SU-9-11	27.54	6.0	74	0.46	929
SU-10-5	34.81	6.0	42	0.46	2406
SU-10-6	34.81	6.0	42	0.46	2750
SU-10-7	34.81	6.0	42	0.46	2556
SR-12-1	40.56	1.0	210	0.13	2563
SR-12-2	40.56	1.0	210	0.13	3500

Note:
1. SU: Single Unreinforced (Web)
2. SR: Single Reinforced (Web)

TABLE 4
THE EVALUATION OF SHEAR TEST DATA

Specimen no.	h/t	a/h	V_t	V_n	Ratio
SU-4-7	45	0.47	2760	11524	0.24
SU-5-3	34	0.74	801	3732	0.21
SU-5-4	34	0.74	778	3732	0.21
SU-5-5	34	0.74	775	3732	0.21
SU-5-6	34	0.74	775	3732	0.21
SU-5-7	34	0.74	756	3732	0.20
SU-6-3	62	0.73	338	2264	0.15
SU-6-4	62	0.73	341	2264	0.15
SU-6-5	62	0.73	328	2264	0.14
SU-6-6	62	0.73	325	2264	0.14
SU-6-7	62	0.73	344	2264	0.15
SU-8-8	54	0.35	550	1614	0.34
SU-8-9	54	0.35	438	1614	0.27
SU-9-10	74	0.46	1125	3371	0.33
SU-9-11	74	0.46	929	3371	0.28
SU-10-5	42	0.46	2406	9213	0.26
SU-10-6	42	0.46	2750	9213	0.30
SU-10-7	42	0.46	2556	9213	0.28
SR-12-1	210	0.13	2563	2700	0.95
SR-12-2	210	0.13	3500	2700	1.30

Note:
1. SU: Single Unreinforced (Web)
2. SR: Single Reinforced (Web)
3. Ratio = V_t/V_n

TABLE 5
COMPARISON OF SHEAR CAPACITY WITH DAVIS AND YU'S REDUCTION EQUATION

Specimen no.	h/t	a/h	V_t	V_n	ratio	q_s
SU-4-7	45	0.47	2760	11524	0.24	0.48
SU-5-3	34	0.74	801	3732	0.21	--
SU-5-4	34	0.74	778	3732	0.21	--
SU-5-5	34	0.74	775	3732	0.21	--
SU-5-6	34	0.74	775	3732	0.21	--
SU-5-7	34	0.74	756	3732	0.20	--
SU-6-3	62	0.73	338	2264	0.15	--
SU-6-4	62	0.73	341	2264	0.15	--
SU-6-5	62	0.73	328	2264	0.14	--
SU-6-6	62	0.73	325	2264	0.14	--
SU-6-7	62	0.73	344	2264	0.15	--
SU-8-8	54	0.35	550	1614	0.34	0.62
SU-8-9	54	0.35	438	1614	0.27	0.62
SU-9-10	74	0.46	1125	3371	0.33	0.49
SU-9-11	74	0.46	929	3371	0.28	0.49
SU-10-5	42	0.46	2406	9213	0.26	0.49
SU-10-6	42	0.46	2750	9213	0.30	0.49
SU-10-7	42	0.46	2556	9213	0.28	0.49
SR-12-1	210	0.13	2563	2700	0.95	0.86
SR-12-2	210	0.13	3500	2700	1.30	0.86

Note:
1. SU: Single Unreinforced (Web)
2. SR: Single Reinforced (Web)
3. The Limit of Davis and Yu's Equation : $0.0 \leq a/h \leq 0.5$

TABLE 6-1
DIMENSIONS OF TEST SPECIMENS
SUBJECTED TO COMBINED BENDING AND SHEAR

Beam Specimen No.	Cross-Section Dimensions (inches)											Hole Geom. (in.)	
	Thick.	D1	D2	B1	B2	B3	B4	d1	d2	d3	d4	b	a
BS-2-16-1A	0.056	2.55	2.55	1.63	1.63	1.64	1.64	0.50	0.49	0.51	0.49	4	0.75
BS-2-16-2A	0.056	2.55	2.55	1.63	1.63	1.63	1.63	0.50	0.49	0.51	0.50	4	0.75
BS-2-16-1B	0.056	2.54	2.54	1.63	1.63	1.63	1.63	0.51	0.47	0.47	0.51	4	0.75
BS-2-16-2B	0.056	2.54	2.55	1.63	1.63	1.63	1.63	0.51	0.47	0.51	0.50	4	0.75
BS-2-16-1C	0.056	2.54	2.55	1.63	1.63	1.63	1.63	0.47	0.52	0.50	0.48	4	0.75
BS-2-16-2C	0.056	2.55	2.55	1.63	1.63	1.63	1.64	0.47	0.51	0.51	0.47	4	0.75
BSB-2-16-1	0.062	2.51	2.51	1.61	1.61	1.63	1.61	0.40	0.45	0.42	0.43	2	0.75
BSB-2-16-2	0.059	2.46	2.46	1.62	1.63	1.62	1.61	0.47	0.46	0.51	0.51	4	1.50
BSB-2-16-3	0.059	2.47	2.46	1.63	1.62	1.62	1.63	0.47	0.52	0.52	0.46	4	1.50
BSS-2-16-1	0.059	2.47	2.46	1.63	1.63	1.62	1.62	0.47	0.49	0.52	0.49	4	1.50
BSS-2-16-2	0.059	2.47	2.46	1.63	1.63	1.62	1.62	0.47	0.49	0.52	0.49	4	1.50
BSS-2-16-3	0.059	2.47	2.46	1.63	1.63	1.62	1.62	0.47	0.49	0.52	0.49	4	1.50
BSS-2-16-4	0.059	2.47	2.46	1.63	1.63	1.62	1.62	0.47	0.49	0.52	0.49	4	1.50
BSS-2-16-5	0.059	2.47	2.46	1.63	1.63	1.62	1.62	0.47	0.49	0.52	0.49	4	1.50

Note:
1. See Fig. 1 for the symbols used for dimensions.
2. See Fig. 2 for the symbols used for the hole geometry.
3. BS: Combined Bending and Shear
4. BSB: Combined Bending and Shear for Pure Bending behavior
5. BSS: Combined Bending and Shear for Pure Shear behavior
6. Specimen Designation: BS-2-16-1A
   2=Nominal Depth, 16=Gage No., 1=Test No.
   Type A:x=0.0 in., Type B:x=0.5h in., Type C:x=h in.

TABLE 6-2
DIMENSIONS OF TEST SPECIMENS
SUBJECTED TO COMBINED BENDING AND SHEAR

Beam Specimen No.	Cross-Section Dimensions (inches)											Hole Geom. (in.)	
	Thick.	D1	D2	B1	B2	B3	B4	d1	d2	d3	d4	b	a
BS-2-20-1A	0.032	2.52	2.51	1.58	1.58	1.57	1.58	0.45	0.48	0.48	0.42	4	0.75
BS-2-20-2A	0.032	2.51	2.51	1.58	1.57	1.57	1.58	0.43	0.48	0.43	0.44	4	0.75
BS-2-20-1B	0.032	2.51	2.51	1.59	1.58	1.58	1.59	0.43	0.47	0.46	0.42	4	0.75
BS-2-20-2B	0.032	2.51	2.51	1.58	1.58	1.57	1.59	0.42	0.47	0.47	0.42	4	0.75
BS-2-20-1C	0.032	2.52	2.51	1.59	1.57	1.57	1.58	0.42	0.48	0.47	0.43	4	0.75
BS-2-20-2C	0.032	2.51	2.52	1.58	1.58	1.58	1.58	0.44	0.48	0.47	0.43	4	0.75
BSB-2-20-1	0.039	2.50	2.48	1.60	1.60	1.60	1.60	0.42	0.41	0.42	0.41	2	0.75
BSB-2-20-2	0.039	2.51	2.52	1.59	1.62	1.58	1.60	0.36	0.42	0.47	0.41	2	0.75
BSB-2-20-3	0.033	2.42	2.42	1.63	1.64	1.63	1.62	0.42	0.42	0.50	0.50	4	1.50
BSB-2-20-4	0.033	2.42	2.43	1.63	1.64	1.63	1.62	0.42	0.41	0.50	0.50	4	1.50
BSS-2-20-1	0.039	2.51	2.50	1.60	1.61	1.59	1.60	0.39	0.42	0.45	0.41	2	0.75
BSS-2-20-2	0.039	2.51	2.50	1.60	1.61	1.59	1.60	0.39	0.42	0.45	0.41	2	0.75
BSS-2-20-3	0.033	2.42	2.43	1.63	1.64	1.63	1.62	0.42	0.42	0.50	0.50	4	1.50
BSS-2-20-4	0.033	2.42	2.43	1.63	1.64	1.63	1.62	0.42	0.42	0.50	0.50	4	1.50
BSS-2-20-5	0.033	2.42	2.43	1.63	1.64	1.63	1.62	0.42	0.42	0.50	0.50	4	1.50
BSS-2-20-6	0.033	2.42	2.43	1.63	1.64	1.63	1.62	0.42	0.42	0.50	0.50	4	1.50
BSS-2-20-7	0.033	2.42	2.43	1.63	1.64	1.63	1.62	0.42	0.42	0.50	0.50	4	1.50

See Table 6-1 for Notes

TABLE 6-3
DIMENSIONS OF TEST SPECIMENS
SUBJECTED TO COMBINED BENDING AND SHEAR

Beam Specimen No.	Cross-Section Dimensions (inches)											Hole Geom. (in.)	
	Thick.	D1	D2	B1	B2	B3	B4	d1	d2	d3	d4	b	a
BS-3-14-1A	0.067	3.66	3.65	1.63	1.63	1.63	1.63	0.55	0.47	0.49	0.55	4	1.50
BS-3-14-2A	0.067	3.65	3.66	1.63	1.63	1.63	1.64	0.54	0.48	0.49	0.56	4	1.50
BS-3-14-1B	0.067	3.66	3.66	1.63	1.63	1.63	1.63	0.55	0.48	0.48	0.55	4	1.50
BS-3-14-2B	0.067	3.66	3.66	1.63	1.63	1.63	1.63	0.54	0.49	0.50	0.55	4	1.50
BS-3-14-1C	0.067	3.66	3.66	1.62	1.63	1.63	1.62	0.54	0.46	0.48	0.54	4	1.50
BS-3-14-2C	0.067	3.66	3.66	1.63	1.63	1.63	1.63	0.52	0.47	0.50	0.54	4	1.50
BSB-3-14-1	0.077	3.68	3.68	1.65	1.64	1.63	1.63	0.57	0.55	0.56	0.52	4	1.50
BSB-3-14-2	0.077	3.69	3.69	1.63	1.62	1.64	1.63	0.53	0.53	0.62	0.55	4	1.50
BSB-3-14-3	0.071	3.65	3.62	1.62	1.66	1.63	1.63	0.54	0.55	0.49	0.50	4	1.50
BSB-3-14-4	0.071	3.64	3.63	1.63	1.62	1.62	1.63	0.54	0.47	0.49	0.54	4	1.50
BSS-3-14-1	0.077	3.69	3.69	1.64	1.63	1.64	1.63	0.55	0.54	0.59	0.54	4	1.50
BSS-3-14-2	0.077	3.69	3.69	1.64	1.63	1.64	1.63	0.55	0.54	0.59	0.54	4	1.50
BSS-3-14-3	0.071	3.65	3.63	1.63	1.64	1.63	1.63	0.54	0.51	0.49	0.52	4	1.50
BSS-3-14-4	0.071	3.65	3.63	1.63	1.64	1.63	1.63	0.54	0.51	0.49	0.52	4	1.50

See Table 6-1 for Notes

TABLE 6-4
DIMENSIONS OF TEST SPECIMENS
SUBJECTED TO COMBINED BENDING AND SHEAR

Beam Specimen No.	Cross-Section Dimensions (inches)											Hole Geom. (in.)	
	Thick.	D1	D2	B1	B2	B3	B4	d1	d2	d3	d4	b	a
BS-3-18-1A	0.045	3.63	3.63	1.63	1.63	1.63	1.63	0.48	0.48	0.47	0.49	4	1.50
BS-3-18-2A	0.045	3.66	3.65	1.59	1.59	1.59	1.59	0.46	0.50	0.49	0.45	4	1.50
BS-3-18-1B	0.045	3.65	3.63	1.59	1.63	1.59	1.63	0.44	0.47	0.50	0.44	4	1.50
BS-3-18-2B	0.045	3.65	3.64	1.59	1.63	1.59	1.62	0.50	0.50	0.43	0.47	4	1.50
BS-3-18-1C	0.045	3.64	3.65	1.63	1.59	1.63	1.59	0.49	0.44	0.48	0.51	4	1.50
BS-3-18-2C	0.045	3.65	3.64	1.63	1.63	1.63	1.63	0.47	0.51	0.49	0.47	4	1.50
BSB-3-18-1	0.044	3.75	3.65	1.56	1.56	1.57	1.58	0.58	0.56	0.58	0.54	4	1.50
BSB-3-18-2	0.044	3.65	3.64	1.56	1.58	1.56	1.57	0.56	0.57	0.54	0.54	4	1.50
BSB-3-18-3	0.044	3.61	3.63	1.61	1.61	1.65	1.62	0.51	0.52	0.50	0.50	4	1.50
BSB-3-18-4	0.044	3.62	3.63	1.62	1.66	1.65	1.64	0.50	0.50	0.52	0.52	4	1.50
BSS-3-18-1	0.044	3.70	3.65	1.56	1.57	1.57	1.58	0.57	0.57	0.56	0.50	4	1.50
BSS-3-18-2	0.044	3.70	3.65	1.56	1.57	1.57	1.58	0.57	0.57	0.56	0.50	4	1.50

See Table 6-1 for Notes

TABLE 6-5
DIMENSIONS OF TEST SPECIMENS
SUBJECTED TO COMBINED BENDING AND SHEAR

Beam Specimen No.	Cross-Section Dimensions (inches)											Hole Geom. (in.)	
	Thick.	D1	D2	B1	B2	B3	B4	d1	d2	d3	d4	b	a
BS-3-20-1A	0.033	3.62	3.62	1.62	1.62	1.61	1.62	0.47	0.42	0.45	0.46	4	1.50
BS-3-20-2A	0.033	3.61	3.61	1.61	1.64	1.62	1.63	0.49	0.48	0.43	0.48	4	1.50
BS-3-20-1B	0.033	3.60	3.60	1.63	1.64	1.64	1.62	0.48	0.47	0.45	0.47	4	1.50
BS-3-20-2B	0.033	3.62	3.60	1.62	1.64	1.64	1.63	0.44	0.45	0.45	0.49	4	1.50
BS-3-20-1C	0.033	3.62	3.61	1.62	1.63	1.62	1.62	0.48	0.46	0.41	0.49	4	1.50
BS-3-20-2C	0.033	3.62	3.62	1.64	1.62	1.62	1.63	0.45	0.44	0.45	0.45	4	1.50
BSB-3-20-1	0.044	3.65	3.71	1.56	1.64	1.55	1.59	0.52	0.56	0.55	0.56	4	1.50
BSB-3-20-2	0.044	3.67	3.69	1.56	1.59	1.55	1.61	0.60	0.56	0.52	0.59	4	1.50
BSB-3-20-3	0.036	3.61	3.60	1.63	1.62	1.63	1.62	0.46	0.47	0.46	0.47	4	1.50
BSB-3-20-4	0.036	3.61	3.61	1.64	1.63	1.64	1.63	0.46	0.47	0.47	0.47	4	1.50
BSB-3-20-5	0.036	3.60	3.60	1.63	1.63	1.62	1.63	0.47	0.46	0.46	0.47	4	1.50

See Table 6-1 for Notes

TABLE 7
MATERIAL PROPERTIES
FOR COMBINED BENDING AND SHEAR TEST SPECIMENS

Specimen No.	Thickness (in.)	F_y (ksi)	F_u (ksi)	Elongation (%)
BS-2-16	0.056	55	68	39
BSB-2-16-1	0.062	37	49	38
BSB-2-16-2,3	0.059	54	75	39
BSS-2-16	0.059	54	75	39
BS-2-20	0.032	55	65	37
BSB-2-20-1,2	0.039	34	48	44
BSB-2-20-3,4	0.033	67	72	35
BSS-2-20-1,2	0.039	34	48	44
BSS-2-20-3,4,5,6,7,	0.033	67	72	35
BS-3-14	0.067	48	55	42
BSB-3-14-1,2	0.077	64	78	23
BSB-3-14-3,4	0.071	81	104	22
BSS-3-14-1,2	0.077	64	78	23
BSS-3-14-3,4	0.071	81	104	22
BS-3-18	0.045	53	64	41
BSB-3-18-1,2	0.044	47	60	31
BSB-3-18-3,4	0.044	53	70	24
BSS-3-18-1,2	0.044	47	60	31
BS-3-20	0.033	59	69	40
BSB-3-20-1,2	0.044	47	60	31
BSB-3-20-3,4,5	0.036	64	79	29

Note:

1. Specimen Designation BS-2-16 is appropriate for test specimens:
   BS-2-16-1A
   BS-2-16-2A
   BS-2-16-1B
   BS-2-16-2B
   BS-2-16-1C
   BS-2-16-2C
2. Specimen Designation BSB-2-16-2,3 is appropriate for test specimens:
   BSB-2-16-2
   BSB-2-16-3
3. See Table 6-1 for Other Notes

TABLE 8-1
EXPERIMENTAL DATA FOR COMBINED BENDING AND SHEAR TEST SPECIMENS

Specimen No.	Span Length (in.)	h/t	a/h	V_t (lbs)	V_n (lbs)	$(V_n)_m$ (lbs)
BS-2-16-1A	40.0	38	0.35	645	3788	1194
BS-2-16-2A	40.0	38	0.35	650	3788	1194
BS-2-16-1B	40.0	38	0.35	688	3788	1194
BS-2-16-2B	40.0	38	0.35	658	3788	1194
BS-2-16-1C	40.0	38	0.35	658	3788	1194
BS-2-16-2C	40.0	38	0.35	675	3788	1194
BSB-2-16-1	150.0	33	0.36	260	2745	1624
BSB-2-16-2	150.0	34	0.74	338	3731	657
BSB-2-16-3	150.0	35	0.74	340	3731	657
BSS-2-16-1	19.1	34	0.74	800	3749	665
BSS-2-16-2	19.1	34	0.74	778	3749	665
BSS-2-16-3	19.1	34	0.74	775	3749	665
BSS-2-16-4	19.1	34	0.74	775	3749	665
BSS-2-16-5	19.1	34	0.74	756	3749	665
BS-2-20-1A	40.0	66	0.35	320	1934	610
BS-2-20-2A	40.0	66	0.35	320	1934	610
BS-2-20-1B	40.0	66	0.35	313	1934	610
BS-2-20-2B	40.0	66	0.35	325	1934	610
BS-2-20-1C	40.0	66	0.35	320	1934	610
BS-2-20-2C	40.0	66	0.35	338	1934	610
BSB-2-20-1	150.0	54	0.36	115	1614	508
BSB-2-20-2	150.0	54	0.35	115	1614	508
BSB-2-20-3	150.0	62	0.73	150	2264	402
BSB-2-20-4	150.0	62	0.73	160	2264	402
BSS-2-20-1	22.1	54	0.35	550	1622	511
BSS-2-20-2	22.1	54	0.35	438	1622	511
BSS-2-20-3	19.2	62	0.73	338	2264	405
BSS-2-20-4	19.2	62	0.73	341	2264	405
BSS-2-20-5	19.2	62	0.73	328	2264	405
BSS-2-20-6	19.2	62	0.73	325	2264	405
BSS-2-20-7	19.2	62	0.73	344	2264	405

See Tables 6-1 and 9 for Notes

TABLE 8-2
EXPERIMENTAL DATA FOR COMBINED BENDING AND SHEAR TEST SPECIMENS

Specimen No.	Span Length (in.)	h/t	a/h	V_t (lbs)	V_n (lbs)	$(V_n)_m$ (lbs)
BS-3-14-1A	40.0	48	0.47	1283	5963	1639
BS-3-14-2A	40.0	48	0.47	1288	5963	1639
BS-3-14-1B	40.0	48	0.47	1320	5963	1639
BS-3-14-2B	40.0	48	0.47	1325	5963	1639
BS-3-14-1C	40.0	48	0.47	1345	5963	1639
BS-3-14-2C	40.0	48	0.47	1350	5963	1639
BSB-3-14-1	150.0	42	0.47	925	9166	2521
BSB-3-14-2	150.0	42	0.47	885	9166	2521
BSB-3-14-3	150.0	45	0.47	1078	11524	3146
BSB-3-14-4	150.0	45	0.47	1065	11524	3146
BSS-3-14-1	34.8	42	0.46	2406	9166	2521
BSS-3-14-2	34.8	42	0.46	2750	9166	2521
BSS-3-14-3	34.8	42	0.46	2556	9166	2521
BSS-3-14-4	26.5	45	0.47	2760	11524	3146
BS-3-18-1A	40.0	72	0.46	650	3738	1035
BS-3-18-2A	40.0	72	0.46	650	3738	1035
BS-3-18-1B	40.0	72	0.46	713	3738	1035
BS-3-18-2B	40.0	72	0.46	638	3738	1035
BS-3-18-1C	40.0	72	0.46	745	3738	1035
BS-3-18-2C	40.0	72	0.46	745	3738	1035
BSB-3-18-1	150.0	75	0.45	338	3371	934
BSB-3-18-2	150.0	74	0.46	343	3371	934
BSB-3-18-3	150.0	73	0.47	400	3580	981
BSB-3-18-4	150.0	73	0.47	378	3580	981
BSS-3-18-1	27.5	74	0.46	1125	3371	937
BSS-3-18-2	29.5	74	0.46	929	3371	937
BS-3-20-1A	40.0	98	0.46	425	1586	437
BS-3-20-2A	40.0	98	0.46	458	1586	437
BS-3-20-1B	40.0	98	0.46	475	1586	437
BS-3-20-2B	40.0	98	0.46	463	1586	437
BS-3-20-1C	40.0	98	0.46	483	1586	437
BS-3-20-2C	40.0	98	0.46	508	1586	437
BSB-3-20-1	150.0	74	0.46	338	3371	941
BSB-3-20-2	150.0	74	0.46	358	3371	941
BSB-3-20-3	150.0	90	0.47	300	2062	567
BSB-3-20-4	150.0	90	0.47	275	2062	567
BSB-3-20-5	150.0	89	0.47	335	2062	567

See Tables 6-1 and 9 for Notes

TABLE 9
THE EVALUATION OF COMBINED BENDING AND SHEAR TEST DATA

Specimen No.	V_t/V_n	M_t/M_n	$V_t/(V_n)_m$	$M_t/(M_n)_m$
BS-2-16-1A	0.17	0.70	0.54	0.72
BS-2-16-2A	0.17	0.71	0.54	0.73
BS-2-16-1B	0.18	0.76	0.58	0.79
BS-2-16-2B	0.17	0.73	0.55	0.75
BS-2-16-1C	0.17	0.73	0.55	0.75
BS-2-16-2C	0.18	0.74	0.57	0.77
BSB-2-16-1	0.10	1.05	0.16	1.06
BSB-2-16-2	0.09	0.98	0.51	1.09
BSB-2-16-3	0.09	0.98	0.52	1.08
BSS-2-16-1	0.21	0.19	1.21	0.21
BSS-2-16-2	0.21	0.20	1.17	0.23
BSS-2-16-3	0.21	0.23	1.17	0.26
BSS-2-16-4	0.21	0.29	1.17	0.32
BSS-2-16-5	0.20	0.18	1.14	0.20
BS-2-20-1A	0.17	0.74	0.52	0.89
BS-2-20-2A	0.17	0.73	0.52	0.89
BS-2-20-1B	0.16	0.72	0.51	0.88
BS-2-20-2B	0.17	0.75	0.53	0.92
BS-2-20-1C	0.17	0.73	0.52	0.90
BS-2-20-2C	0.18	0.77	0.55	0.94
BSB-2-20-1	0.07	0.95	0.23	0.99
BSB-2-20-2	0.07	0.99	0.23	1.04
BSB-2-20-3	0.07	0.85	0.37	1.08
BSB-2-20-4	0.07	0.89	0.40	1.14
BSS-2-20-1	0.15	0.14	0.84	0.18
BSS-2-20-2	0.15	0.16	0.84	0.20
BSS-2-20-3	0.14	0.17	0.81	0.22
BSS-2-20-4	0.14	0.21	0.80	0.27
BSS-2-20-5	0.15	0.18	0.85	0.23
BSS-2-20-6	0.34	0.45	1.08	0.48
BSS-2-20-7	0.27	0.36	0.86	0.38

Notes:
1. V_t & M_t: Test Results
2. V_n & M_n: Nominal Shear Strength and Moment Capacity Based on the 1986 AISI Specification
3. $(V_n)_m$: Calculation of Shear Strength Based on the Reduction Factor
4. $(M_n)_m$: Calculation of Moment capacity Based on the Effective Net Section Modulus

TABLE 9 (Continued)
THE EVALUATION OF COMBINED BENDING AND SHEAR TEST DATA

Specimen No.	V_t/V_n	M_t/M_n	$V_t/(V_n)_m$	$M_t/(M_n)_m$
BS-3-14-1A	0.22	0.83	0.78	0.86
BS-3-14-2A	0.22	0.83	0.79	0.86
BS-3-14-1B	0.22	0.85	0.81	0.88
BS-3-14-2B	0.22	0.85	0.81	0.88
BS-3-14-1C	0.23	0.87	0.82	0.91
BS-3-14-2C	0.23	0.87	0.82	0.91
BSB-3-14-1	0.10	0.91	0.37	0.93
BSB-3-14-2	0.10	0.89	0.35	1.00
BSB-3-14-3	0.09	0.97	0.34	1.01
BSB-3-14-4	0.09	0.97	0.34	1.04
BSS-3-14-1	0.26	0.29	0.88	0.24
BSS-3-14-2	0.30	0.45	0.95	0.31
BSS-3-14-3	0.28	0.52	1.09	0.48
BSS-3-14-4	0.24	0.22	1.01	0.55
BS-3-18-1A	0.17	0.63	0.63	0.69
BS-3-18-2A	0.17	0.63	0.63	0.69
BS-3-18-1B	0.19	0.70	0.69	0.77
BS-3-18-2B	0.17	0.62	0.62	0.66
BS-3-18-1C	0.20	0.73	0.72	0.81
BS-3-18-2C	0.20	0.71	0.72	0.77
BSB-3-18-1	0.10	0.86	0.36	0.91
BSB-3-18-2	0.10	0.88	0.37	0.92
BSB-3-18-3	0.11	0.98	0.41	1.07
BSB-3-18-4	0.09	0.92	0.34	1.03
BSS-3-18-1	0.33	0.41	1.20	0.43
BSS-3-18-2	0.28	0.36	0.99	0.38
BS-3-20-1A	0.27	0.55	0.97	0.76
BS-3-20-2A	0.29	0.59	1.04	0.78
BS-3-20-1B	0.30	0.60	1.09	0.83
BS-3-20-2B	0.29	0.59	1.06	0.81
BS-3-20-1C	0.30	0.62	1.10	0.84
BS-3-20-2C	0.32	0.64	1.16	0.89
BSB-3-20-1	0.10	0.87	0.36	0.95
BSB-3-20-2	0.11	0.92	0.38	0.95
BSB-3-20-3	0.15	0.83	0.53	0.95
BSB-3-20-4	0.13	0.77	0.49	0.88
BSB-3-20-5	0.16	0.91	0.59	1.05

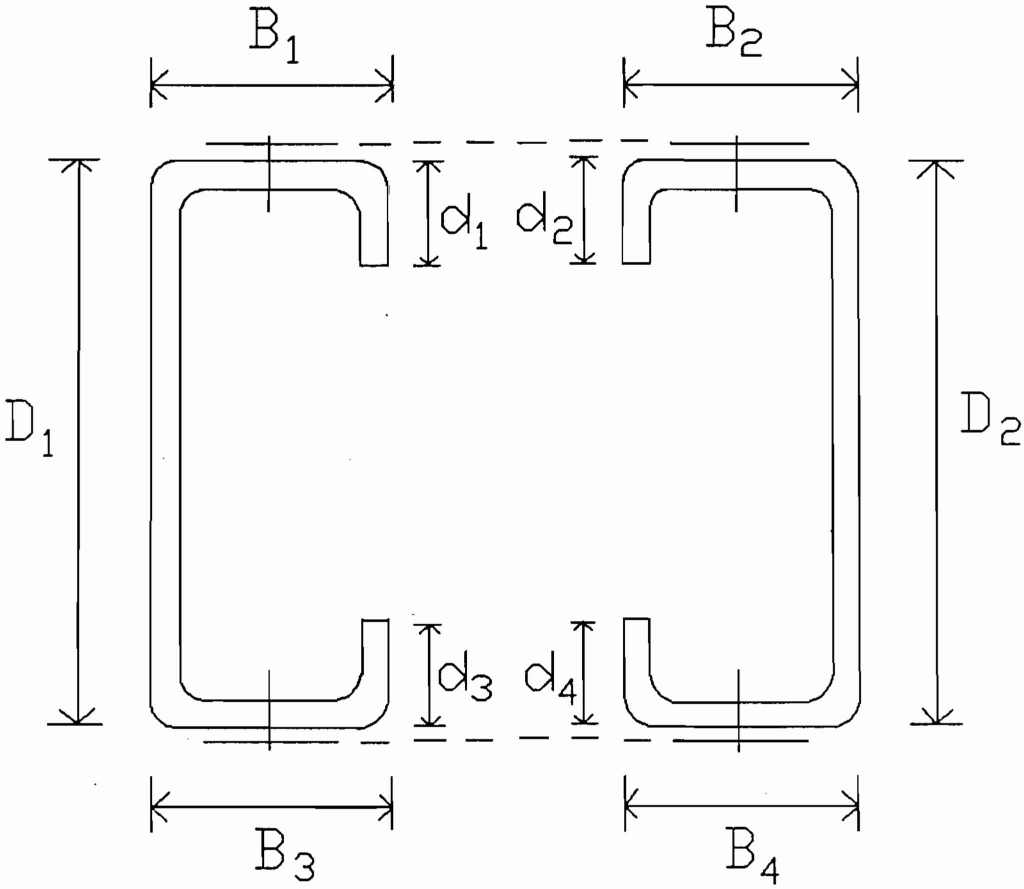


Fig. 1. Beam Cross-Section

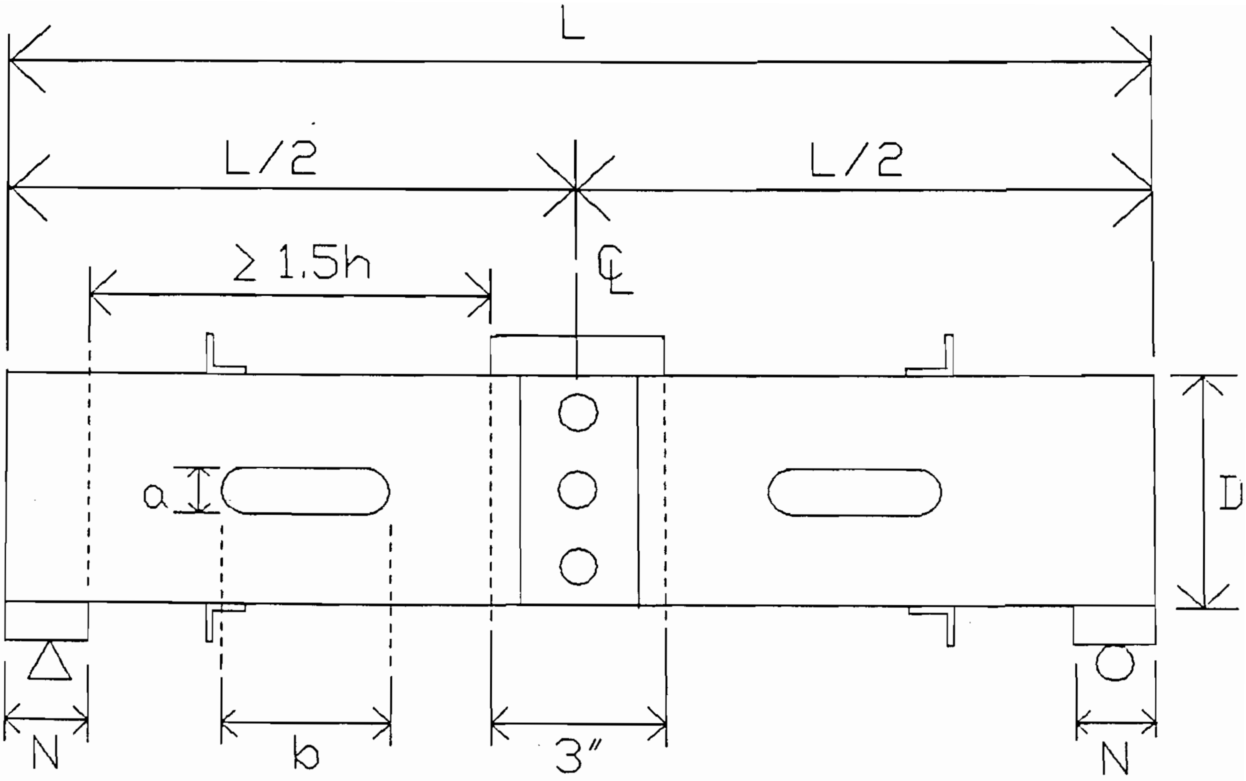


Fig. 2. Test Setup

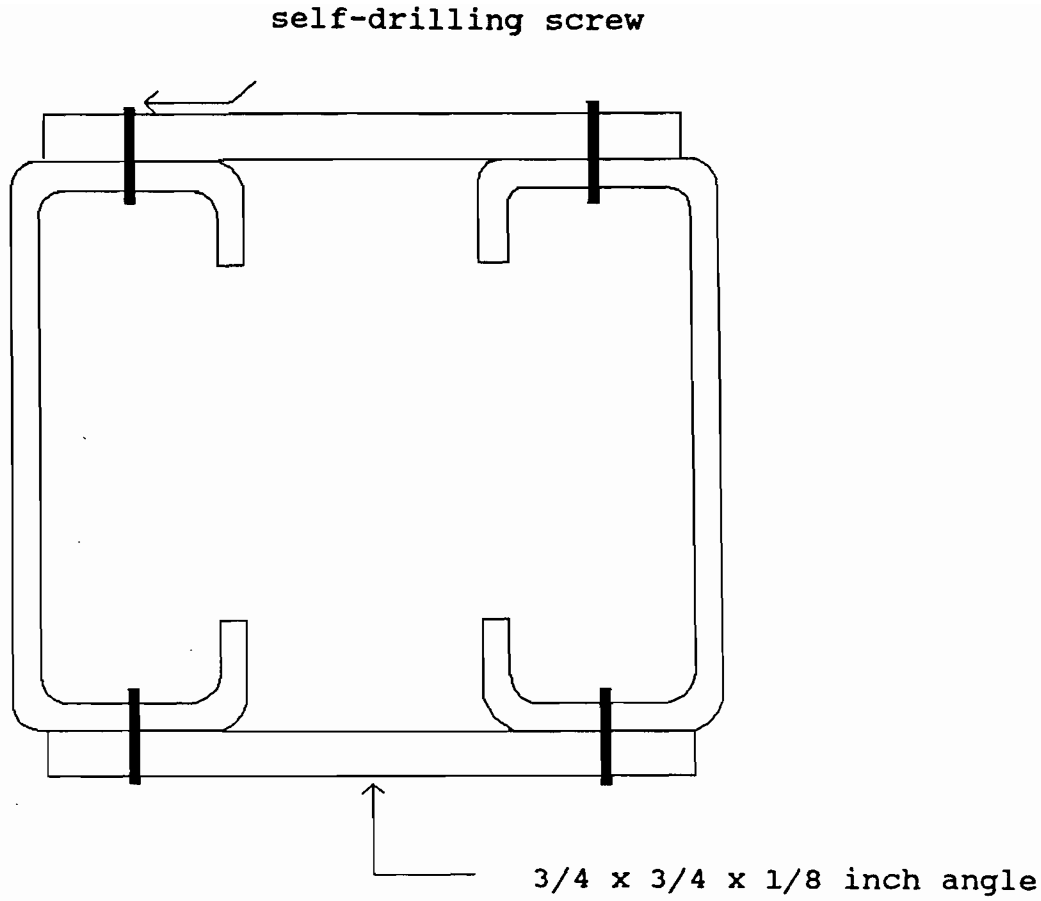


Fig. 3. Cross Section of 2.5 and 3.625-in Deep Test Specimen

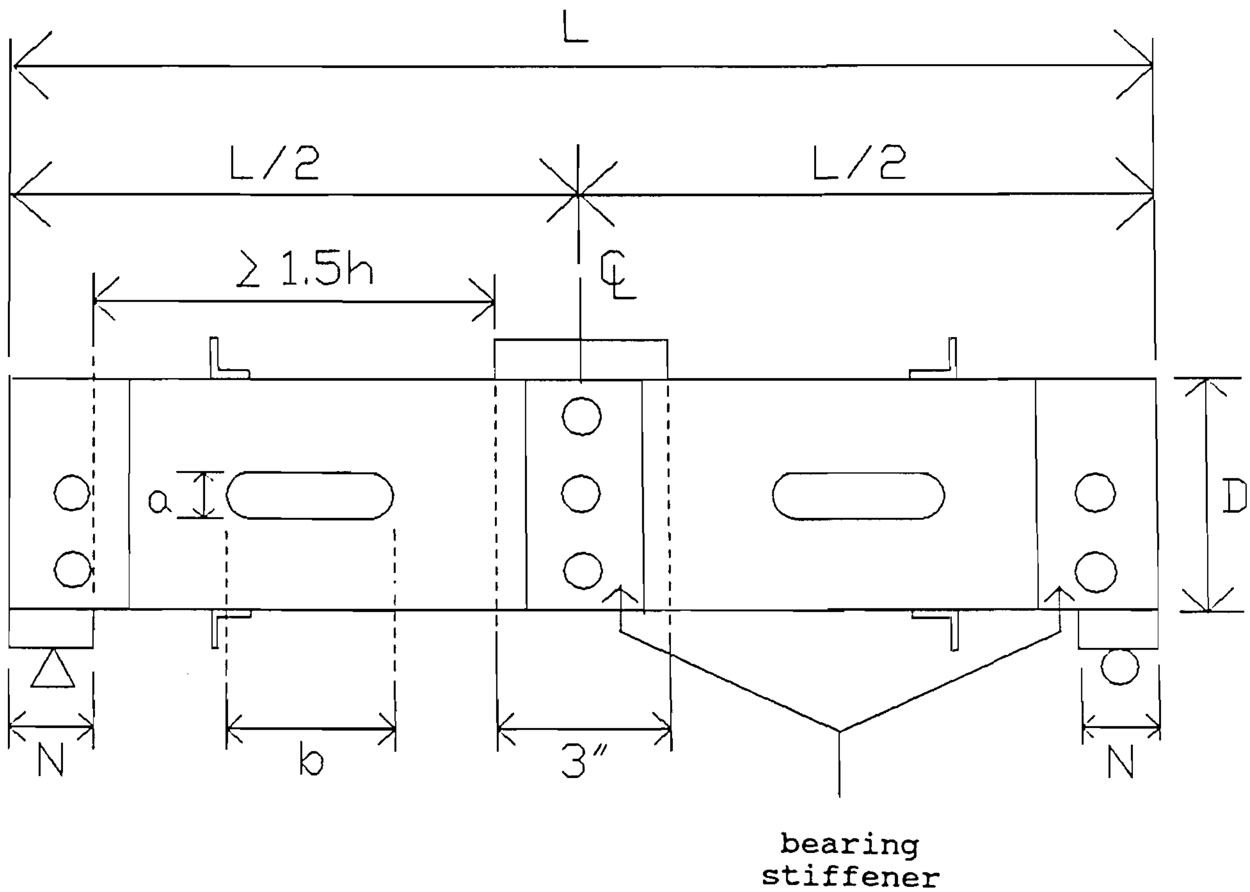


Fig. 4. Test Setup (for 12" depth section)

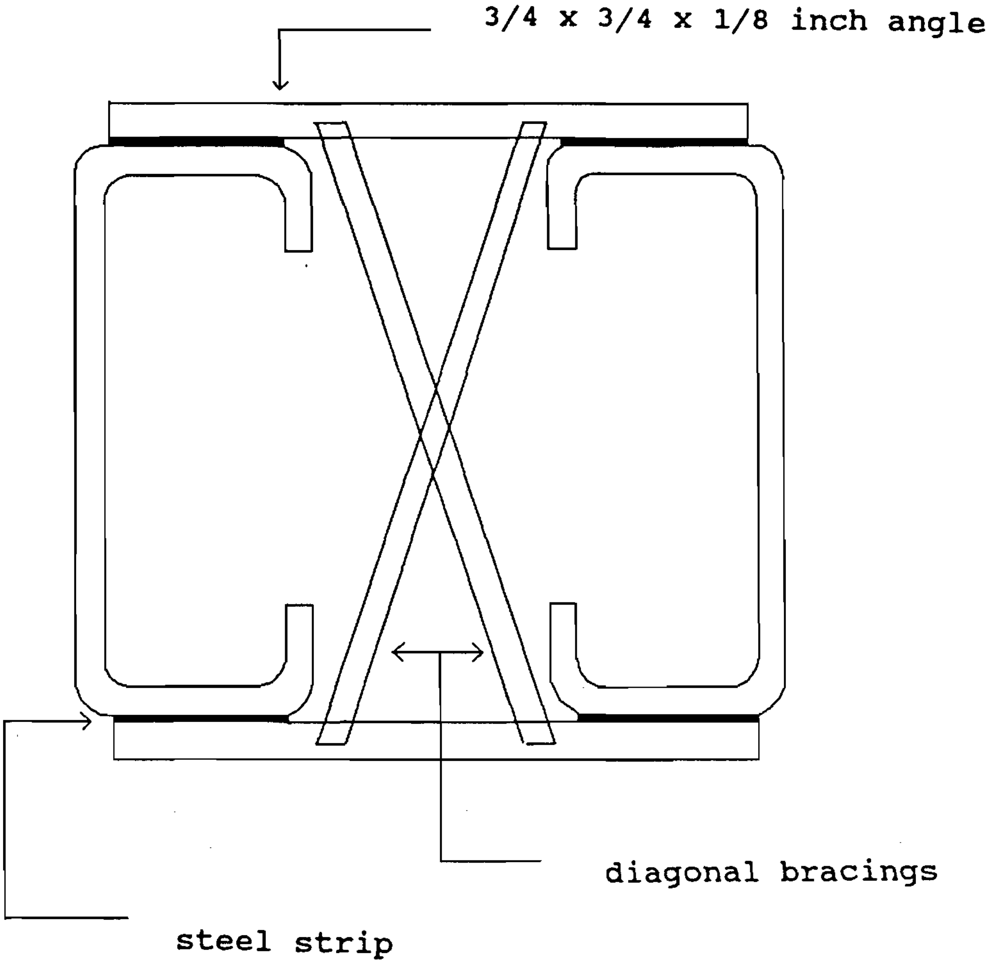


Fig. 5. Cross Section of 12-in Test Specimen

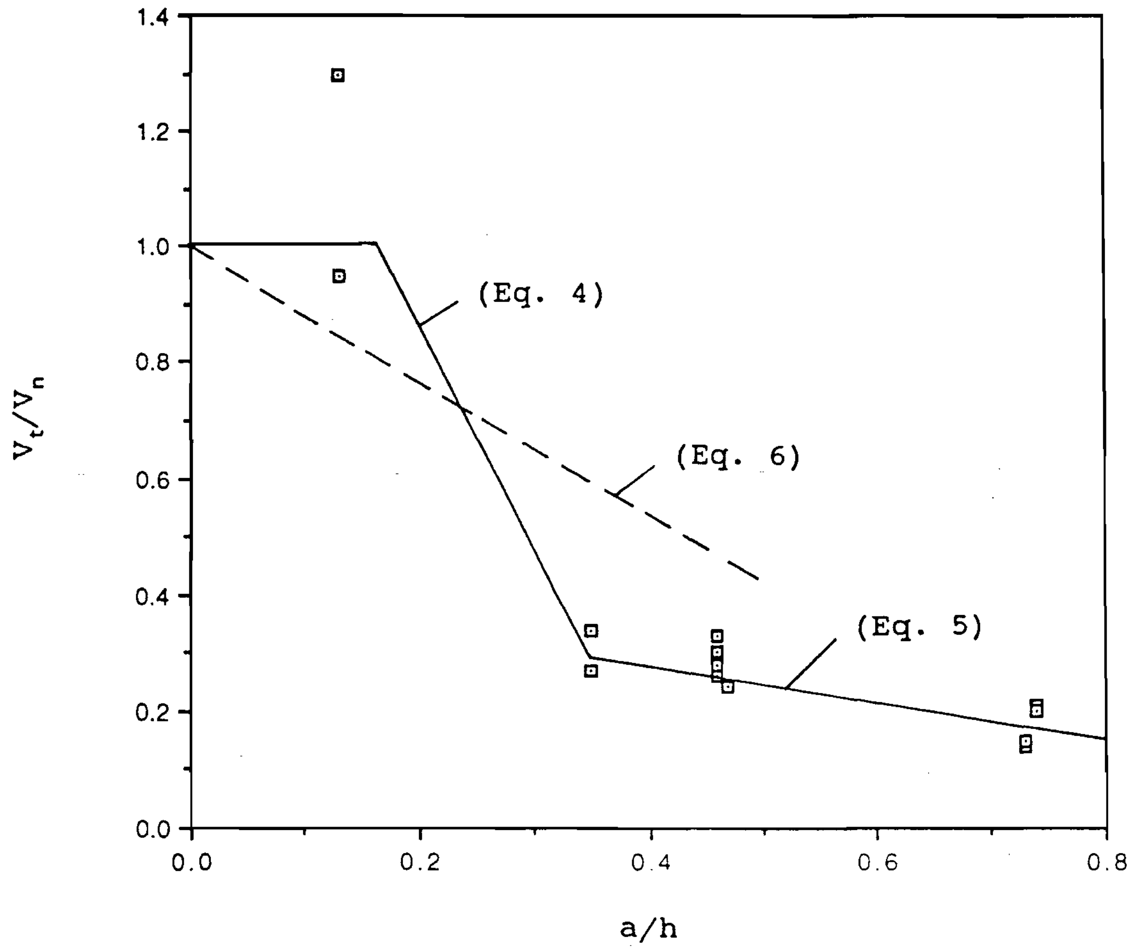
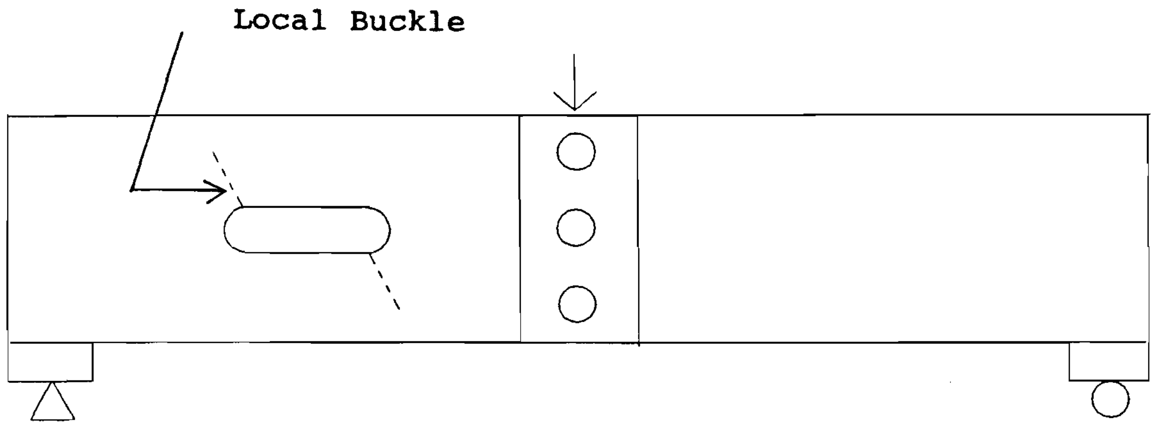
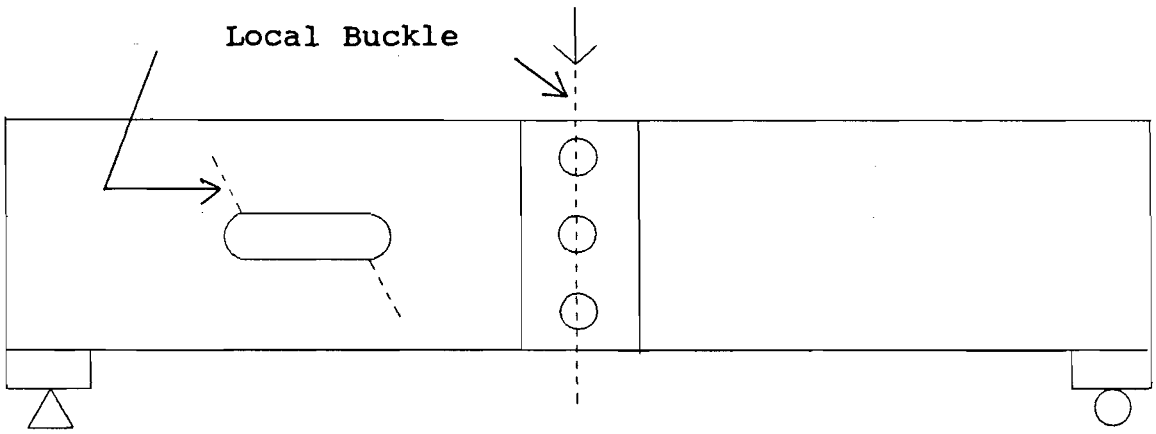


Fig. 6. Load Reduction Factor V_t/V_n Verse a/h Ratio



(a) Shear Failure Mode



(b) Combined Bending and Shear

Fig. 7. Failure Modes

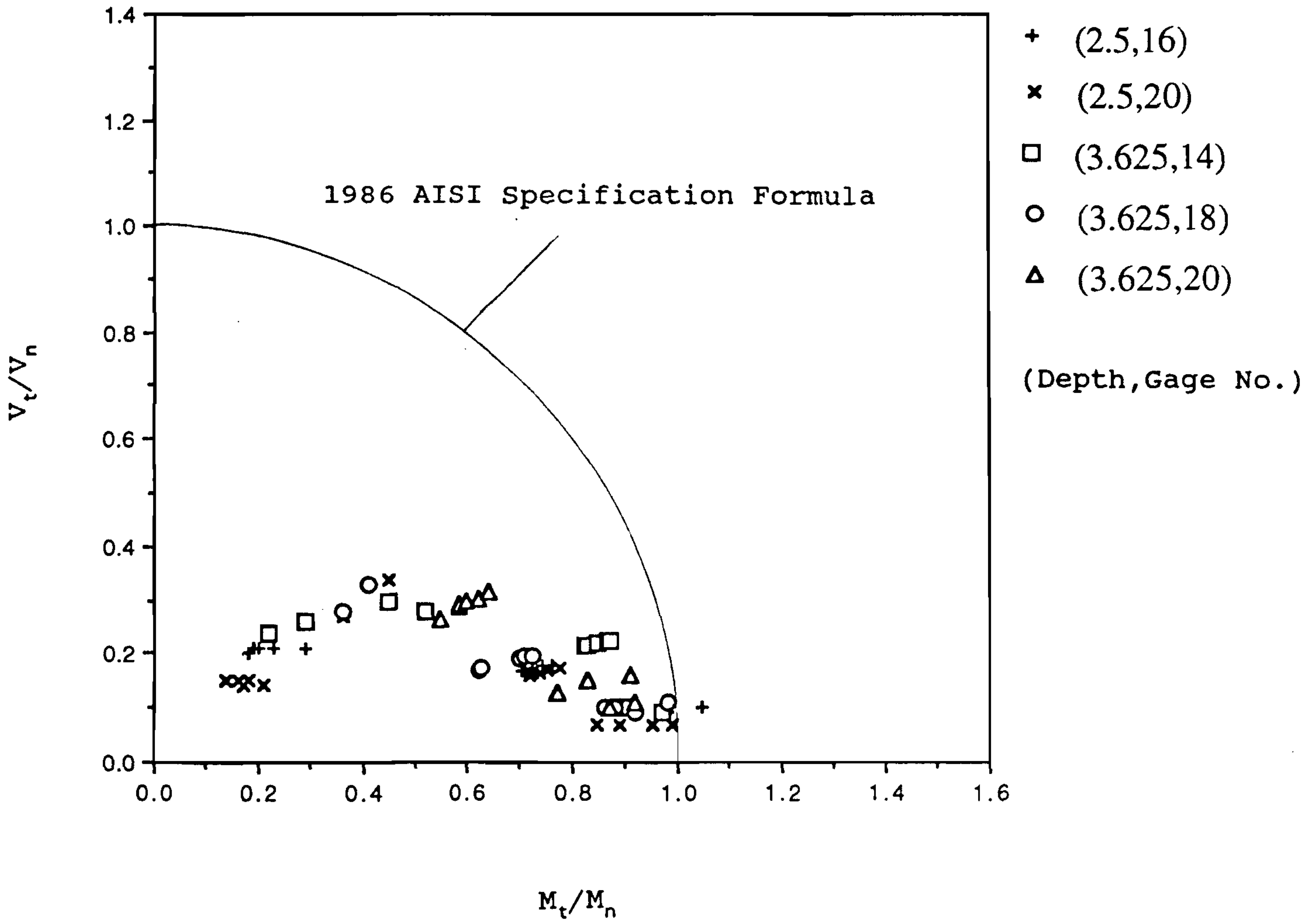


Fig. 8. Interaction Diagram for V_t/V_n and M_t/M_n Based on 1986 AISI Specification

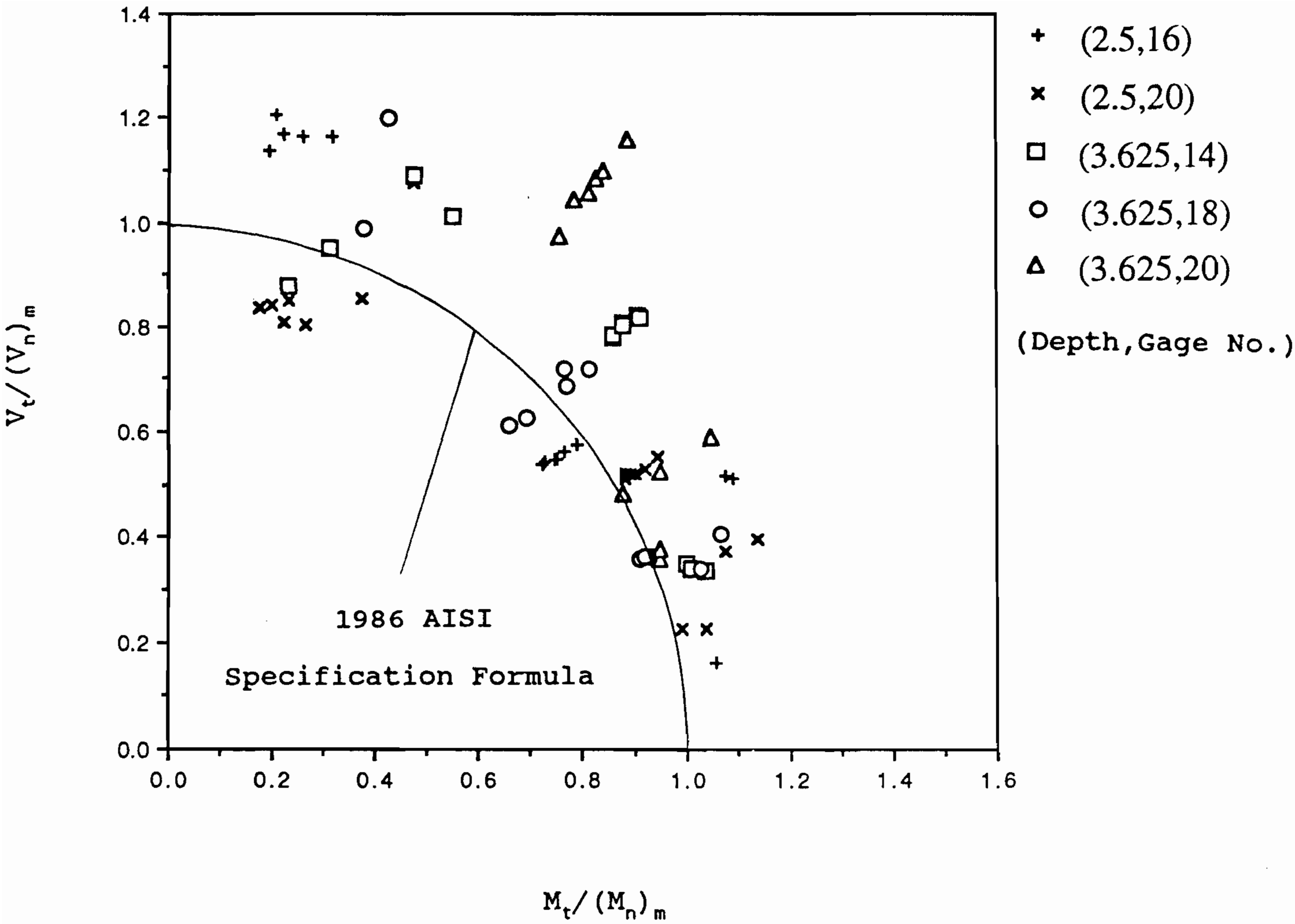


Fig. 9. Interaction Diagram for $V_t/(V_n)_m$ and $M_t/(M_n)_m$
Based on the Reduction Factor and Effective Net Section Modulus

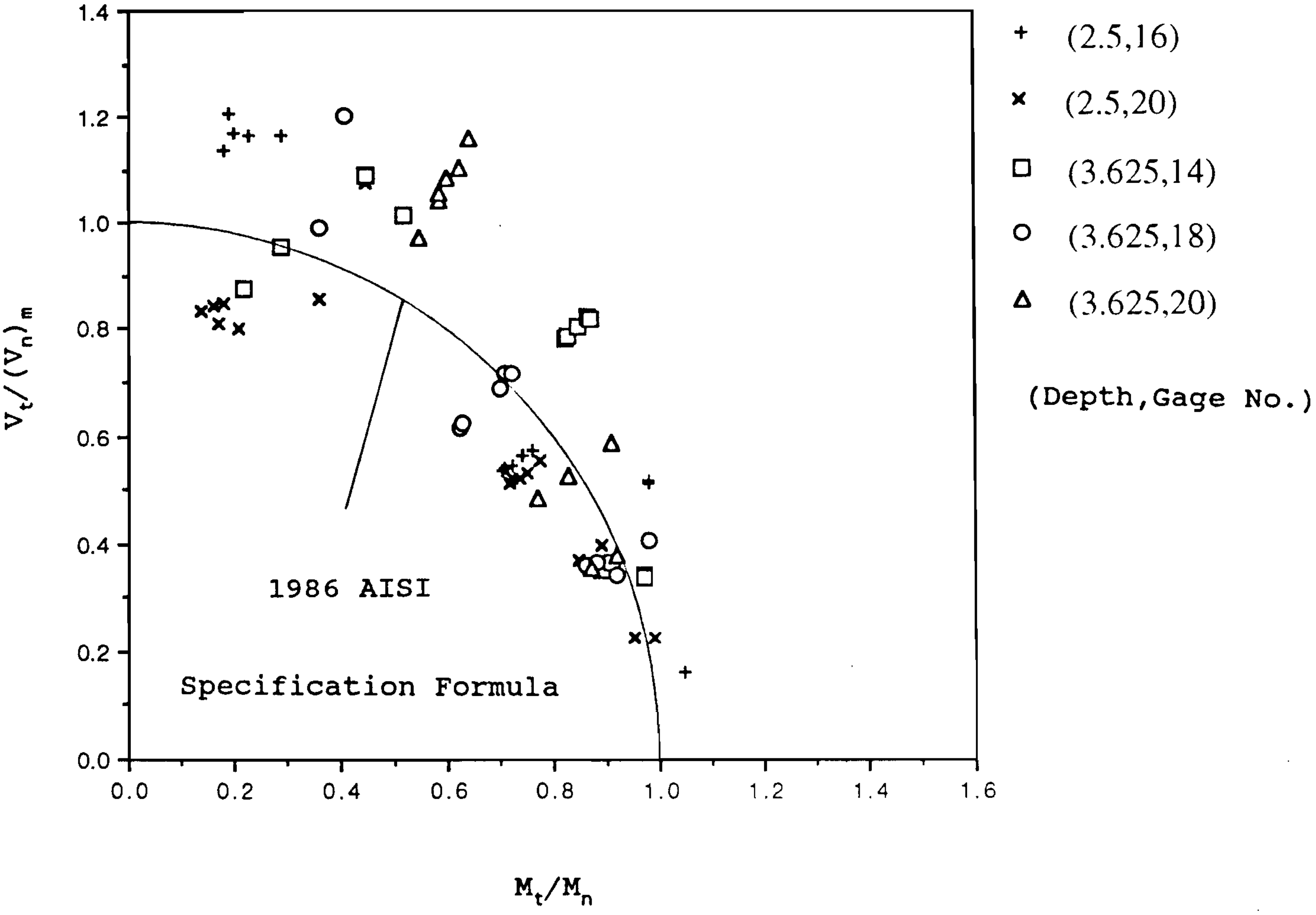


Fig. 10. Interaction Diagram for $V_t/(V_n)_m$ and M_t/M_n
Based on the Shear Reduction Factor only