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Web crippling behavior of sections with web openings

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First, Second, Third and Fourth Progress Reports

Web Crippling Behavior of Sections with Web Openings

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First Progress Report
Web Crippling Behavior of Sections with Web Openings

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Introduction

The purpose of this phase of the research is to investigate the web crippling behavior of single unreinforced webs with web openings subjected to End-One-Flange (EOF) loading. The web openings were centered at the mid-height of the web. Tests were limited to C-shaped sections with stiffened flanges. The major parameter varied within each common cross section was the horizontal clear distance of the opening from the near edge of bearing plate. Figure 1 shows this as distance "x". Additionally, the effect of the end reaction bearing length, N, on web crippling strength was investigated. The primary goals of this phase were (1) to examine the anticipated increase in EOF web crippling strength as distance "x" increased, (2) to compare the test results to specimens having the same cross section with no web opening, and (3) evaluate the adequacy of the AISI provisions, based on no web openings, for predicting the web crippling strength for web elements with web openings.

Test Specimens

The test specimens were fabricated from industry standard C-sections. See Figures 1 and 2 for the geometric parameters of each test specimen. Figures 3(a) and (b) show the parameters on a test specimen.

screws. To prevent web crippling at mid-span due to an Interior-One-Flange (IOF) loading, a narrow, rigid stiffener was attached vertically on the webs of both sections at mid-span. Using a Tinius-Olson testing machine, a concentrated load was applied at mid-span to a bearing plate in contact with the top flanges. The reactions creating the EOF loading were introduced to the specimen by bearing plates flush with the ends of the specimen. Rollers were placed at the centerline of the bearing reactions to achieve a simple support condition.

Test Procedure

The load was applied to the test specimens at a constant and gradual rate until the specimen failed. Failure was defined when the specimen could carry no additional load. Two tests were conducted for most cross sections. Duplicate test results are shown in Table 3 as $(Pu)_{test}$, per web under sub-columns "test 1" and "test 2".

Test Results

One hundred fifty-two tests were conducted to date. Of these, 99 are valid for web crippling analysis, 30 failed in shear, four failed at mid-span in the compression flange, and 19 were conducted to perform various diagnostic tests to ensure validity of the testing procedure. The applied failure load of $(Pu)_{test}$, per web, for each of the web crippling and shear tests are given in Table 3. The results from many of the diagnostic tests are given in Table 4. The failure load per web is taken as

1/4 of the applied mid-span load.

Figures 4 thru 7 show typical web crippling failures of several specimens with the failure load still applied. Figure 8 shows a typical shear failure of a specimen with the failure load still applied.

Observations

The following discussion is generally limited to only N equals 1 inch. As previously stated, the primary goals of this phase of the study were to: (1) examine the anticipated increase in EOF web crippling strength as the clear distance, x, increased, (2) compare the results to specimens from the same cross section with no web opening, and (3) evaluate the adequacy of the AISI provisions, based on no web openings, for predicting the web crippling strength for web elements with web openings.

A notable trend existed within the test results. For Alpha increased from 0 to 1.5, the web crippling strength increased. This is shown in Table 3 under the column titled "% no opening", which is the ratio of the failure load with web opening divided by failure load for the solid web specimen. This trend is shown graphically for six typical cross sections in Figure 9 as Alpha vs. "% no web opening."

For specimens identified as having a web crippling failure, the tested failure load was also compared with AISI Eq.C3.4-1 multiplied by 1.85 to account for the factor of safety. As indicated by the ratio $(Pu)_{test}/(Pu)_{comp}$, the specification generally yields a satisfactory estimate of the web crippling failure load for solid web specimens as indicated by the fact that $(Pu)_{test}/(Pu)_{comp}$ is approximately equal to or greater than unity.

For values greater than N = 1 inch, few tests were conducted as shown in Table 3. Many of these specimens failed in shear.

Comparison with previous studies

As shown in Table 3, many of the values for $(Pu)_{test}/(Pu)_{comp}$ for specimens without a web opening are significantly greater than 1.0. Results for the specimens without a web opening were compared to Figure 24 of Reference 2 (Fig. 10). Reference 2 serves as the basis for the current web crippling formulas in the AISI specification. Test results from the study were superimposed on Figure 24 (Ref. 2), and as indicated by Figure 10, the conservative results obtained in the present study are consistent with results from previous studies.

Shear

Thirty test specimens failed in shear. The shear failures were very pronounced at the location of the web opening. Shear failures usually occurred with little or no web crippling deformation at the end reaction.

Shear failures generally occurred at a higher end bearing length, N. An increase in N provided an increase in the web crippling strength of the section, as can be seen from the values of $(Pu)_{comp}$ in Table 3.

To determine the web crippling - shear failure transition, tests were conducted on cross section EOF-SU-9, with varying values of N. For the EOF-SU-9 cross section, the transition occurred distinctly between N = 4 and 5 inches. Alpha was arbitrarily maintained at a constant value of 0.5 for these tests. In other cross sections or other Alpha values this transition will occur at different N values. For example, for the EOF-SU-4 cross section, the transition occurred between N = 1 and 3 inches. Again, this pertains to only Alpha equals 0.5.

Shear failures also occurred at high values of the ratio of web opening height (a) to web height (h). The specimen series EOF-SU-5 and series EOF-SU-6 demonstrate this phenomenon for a/h ratios of 0.74 and 0.73 respectively. These high a/h ratios frequently failed in shear even at N = 1 inch. Because of the pronounced shear deformation, these failures were readily identified, and the data is valid for future studies on sections with web openings subjected to shear. An additional observation is that many of the specimens that failed due to web crippling had a slight amount of shear deformation. The location of the shear "bulges" was the same as distinct shear failures, but the magnitude of the deformation was very slight. Failure modes were identified as either web crippling or shear. No attempt has been made to establish the interaction of shear and web crippling.

Rate of loading

UMR Civil Engineering Study 78-4 (Ref. 2) states that the specimens were loaded in 15% increments of the expected failure load, and the load maintained for five minutes at each increment. However, all tests for this study were loaded at a constant and gradual rate. To ascertain the difference between these two methods, six identical specimens were tested. Three specimens were tested under each loading conditions. The results are shown in Table 4 for cross section EOF-SU-11-1a and EOF-SU-11-1b. Both loading rates resulted in web crippling failure loads within the realm of experimental error. Thus, both loading rates are acceptable.

Specimen length

As previously stated, the minimum length of each specimen was determined to satisfy the requirement for one flange loading: greater than or equal to 1.5h clear distance between end plate and mid-span loading plate. Most specimens were longer than the minimum to allow for the desired clear distance "x" between the end plate and the web opening (Fig. 1). The length of the specimen, L, and the horizontal clear distance of the web opening to the mid-span loading plate, x', were determined not to affect web crippling strength. See Table 4 for the diagnostic tests conducted to ascertain the effects of L and x'. These specimens are EOF-SU-9-12a,b, and c. Additionally, specimens EOF-SU-9-(5 and 6) showed no significant difference with the variance of only L and x'.

Several specimens failed at mid-span because of either yielding in the flanges or compression flange buckling. These specimens were probably of excessive length and therefore resulted in a high bending moment at mid-span. These mid-span failure modes were readily identified and are not included as part of the web crippling data.

Deformation at Failure

At failure, most specimens were severely deformed and would be considered unserviceable under most applications. See Figures 4 thru 7, which were taken while the failure load was still applied.

Future work

The research reported herein is one phase of a comprehensive study of web elements with web openings. Future phases will address:

(1) Shear failure of sections with web openings. The shear study will emphasize high a/h ratios and N values. A desired goal of the study is to determine the shear strength for web elements with openings and to determine the parameters that predict the web crippling - shear failure transition.

(2) The web profile at design load. The deformed web at

design load will be measured, not necessarily to develop serviceability criteria, but to verify that the section is not severely deformed even if the applied load equals the design strength.

(3) Develop appropriate design recommendations to be proposed for adoption by AISI specification.

(4) A study for Interior-One-Flange, IOF, loading will be initiated.

(5) The use of web stiffeners for the EOF and IOF loadings will be investigated.

References

1. "Cold-Formed Steel Design Manual", American Iron and Steel Institute, August 19, 1986, with December 11, 1989 Addendum.

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

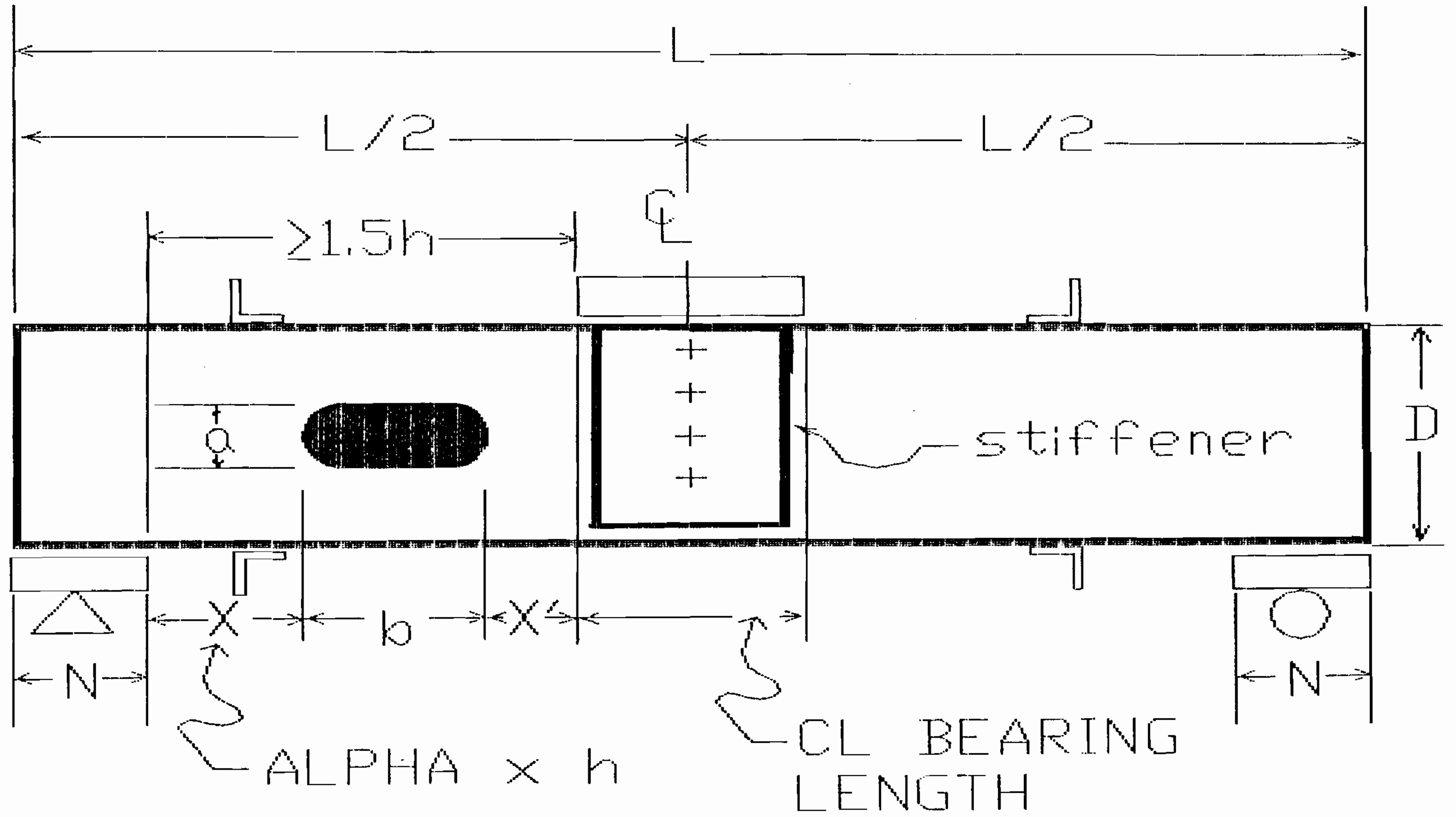


FIGURE 1: SPECIMEN PARAMETERS LONGITUDINAL VIEW

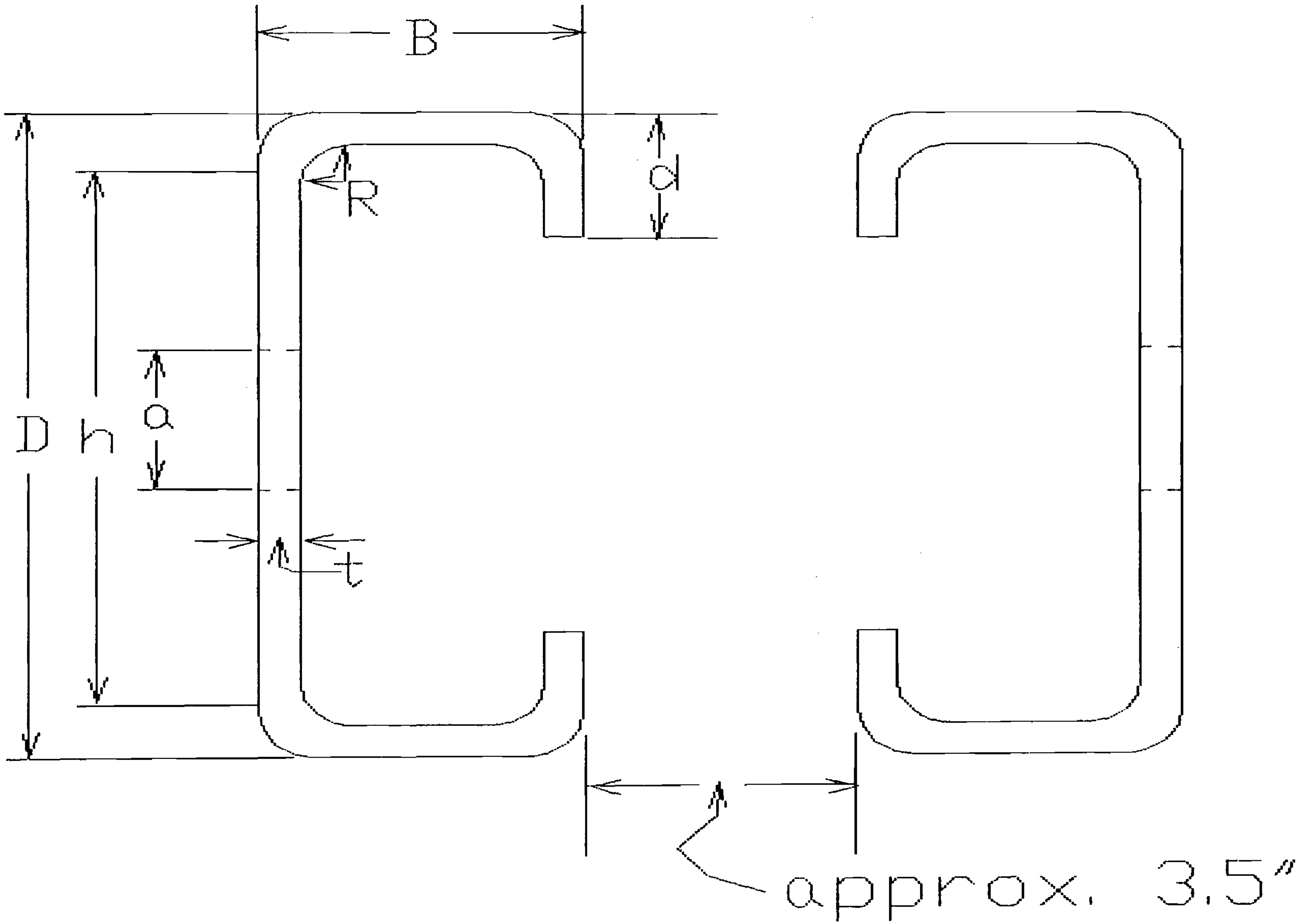
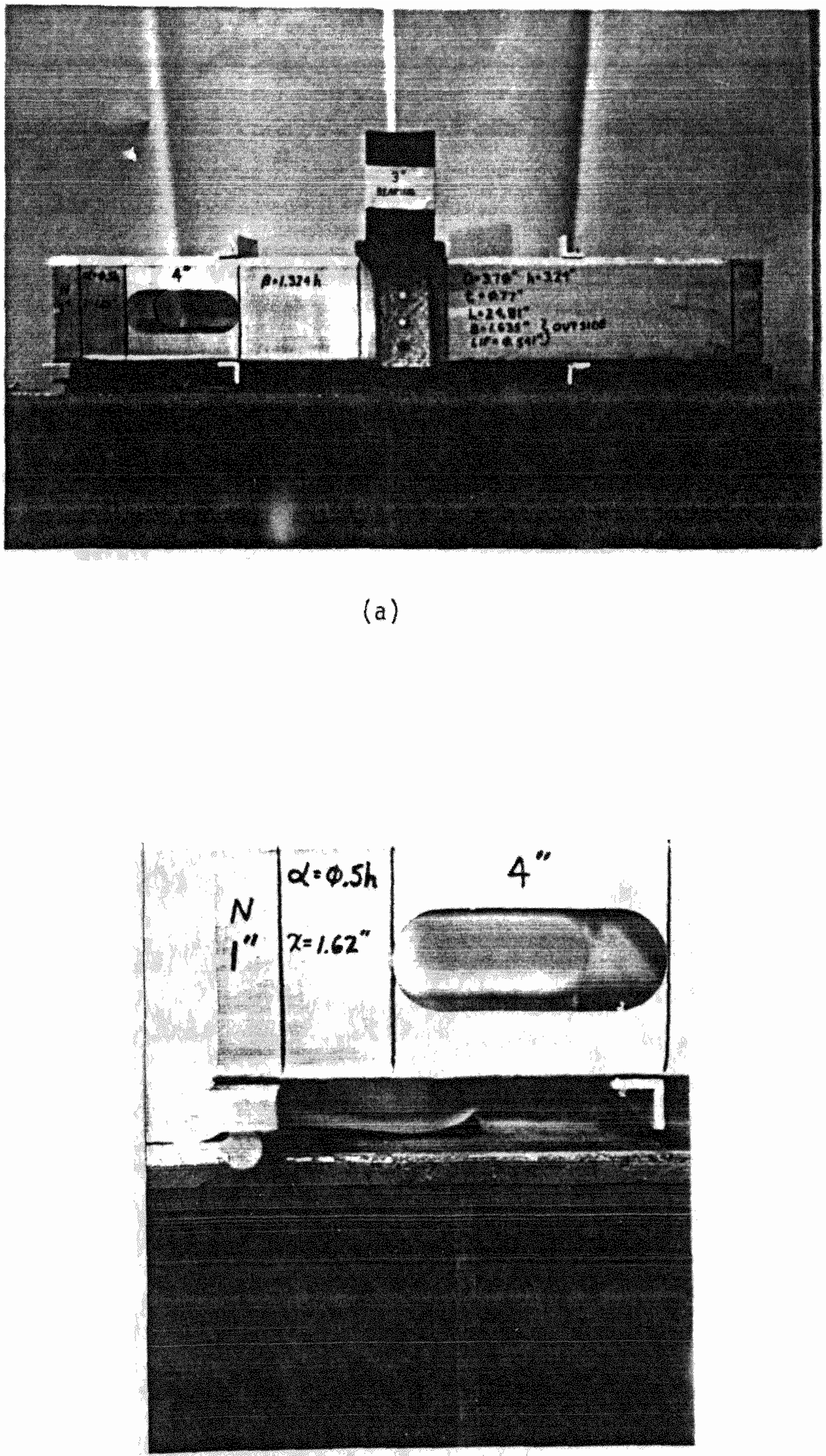


FIGURE 2: SPECIMEN PARAMETERS
END VIEW



(a)

(b)

Figure 3a and b: Typical Specimen Parameters, Specimen EOF-SU-10-3(#1)

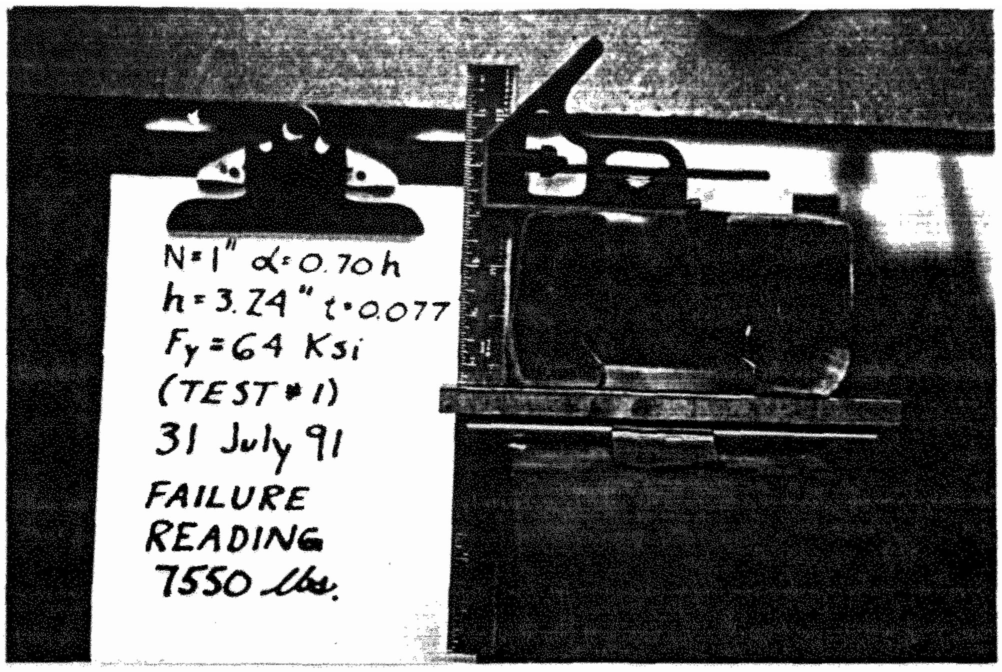


Figure 4: Typical Web Crippling Failure, Specimen EOF-SU-10-4(#1)

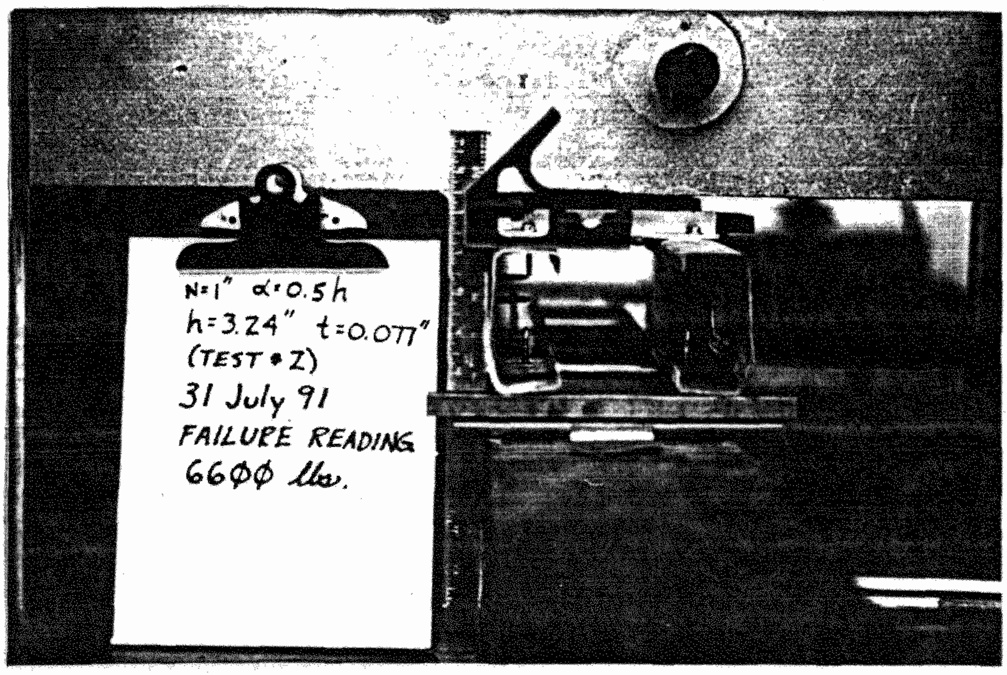
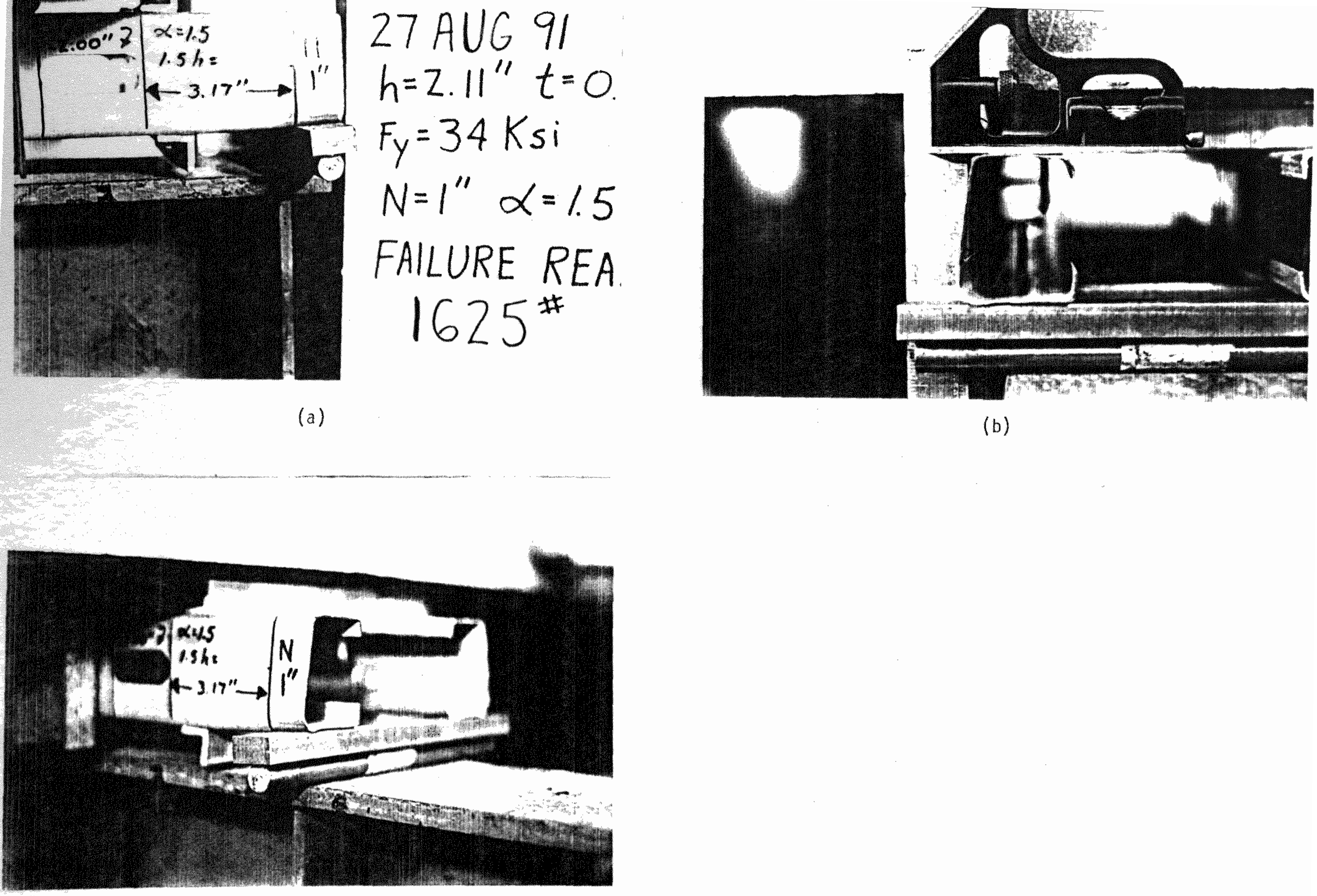


Figure 5: Typical Web Crippling Failure, Specimen EOF-SU-10-3(#2)



(a)

(b)

(c)

Figure 6a, b, and c: Typical Web Crippling Failure, Specimen EOF-SU-8-6 (#2)

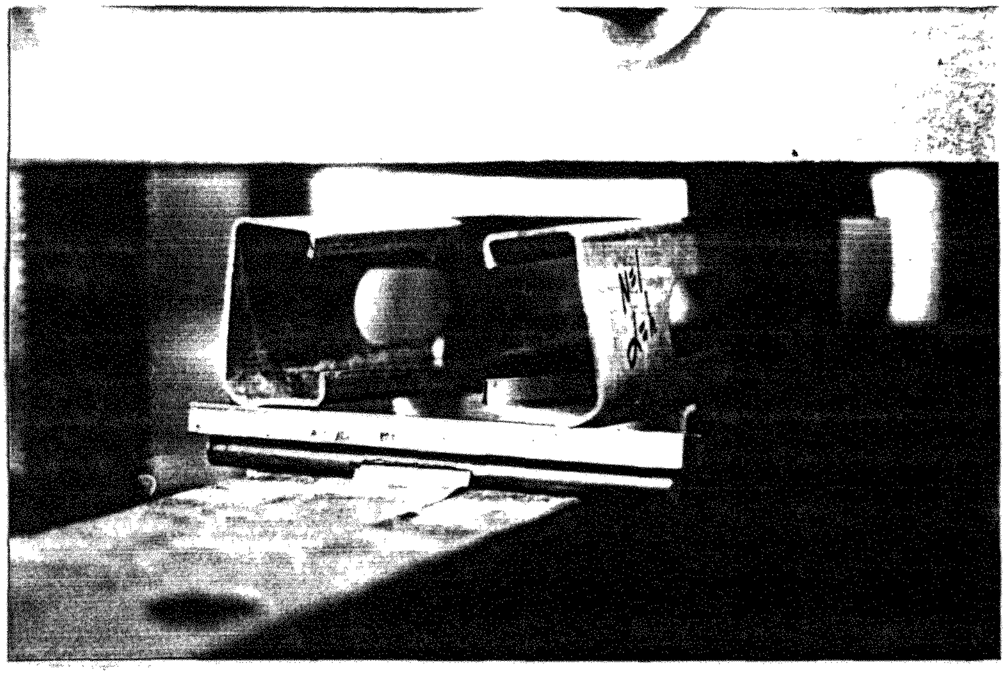


Figure 7: Typical Web Crippling Failure, Specimen EOF-SU-4-5(#1)

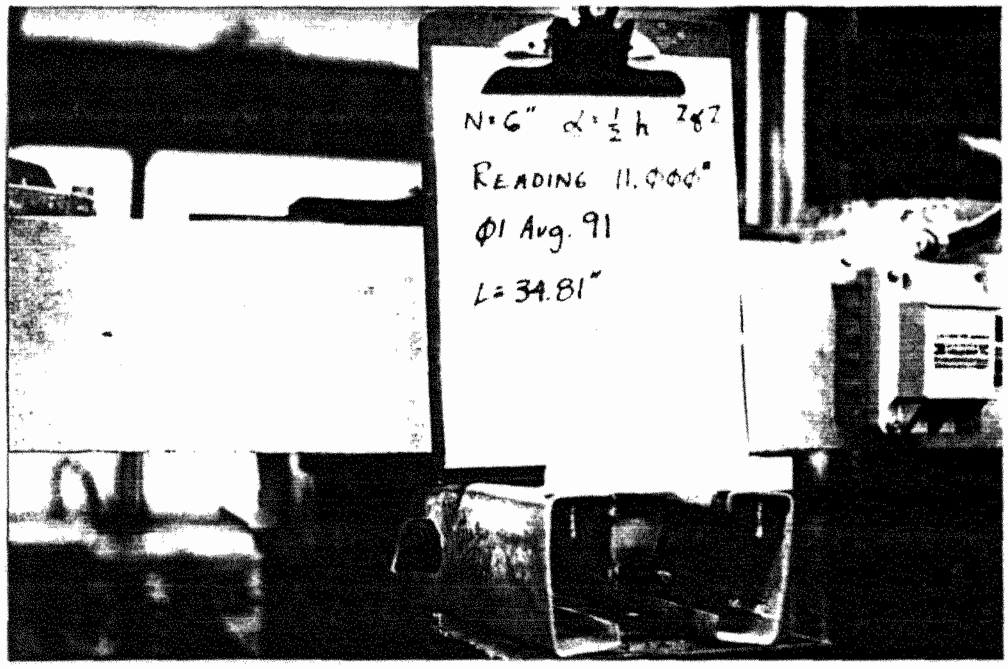


Figure 8: Typical Shear Failure,
Specimen EOF-SU-10-6(#2)

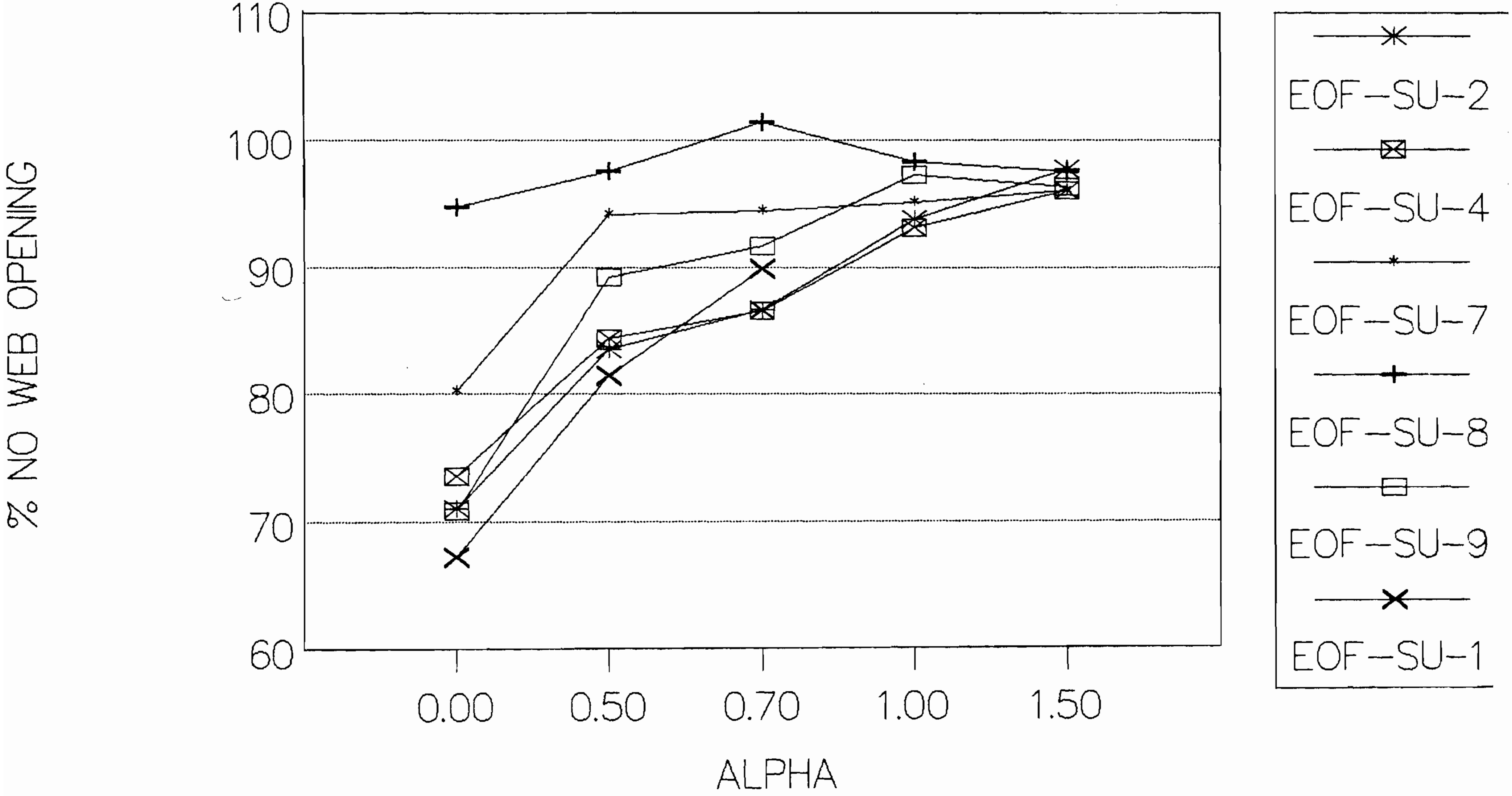
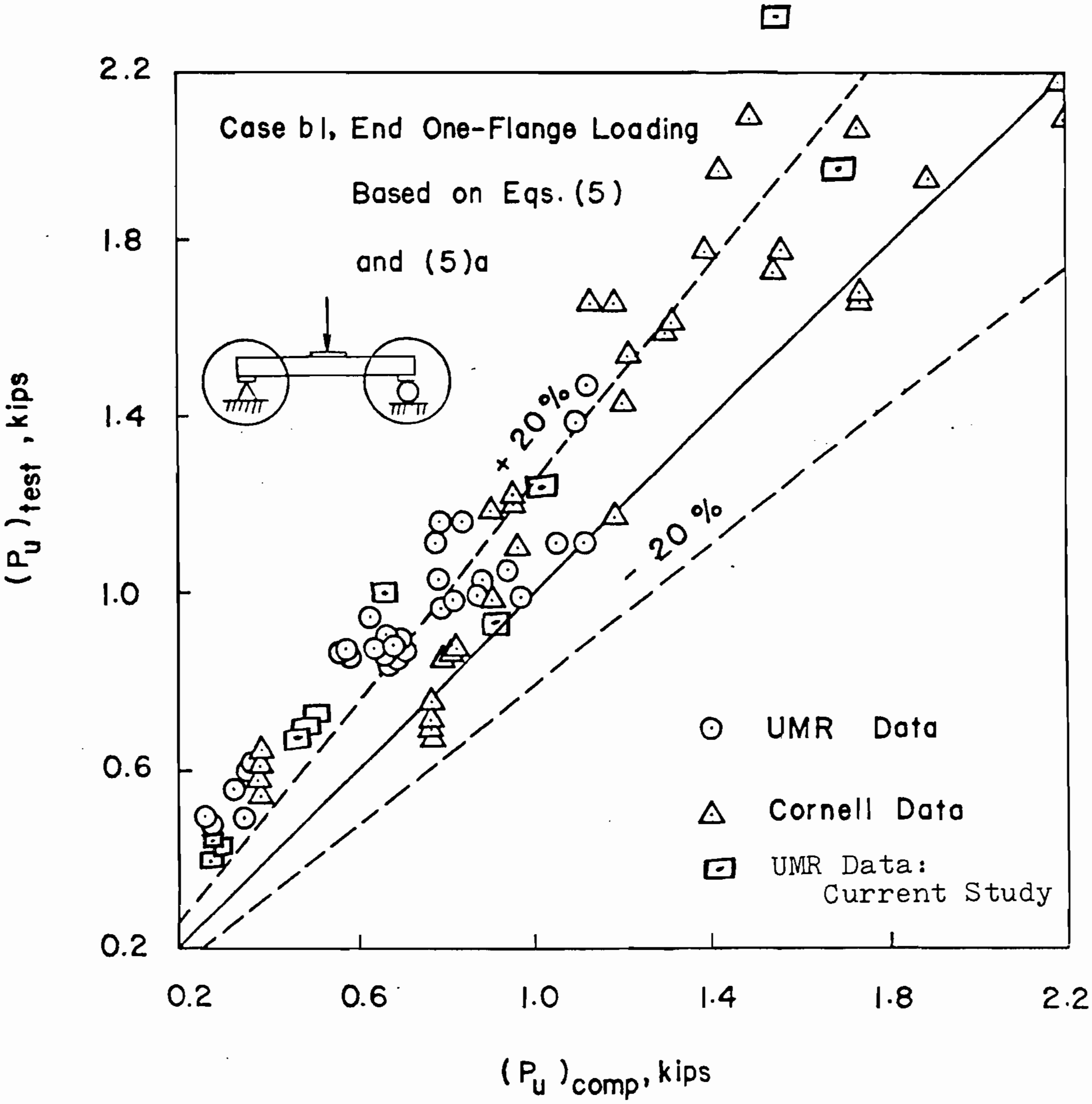


Figure 9: Alpha vs. % No Web Opening (N=1 inch)



(Ref. 2) **Figure 24.** Plot of $(P_u)_{test}$ v.s. $(P_u)_{comp}$ by Using the Original Formulas Applied to both UMR and Cornell Data under End One-Flange Loading (Specimens with Stiffened Flanges)

Figure 10: Comparison with Previous Studies, Specimens with No Web Openings

Table 1: Cross Section Properties

Cross Section	D(in.)	t(in.)	R(in.) nominal	h(in.)	B(in.)	d(in.)	a(in.)	b(in.)	Fy Ksi	h/t	a/h	R/t
EOF-SU-1	11.97	0.060	0.156	11.54	1.63	0.52	1.50	4.00	60	192	0.13	2.6
EOF-SU-2	3.62	0.044	0.156	3.22	1.64	0.51	1.50	4.00	53	73	0.47	3.6
EOF-SU-3	3.61	0.036	0.156	3.22	1.63	0.47	1.50	4.00	64	90	0.47	4.3
EOF-SU-4	3.63	0.071	0.156	3.18	1.63	0.51	1.50	4.00	81	45	0.47	2.2
EOF-SU-5	2.46	0.059	0.156	2.03	1.62	0.49	1.50	4.00	54	34	0.74	2.6
EOF-SU-6	2.42	0.033	0.156	2.05	1.63	0.46	1.50	4.00	67	62	0.73	4.7
EOF-SU-7	2.52	0.062	0.156	2.08	1.62	0.42	0.75	2.00	37	34	0.36	2.5
EOF-SU-8	2.50	0.039	0.156	2.11	1.60	0.41	0.75	2.00	34	54	0.35	4.0
EOF-SU-9	3.67	0.044	0.156	3.27	1.58	0.56	1.50	4.00	47	74	0.46	3.6
EOF-SU-10	3.71	0.077	0.156	3.24	1.63	0.54	1.50	4.00	64	42	0.46	2.0
EOF-SU-11	3.65	0.044	0.156	3.25	1.64	0.49	0.00	0.00	63	74	0.00	3.6

Notes:
1. See Figures 1 and 2 for definition of dimensions.
2. Cross section designations:
   EOF: End-One-Flange (loading)
   SU: Single Unreinforced (web)

Table 2: Ranges of Parameters and Aspect Ratios

	minimum	maximum
h (in.)	2.03	11.54
t (in.)	0.033	0.077
Fy (Ksi)	34	81
N (in.)	1.00	6.00
Alpha	0	1.5
a (in.)	0.00	1.50
b (in.)	0.00	4.00
a/h	0.13	0.74
h/t	34	192
R/t	2.20	4.70

Table 3: Test Results

Specimem no.	L (in.)	N (in.)	ALPHA	FAILURE MODE	(Pu)test, per web (lbs.)			% NO HOLES (@N=1)	(Pu)comp (lbs.)	(Pu)test/ (Pu)comp
					TEST1	TEST2	AVG			
EOF-SU-1-1	39.64	1.0	N/A	CRIPPLING	994	1050	1022	100	905	1.13
EOF-SU-1-2	39.64	1.0	0.00	CRIPPLING	1175	1100	1138	111	905	1.26
EOF-SU-2-1	20.00	1.0	N/A	CRIPPLING	706	694	700	100	540	1.30
EOF-SU-2-2	22.66	1.0	0.00	CRIPPLING	488	506	497	71	540	0.92
EOF-SU-2-3	22.66	1.0	0.50	CRIPPLING	581	588	585	84	540	1.08
EOF-SU-2-4	22.66	1.0	0.70	CRIPPLING	600	613	607	87	540	1.12
EOF-SU-2-5	22.66	1.0	1.00	CRIPPLING	663	650	657	94	540	1.22
EOF-SU-2-6	22.66	1.0	1.50	CRIPPLING	688	681	685	98	540	1.27
EOF-SU-2-7	26.66	3.0	0.50	CRIPPLING	831	775	803	N/A	740	1.09
EOF-SU-3-1	20.00	1.0	N/A	CRIPPLING	463	456	460	100	306	1.50
EOF-SU-3-2	22.66	1.0	0.00	CRIPPLING	363	338	351	76	306	1.14
EOF-SU-3-3	22.66	1.0	0.50	CRIPPLING	431	406	419	91	306	1.37
EOF-SU-3-4	22.66	1.0	1.00	CRIPPLING	444	444	444	97	306	1.45
EOF-SU-4-1	19.75	1.0	N/A	CRIPPLING	2413	2394	2404	100	1828	1.31
EOF-SU-4-2	22.54	1.0	0.00	CRIPPLING	1763	1775	1769	74	1828	0.97
EOF-SU-4-3	22.54	1.0	0.50	CRIPPLING	2038	2019	2029	84	1828	1.11
EOF-SU-4-4	22.54	1.0	0.70	CRIPPLING	2100	2062	2081	87	1828	1.14
EOF-SU-4-5	22.54	1.0	1.00	CRIPPLING	2219	2256	2238	93	1828	1.22
EOF-SU-4-6	22.54	1.0	1.50	CRIPPLING	2269	2350	2310	96	1828	1.26
EOF-SU-4-7	26.54	3.0	0.50	SHEAR	2738	2781	2760	N/A	2280	N/A
EOF-SU-5-1	19.10	1.0	N/A	CRIPPLING	1331	1256	1294	100	1229	1.05
EOF-SU-5-2	19.10	1.0	0.00	CRIPPLING	781	781	781	60	1229	0.64
EOF-SU-5-3	19.10	1.0	0.50	SHEAR	813	788	801	62	1229	N/A
EOF-SU-5-4	19.10	1.0	0.70	SHEAR	775	781	778	60	1229	N/A
EOF-SU-5-5	19.10	1.0	1.00	SHEAR	769	781	775	60	1229	N/A
EOF-SU-5-6	19.10	1.0	1.50	SHEAR	781	769	775	60	1229	N/A
EOF-SU-5-7	23.10	3.0	0.50	SHEAR	731	781	756	N/A	1585	N/A
EOF-SU-6-1	19.16	1.0	N/A	CRIPPLING	475	475	475	100	279	1.70
EOF-SU-6-2	19.16	1.0	0.00	CRIPPLING	288	288	288	61	279	1.03
EOF-SU-6-3	19.16	1.0	0.50	SHEAR	331	344	338	71	279	N/A
EOF-SU-6-4	19.16	1.0	0.70	SHEAR	356	325	341	72	279	N/A
EOF-SU-6-5	19.16	1.0	1.00	SHEAR	331	325	328	69	279	N/A
EOF-SU-6-6	19.16	1.0	1.50	SHEAR	325	325	325	68	279	N/A
EOF-SU-6-7	19.16	3.0	0.50	SHEAR	356	331	344	N/A	409	N/A

Table 3: Test Results (cont.)

Specimem no.	L (in.)	N (in.)	ALPHA	FAILURE MODE	(Pu)test, per web (lbs.)			% NO HOLES (@N=1)	(Pu)comp (lbs.)	(Pu)test/ (Pu)comp
					TEST1	TEST2	AVG			
EOF-SU-7-1	11.24	1.0	N/A	CRIPPLING	994	1063	1029	100	1152	0.89
EOF-SU-7-2	15.24	1.0	0.00	CRIPPLING	850	800	825	80	1152	0.72
EOF-SU-7-3	15.24	1.0	0.50	CRIPPLING	994	944	969	94	1152	0.84
EOF-SU-7-4	15.24	1.0	0.70	CRIPPLING	988	956	972	94	1152	0.84
EOF-SU-7-5	15.24	1.0	1.00	CRIPPLING	963	994	979	95	1152	0.85
EOF-SU-7-6	15.24	1.0	1.50	CRIPPLING	988	988	988	96	1152	0.86
EOF-SU-8-1	15.33	1.0	N/A	CRIPPLING	406	419	413	100	319	1.29
EOF-SU-8-2	15.33	1.0	0.00	CRIPPLING	388	394	391	95	319	1.23
EOF-SU-8-3	15.33	1.0	0.50	CRIPPLING	400	406	403	98	319	1.26
EOF-SU-8-4	15.33	1.0	0.70	CRIPPLING	419	419	419	101	319	1.31
EOF-SU-8-5	15.33	1.0	1.00	CRIPPLING	406	406	406	98	319	1.27
EOF-SU-8-6	15.33	1.0	1.50	CRIPPLING	400	406	403	98	319	1.26
EOF-SU-8-7	19.33	3.0	0.50	CRIPPLING	550	538	544	N/A	449	1.21
EOF-SU-9-1	19.54	1.0	N/A	CRIPPLING	669	681	675	100	513	1.31
EOF-SU-9-2	19.54	1.0	0.00	CRIPPLING	481	475	478	71	513	0.93
EOF-SU-9-3	19.54	1.0	0.50	CRIPPLING	585	619	602	89	513	1.17
EOF-SU-9-4	19.54	1.0	0.70	CRIPPLING	619	619	619	92	513	1.21
EOF-SU-9-5	19.54	1.0	1.00	CRIPPLING	681	656	669	99	513	1.30
EOF-SU-9-6	24.81	1.0	1.00	CRIPPLING	638	675	657	97	513	1.28
EOF-SU-9-7	24.81	1.0	1.50	CRIPPLING	681	619	650	96	513	1.27
EOF-SU-9-8	23.54	3.0	0.50	CRIPPLING	819	831	825	N/A	704	1.17
EOF-SU-9-9	25.54	4.0	0.50	CRIPPLING	919	--	919	N/A	799	1.15
EOF-SU-9-10	27.54	5.0	0.50	SHEAR	1125	--	1125	N/A	894	N/A
EOF-SU-9-11	29.54	6.0	0.50	SHEAR	919	938	929	N/A	989	N/A
EOF-SU-10-1	19.54	1.0	N/A	CRIPPLING	2000	--	2000	100	2315	0.86
EOF-SU-10-2	24.81	1.0	0.00	CRIPPLING	1338	1350	1344	67	2315	0.58
EOF-SU-10-3	24.81	1.0	0.50	CRIPPLING	1606	1650	1628	81	2315	0.70
EOF-SU-10-4	24.81	1.0	0.70	CRIPPLING	1888	1706	1797	90	2315	0.78
EOF-SU-10-5	34.81	6.0	0.00	SHEAR	2406	--	2406	N/A	3646	N/A
EOF-SU-10-6	34.81	6.0	0.50	SHEAR	2750	2750	2750	N/A	3646	N/A
EOF-SU-10-7	34.81	6.0	1.00	SHEAR	2506	2606	2556	N/A	3646	N/A

NOTES:

1. See Figure 1 for definition of geometric parameters.
2. The centerline bearing length for all tests equals 3.00 inches.
3. ALPHA N/A denotes specimens with no web opening.
4. % No holes @ N=1 (in.) is based on the strength of the specimen with no web opening at N = 1 inch. The value is 100 x (Pu)test/[(Pu)test with no opening].
5. (Pu)comp = SF x 1000 (lb./Kip) x AISI Eq.C3.4-1. Safety Factor (SF) is 1.85

Table 4: Diagnostic Test Results

					(Pu)test, per web (lbs.)			
Specimem no.	L (in.)	x' (in.)	N (in.)	ALPHA	TEST1	TEST2	TEST3	AVG
LOAD RATE STUDY:								
1. Gradual and constant rate:								
EOF-SU-11-1a	18.00	---	1.0	N/A	750	738	725	738
2. Loaded in 15% increments of expected failure load and maintained for 5 minutes at each increment. Expected failure load equaled average of constant and gradually loaded specimens.								
EOF-SU-11-1b	18.00	---	1.0	N/A	806	738	825	790
LENGTH AND X' SENSITIVITY STUDY:								
EOF-SU-9-12a	16.28	0.00	1.0	0.50	669	656	--	663
EOF-SU-9-12b	19.54	h/2 =1.67	1.0	0.50	675	--	--	675
EOF-SU-9-12c	22.81	h =3.27	1.0	0.50	663	644	--	654

NOTES:
1. See Figure 1 for definition of geometric parameters.
2. The centerline bearing length for all tests equals 3.00 inches.
3. ALPHA N/A denotes specimens with no web opening.

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June 11, 1992

Foreword

This is the second report in the investigation of web crippling behavior of single unreinforced webs with web openings at mid-height of the web subjected to End-One-Flange (EOF) and Interior-One-Flange (IOF) loading. Report 1 (Ref. 1) considered strictly EOF loading, and provided experimental results of the EOF tests. This report presents the experimental results for the IOF load case.

Literature Review

Limited previous research has been performed on the effect of web openings on the web crippling strength of thin-walled members. As stated by K.S. Sivakumaran and K.M. Zielonka in Reference 2:

> "To the authors' knowledge only one published study exists on the web crippling strength of members having openings. In it, Yu and Davis (Ref. 3) reported the experimental results of 20 tests conducted on cold-formed steel members ... However, the tests were confined to square or circular openings on symmetric members (I-sections) and to interior two flange loading conditions."

The research by Sivakumaran and Zielonka was based on 103 tests using the IOF loading condition. The experimental research was performed on C-shaped lipped sections. The sections had rectangular web openings at mid-height of the web, and the web openings were centered on the load bearing plate. The tests had no significant bending moment interaction. Sivakumaran and Zielonka state, "The bending moments associated with the present tests were calculated and were compared to the corresponding moment capacity of the section and the effects were found negligible."

The current UMR investigation is the first known research performed on C-shaped sections using IOF loading which considers the effect of the web opening location when it is not centered on the bearing plate.

Introduction to UMR Research

The purpose of this phase of the study was to investigate web crippling behavior of single unreinforced webs with web openings at mid-height of the web subjected to IOF loading. Tests were limited to C-shaped sections with edge stiffened flanges. The major parameter varied within each common cross section was the horizontal clear distance of the opening from the near edge of bearing plate. Figure 1 shows this as distance "x". Instead of using the dimensional distance "x" , the related non-dimensional parameter of "Alpha" was used, where Alpha equals x/h. Tests were conducted for Alpha in increments of 0, 0.5, 0.7, 1.0, and 1.5.

Test Specimens

The test specimens were fabricated from industry standard C-sections with edge stiffened flanges. Figures 1 and 2 define the geometric parameters of the test specimens. Eight cross sections were tested with cross section dimensions and yield strength as shown in Table 1. The range of major parameters and aspect ratios of a/h, h/t, and R/t are given in Table 2. The range of parameters was selected as representative of industry practice. Inside bend radius, R, was nominally 5/32 inch. Two sizes of web openings were used: 0.75 x 4 inches and 1.50 x 4 inches designated by dimensions a and b in Figure 1.

As depicted in Figure 1, the minimum length of each specimen, L, was chosen in order to satisfy the requirement for one-flange loading. Specifically, the clear distance between each end plate and the mid-span loading plate must be greater than or equal to 1.5h. Also, the length had to be sufficient to ensure that the distance x' was greater than or equal to zero. This requirement typically resulted in specimen lengths in excess of that required for one-flange loading, especially at large Alpha values. Table 3 contains a summary of the overall specimen length and bearing length, N, of each specimen.

Test Setup

To stabilize the specimens against lateral-torsional buckling, each test specimen consisted of two C-shaped lip stiffened sections connected by 3/4 x 3/4 x 1/8 inch angles and self-drilling screws. To prevent web crippling at the ends of the span due to an EOF loading, a stiffener was attached vertically on the webs of both sections centered above the end bearing plates as shown in Fig. 1. Using a Tinius-Olson testing machine, a concentrated load was applied at mid-span to a bearing plate in contact with the top flanges. At the end reactions, three inch long bearing plates flush with the ends of the specimen were used. Rollers were placed at the centerline of the end reactions to achieve a simple support condition.

Test Procedure

The load was applied to the test specimens at a constant and gradual rate until the specimen failed. Failure was defined when the specimen could carry no additional load. Two identical tests were conducted for each specimen number.

Test Results

One hundred twenty four IOF tests were conducted to date. Of these, 114 tests are valid for web crippling analysis, and 10 tests failed in shear. No specimens failed in bending. The applied failure load, P_t, per web, for each test specimen is given in Table 3. AISI Equation C3.4-4 (Ref. 4) provides the allowable web crippling load, P_a, for sections with single-unreinforced webs with stiffened or unstiffened flanges subjected to Interior-One-Flange (IOF) loading. AISI Eq. C3.4-4 incorporates a factor of safety of 1.85. Therefore, the nominal capacity, P_n, is equal to 1.85 x AISI Eq. C3.4-4. Table 3 shows the values of P_n, and P_t/P_n.

Shear

Ten test specimens, performed on five pairs of identical specimens, failed in shear. The shear failures were very pronounced in the vicinity of the web opening. Shear failures usually occurred with little or no web crippling deformation at the load plate.

Shear failures generally occurred for two reasons. First, higher bearing lengths, N, increased the likelihood of a shear failure because an increase in N provides an increase in the web crippling strength of the section.

Secondly, shear failures also occurred at high values of the ratio of web opening height, a, to web height, h. This occurred because of the removal of a considerable portion of the shear carrying portion of the cross section. Cross section IOF-SU-4 demonstrates this phenomenon for an a/h ratio of 0.73. Test IOF-SU-4-2 was the only test which failed at N is equal to three inches.

Since the specific web crippling - shear transition parameters values are not defined, shear must be checked separately. A concurrent UMR study is investigating the shear strength of specimens with web openings.

Future Work

Upcoming phases of the investigation are:

1. Additional EOF and IOF tests will be performed. Tests will be performed on cross sections will a/h values between 0.13 and 0.35.
2. Design recommendations will be developed for the EOF and IOF load cases.

References

1. "Web Crippling Behavior of Sections with Web Openings", by J.E. Langan, R.A. LaBoube, and W.W. Yu, First Progress Report, University of Missouri - Rolla, October 20, 1991.

2. "Web Crippling Strength of Thin-Walled Steel Members with Web Opening", contained in publication titled, "Thin-Walled Structures", by K.S. Sivakumaran and K.M. Zielonka, Elsevier Science Publishers Ltd., England, 1989.

3. "Cold-Formed Steel Members with Perforated Elements", Journal of Structural Engineering, Vol. 99, No. 10, October 1973, by Yu, W.W. and Davis, C.S., American Society of Civil Engineers,

Structural Division.

4. "Cold-Formed Steel Design Manual", American Iron and Steel Institute, August 19, 1986, with December 11, 1989 Addendum.

Table 1: Cross Section Properties

Cross Section	D(in.)	t(in.)	R(in.) nominal	h(in.)	B(in.)	d(in.)	WEB OPENING a(in.)	b(in.)	Fy Ksi	h/t	a/h	R/t
IOF-SU-1	12.05	0.098	0.156	11.54	1.65	0.64	1.50	4.00	36	118	0.13	1.6
IOF-SU-2	2.51	0.032	0.156	2.12	1.57	0.41	0.75	4.00	55	66	0.35	4.9
IOF-SU-3	2.55	0.055	0.156	2.12	1.65	0.47	0.75	4.00	55	39	0.35	2.8
IOF-SU-4	2.42	0.033	0.156	2.05	1.63	0.46	1.50	4.00	67	62	0.73	4.7
IOF-SU-5	3.62	0.033	0.156	3.23	1.62	0.44	1.50	4.00	59	98	0.46	4.7
IOF-SU-6	3.67	0.045	0.156	3.26	1.63	0.47	1.50	4.00	53	72	0.46	3.5
IOF-SU-7	3.65	0.044	0.156	3.25	1.64	0.49	NO OPENING		63	74	0.00	3.6
IOF-SU-8	3.69	0.067	0.156	3.22	1.63	0.49	1.50	4.00	48	48	0.47	2.3
AVERAGE	4.27	0.051	0.156	3.85	1.63	0.48			55	72	0.37	3.52

Notes:

1. See Figures 1 and 2 for definition of dimensions.
2. Cross section designations:
   IOF: End-One-Flange (loading)
   SU: Single Unreinforced (web)

Table 2: Ranges of Parameters and Aspect Ratios

	minimum	maximum
h(in.)	2.12	11.54
t(in.)	0.033	0.098
Fy(Ksi)	36	67
N(in.)	3.00	6.00
Alpha	0.00	1.50
a(in.)	0.00	1.50
b(in.)	0.00	4.00
a/h	0.13	0.73
h/t	39	118
R/t	1.0	4.9

Note: a/h range excludes cross section IOF-SU-7, which had no web opening.

Table 3: Test Results

Specimen number	L(in.)	N(in.)	ALPHA	Pt, per web (lbs.) TEST1	TEST2	AVG	PERCENT SOLID WEB STRENGTH (@ same N)	FAILURE MODE	Pn (lbs.)	Pt/Pn
IOF-SU-1-1	44.00	3.0	SOLID	5785	6075	5930	100.0	CRIPPLING	5425	1.09
IOF-SU-1-2	44.00	3.0	0.00	6100	6000	6050	102.0	CRIPPLING	5425	1.12
IOF-SU-2-1	17.00	3.0	SOLID	925	900	913	100.0	CRIPPLING	974	0.94
IOF-SU-2-2	17.00	3.0	0.00	825	838	832	91.1	CRIPPLING	974	0.85
IOF-SU-2-3	20.00	3.0	0.50	800	813	807	88.3	CRIPPLING	974	0.83
IOF-SU-2-4	22.00	3.0	1.00	813	813	813	89.0	CRIPPLING	974	0.84
IOF-SU-2-5	24.00	3.0	1.50	788	800	794	87.0	CRIPPLING	974	0.82
IOF-SU-2-6	17.00	4.0	SOLID	1050	1063	1057	100.0	CRIPPLING	1162	0.91
IOF-SU-2-7	18.00	4.0	0.00	950	950	950	89.9	SHEAR		
IOF-SU-2-8	18.50	6.0	SOLID	1338	1288	1313	100.0	CRIPPLING	1537	0.85
IOF-SU-2-9	20.00	6.0	0.00	1038	1050	1044	79.5	SHEAR		
IOF-SU-3-1	17.00	3.0	SOLID	1975	1925	1950	100.0	CRIPPLING	2696	0.72
IOF-SU-3-2	17.00	3.0	0.00	1775	1763	1769	90.7	CRIPPLING	2696	0.66
IOF-SU-3-3	20.00	3.0	0.50	1788	1788	1788	91.7	CRIPPLING	2696	0.66
IOF-SU-3-4	22.00	3.0	1.00	1588	1575	1582	81.1	CRIPPLING	2696	0.59
IOF-SU-3-5	24.00	3.0	1.50	1638	1588	1613	82.7	CRIPPLING	2696	0.60
IOF-SU-3-6	17.00	4.0	SOLID	2300	2263	2282	100.0	CRIPPLING	3024	0.75
IOF-SU-3-7	18.00	4.0	0.00	2013	1975	1994	87.4	CRIPPLING	3024	0.66
IOF-SU-3-8	18.50	6.0	SOLID	2763	2763	2763	100.0	CRIPPLING	3805	0.73
IOF-SU-3-9	20.00	6.0	0.00	2075	2063	2069	74.9	SHEAR		
IOF-SU-4-1	16.00	3.0	SOLID	1150	1100	1125	100.0	CRIPPLING	1143	0.98
IOF-SU-4-2	17.00	3.0	0.00	750	750	750	66.7	SHEAR		
IOF-SU-4-3	19.00	6.0	SOLID	1550	1525	1538	100.0	CRIPPLING	1796	0.86
IOF-SU-4-4	20.00	6.0	0.00	850	825	838	54.5	SHEAR		
IOF-SU-5-1	18.69	3.0	SOLID	925	925	925	100.0	CRIPPLING	1018	0.91
IOF-SU-5-2	18.69	3.0	0.00	838	825	832	89.9	CRIPPLING	1018	0.82
IOF-SU-5-3	21.00	3.0	0.50	838	863	851	91.9	CRIPPLING	1018	0.84
IOF-SU-5-4	22.00	3.0	0.70	838	863	851	91.9	CRIPPLING	1018	0.84
IOF-SU-5-5	24.00	3.0	1.00	813	788	801	86.5	CRIPPLING	1018	0.79
IOF-SU-5-6	27.00	3.0	1.50	688	738	713	77.1	CRIPPLING	1018	0.70
IOF-SU-5-7	20.00	4.0	SOLID	963	975	969	100.0	CRIPPLING	1212	0.80
IOF-SU-5-8	20.00	4.0	0.00	863	888	876	90.4	CRIPPLING	1212	0.72
IOF-SU-5-9	25.00	4.0	0.00	850	825	838	86.4	CRIPPLING	1212	0.69
IOF-SU-5-10	21.69	6.0	SOLID	1125	1150	1138	100.0	CRIPPLING	1600	0.71
IOF-SU-5-11	22.00	6.0	0.00	1100	1075	1088	95.6	CRIPPLING	1600	0.68

Table 3: Test results (cont.)

Specimen number	L(in.)	N(in.)	ALPHA	Pt, per web (lbs.)			PERCENT SOLID WEB STRENGTH (@ same N)	FAILURE MODE	Pn (lbs.)	Pt/Pn
				TEST1	TEST2	AVG				
IOF-SU-6-1	18.78	3.0	SOLID	1438	1363	1401	100.0	CRIPPLING	1726	0.81
IOF-SU-6-2	18.78	3.0	0.00	1188	1200	1194	85.2	CRIPPLING	1726	0.69
IOF-SU-6-3	25.00	3.0	0.00	1150	1138	1144	81.7	CRIPPLING	1726	0.66
IOF-SU-6-4	21.00	3.0	0.50	1225	1205	1215	86.7	CRIPPLING	1726	0.70
IOF-SU-6-5	25.00	3.0	0.50	1188	1163	1176	83.9	CRIPPLING	1726	0.68
IOF-SU-6-6	22.00	3.0	0.70	1250	1238	1244	88.8	CRIPPLING	1726	0.72
IOF-SU-6-7	25.00	3.0	0.70	1188	1138	1163	83.0	CRIPPLING	1726	0.67
IOF-SU-6-8	24.00	3.0	1.00	1225	1250	1238	88.3	CRIPPLING	1726	0.72
IOF-SU-6-9	27.00	3.0	1.50	1213	1238	1226	87.5	CRIPPLING	1726	0.71
IOF-SU-6-10	20.00	4.0	SOLID	1375	1363	1369	100.0	CRIPPLING	2011	0.68
IOF-SU-6-11	20.00	4.0	0.00	1338	1313	1326	96.8	CRIPPLING	2011	0.66
IOF-SU-6-12	25.00	4.0	0.00	1238	1250	1244	90.9	CRIPPLING	2011	0.62
IOF-SU-6-13	21.78	6.0	SOLID	1725	1675	1700	100.0	CRIPPLING	2579	0.66
IOF-SU-6-14	22.00	6.0	0.00	1638	1600	1619	95.2	CRIPPLING	2579	0.63
IOF-SU-7-1	18.76	3.0	SOLID	1888	1938	1913		CRIPPLING	1817	1.05
IOF-SU-7-2	20.00	3.0	SOLID	1913	1875	1894		CRIPPLING	1817	1.04
IOF-SU-7-3	22.00	3.0	SOLID	1875	1800	1838		CRIPPLING	1817	1.01
IOF-SU-7-4	24.00	3.0	SOLID	2175	2175	2175		CRIPPLING	1817	1.20
IOF-SU-7-5	26.00	3.0	SOLID	2100	2138	2119		CRIPPLING	1817	1.17
IOF-SU-8-1	18.66	3.0	SOLID	2950	3025	2988	100.0	CRIPPLING	3571	0.84
IOF-SU-8-2	18.66	3.0	0.00	2675	2688	2682	89.7	CRIPPLING	3571	0.75
IOF-SU-8-3	21.00	3.0	0.50	2813	2775	2794	93.5	CRIPPLING	3571	0.78
IOF-SU-8-4	22.00	3.0	0.70	2788	2738	2763	92.5	CRIPPLING	3571	0.77
IOF-SU-8-5	24.00	3.0	1.00	2713	2738	2726	91.2	CRIPPLING	3571	0.76
IOF-SU-8-6	27.00	3.0	1.50	2650	2600	2625	87.9	CRIPPLING	3571	0.74
IOF-SU-8-7	21.66	6.0	SOLID	3613	3663	3638	100.0	CRIPPLING	4717	0.77
IOF-SU-8-8	22.00	6.0	0.00	3213	3150	3182	87.5	CRIPPLING	4717	0.67

Notes:
1. See Figures 1 and 2 for definition of geometric parameters.
2. The end bearing lengths of all specimens (both ends) equals 3.00 inches.
3. ALPHA "SOLID" denotes specimens with no web openings.

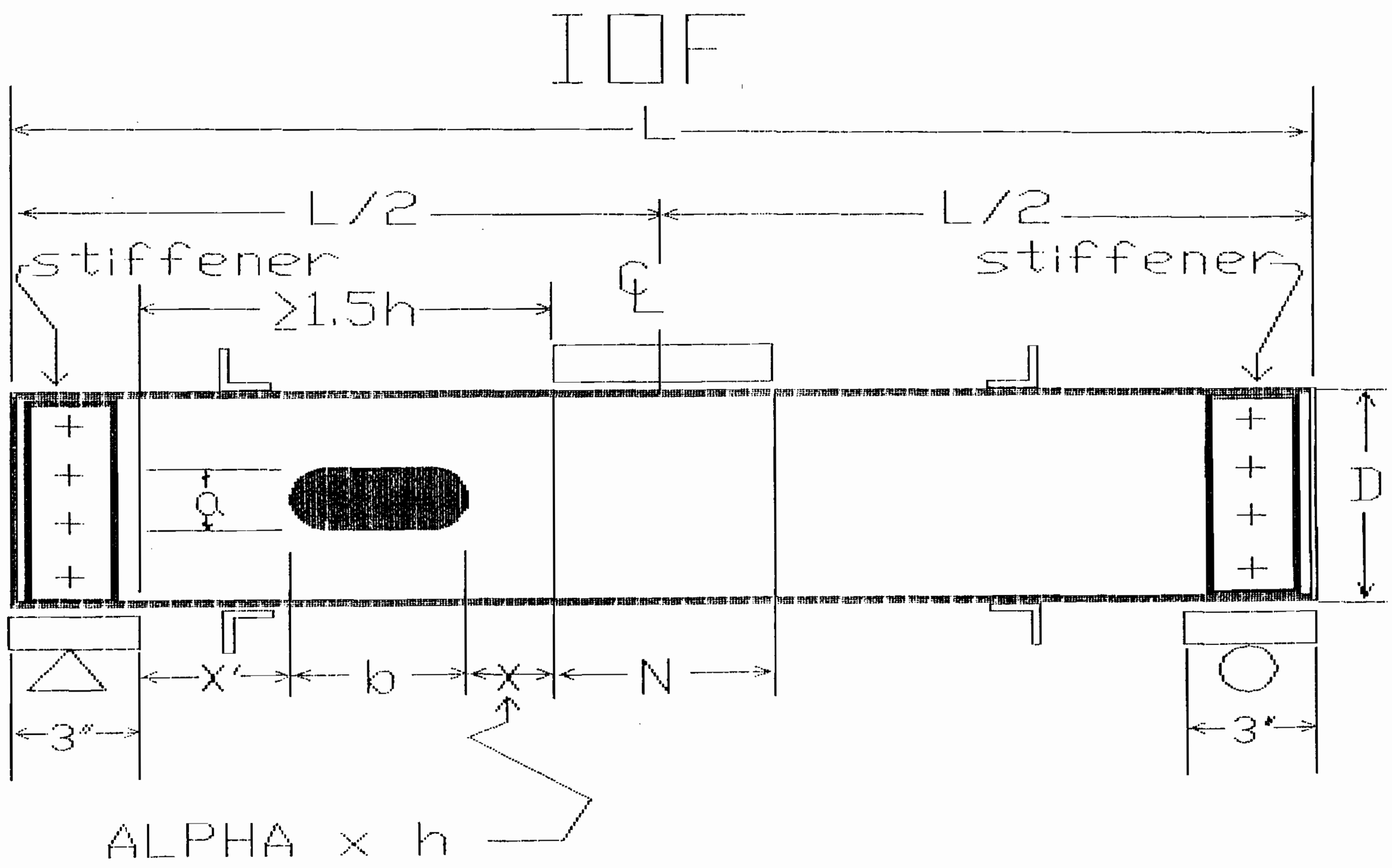

FIGURE 1: SPECIMEN PARAMETERS LONGITUDINAL VIEW

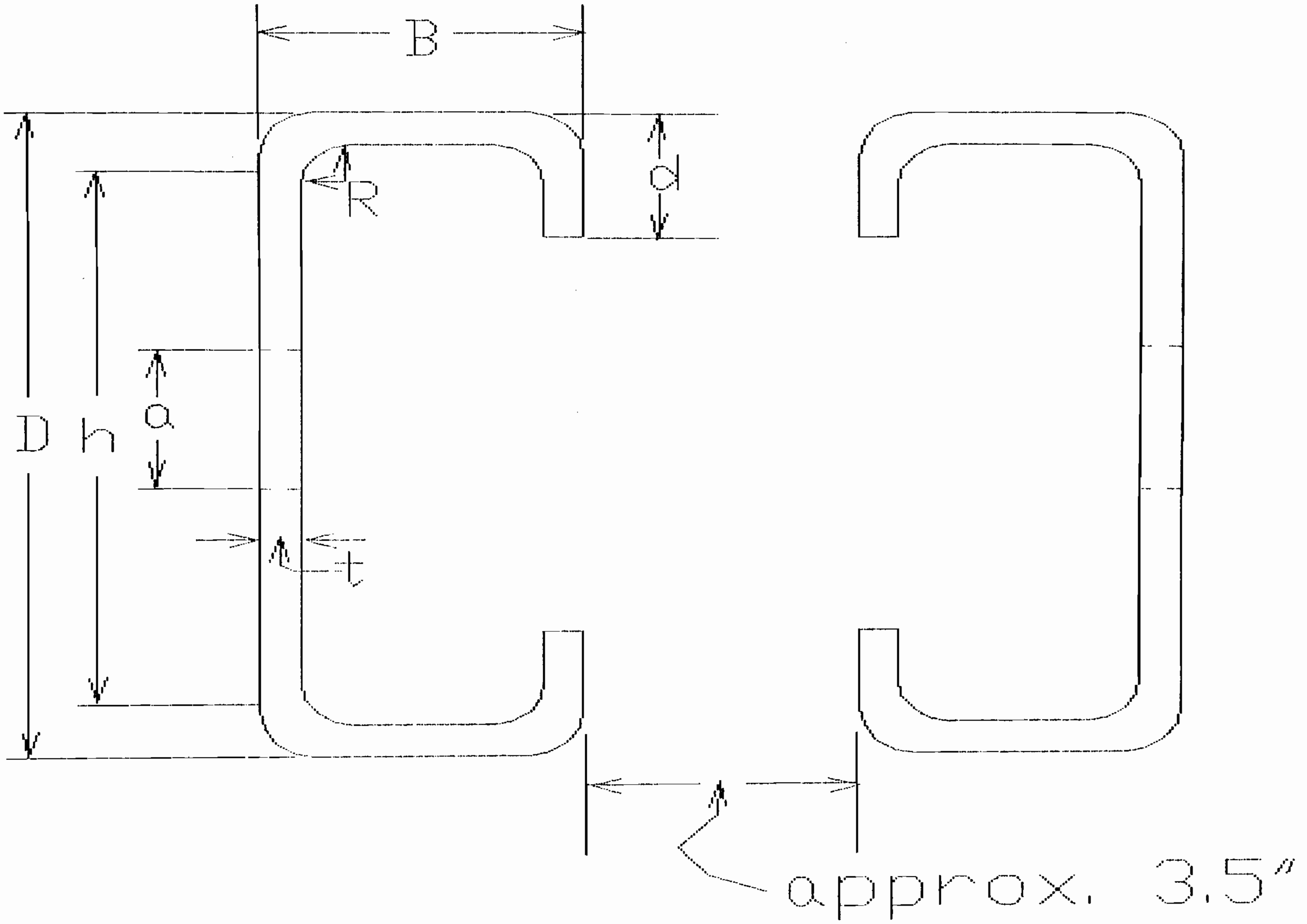

FIGURE 2: SPECIMEN PARAMETERS
END VIEW

Third Progress Report
Web Crippling Behavior of Sections with Web Openings

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October 14, 1992

Foreword

A comprehensive study of the behavior of web elements with openings subjected to bending, shear, and web crippling, and combinations thereof is being conducted at the University of Missouri - Rolla (UMR).

This is the third report in the investigation of the effect of web crippling behavior of single unreinforced webs with web openings at mid-height of the web. Report 1 (Langan, LaBoube, and Yu, 1991) provided test results from End-One-Flange (EOF) loading. This report supersedes Report 1 in its entirety. This is necessary because additional EOF tests were performed since publication of Report 1, and most tables and figures required updating to reflect the additional test results. Therefore, this report is the sole source for the current UMR study of web crippling behavior for sections with web openings subjected to EOF loading. Report 2 (Langan, LaBoube, and Yu, 1992) provided the results for Interior-One-Flange (IOF) loading.

Introduction

The terms "solid web", "no web opening(s)", and "without web opening(s)" are used synonymously throughout this report.

The purpose of this phase of the research was to investigate the web crippling behavior of single unreinforced webs with web openings subjected to EOF loading. The web openings were centered at the mid-height of the web. Tests were limited to C-shaped sections with edge-stiffened flanges. The major parameter varied within each common cross section was the horizontal clear distance of the opening from the near edge of bearing plate, x, (Fig. 1).

The primary goals of this study were (1) to examine web the crippling behavior as x was varied, (2) to evaluate the adequacy of the AISI provisions, based on no web openings, for predicting the web crippling strength for web elements with web openings, and (3) to develop appropriate design recommendations. All three goals will be discussed in this report.

Previous Research on Sections with Web Openings

Only two previous studies for web crippling behavior of thin-walled members with web openings have been documented. This study is the first for EOF loading.

Yu and Davis (1973) reported the results of 20 IOF tests conducted on cold-formed steel members. The tests were conducted on specimens composed of two channels with square or circular web openings. The channels were connected either back-to-back or through the edge stiffeners.

Sivakumaran and Zielonka (1989) developed the following reduction factor for sections with web openings subjected to IOF loading:

$$RF = \left(1-0.197\left(\frac{a}{h}\right)^2\right)\left(1-0.127\left(\frac{b}{n_1}\right)^2\right) \qquad \text{(Eq. 1)}$$

where: $n_1 = N + h - a$
N = bearing load length
h = flat height of web
a = height of web opening
b = longitudinal length of web opening
limits: $b/n_1 \leq 2.0$
$a/h \leq 0.75$

The computed strength reduction is accomplished by multiplying the solid web strength by the Sivakumaran and Zielonka reduction factor (Eq.1), which is always less than unity for sections with web openings. This reduction factor was developed based on the results of 103 tests with the web opening centered on the load plate. This experimental research was performed on C-shaped, edge-stiffened, channel sections subjected to IOF loading having rectangular web openings at mid-height of the web.

LaBoube (1990) proposed using a simplified form of the Sivakumaran and Zielonka reduction factor as an interim design recommendation to account for web openings. The effectiveness of the Sivakumaran and Zielonka reduction factor as applied to the EOF loading condition is discussed herein.

Test Specimens

The test specimens were fabricated from industry standard C-sections. See Figures 1 and 2 for the geometry of each test specimen. Figures 3(a) and (b) show a typical test specimen.

The sections were cut to the desired length to ensure that the web opening in each section was at the desired distance x from the end bearing reaction. Thirteen cross sections were tested with cross section dimensions and yield strength as listed in Table 1. The range of major parameters and ratios of a/h, h/t, and R/t are given in Table 2. Inside bend radius was nominally 5/32 inch. Two sizes of web openings were used in this test program, 0.75 x 2 inches and 1.50 x 4 inches, and are designated by dimensions a and b of Figure 1. The web openings were rectangular with fillet corners.

The major parameter varied within each cross section was the distance x. This was varied as a percent of section depth, $\alpha = x/h$. Tests were conducted for α values in increments of 0, 0.5, 0.7, 1.0, and 1.5.

As depicted by Figure 1, the minimum length of each specimen was chosen to satisfy the requirement for one-flange loading. This minimum length is defined as a clear distance between the end bearing plate and mid-span loading plate greater than or equal to 1.5h. Table 3 contains a summary of the overall specimen length, L, bearing length, N, and α of each specimen.

Test Setup

To stabilize the specimens against lateral-torsional buckling, each test specimen consisted of two C-shaped sections inter-connected by 3/4 x 3/4 x 1/8 inch angles using self-drilling screws. To prevent web crippling at mid-span due to an IOF loading, a stiffener was attached vertically on the webs of both sections at mid-span. Using a Tinius-Olson testing machine, a concentrated load was applied at mid-span to a three inch bearing plate in contact with the top flanges of the test specimen. The reactions creating the EOF loading were introduced to the specimen by bearing plates flush with the ends of the specimen. Rollers were placed at the centerline of the bearing reactions to achieve a simple support condition.

Test Procedure

The load was applied to the test specimens at a constant and gradual rate until the specimen failed. Failure was defined when the specimen could carry no additional load. Two identical tests were conducted for most test specimens. Duplicate tests on identical specimens are identified by the specimen number designations in Tables 3 and 4.

Test Results

One hundred fifty seven tests were conducted to date. Of these, 108 are valid for web crippling analysis, 34 failed in shear, four failed by flexure at mid-span in the compression flange, and 11 were conducted to perform diagnostic tests to ensure validity of the testing procedure.

The tested failure load, $(P_n)_{test}$, per web, for specimens exhibiting either a web crippling or a shear failure are given in Table 3. The results from the diagnostic tests are given in Table 5. The tested failure load per web is 1/4 of the applied mid-span load at failure.

Figures 4 thru 7 show typical web crippling failures with the failure load still applied. Figure 8 shows a typical shear failure of a specimen with the failure load still applied.

Observations

Based on the results of the specimens tested in this study, the following observations can be drawn.

A notable trend exists within the test results. As α increased from 0 to 1.5, the web crippling strength increased. This is shown in Table 3 under the column titled "percent of solid web average strength". This percentage is the value of $(P_n)_{test}$ for a specimen with a web opening divided by the average $(P_n)_{test}$ for all solid web specimens from the same cross section. This percentage is abbreviated as "PSW" or *percent* of *solid web* average strength. PSW values only pertain to N equal to one inch, because no solid web tests were performed at other N values.

Figures 9(a) and (b) graphically show the trend of increasing PSW values as α increased for ten cross sections. For visual clarity, five cross sections are shown on each figure. Cross sections EOF-SU-5 and 6 were excluded from Figures 9(a) and (b) because they failed in shear for all tests with web openings. Cross section EOF-SU-11 was excluded from Figures 9(a) and (b) because it was a solid web cross section which was only used in diagnostic tests. The data points in Figures 9(a) and (b) are the average PSW values for all specimens, from the same cross section, tested at the same α value at N equal to one inch. The PSW values were averaged to facilitate plotting a curve for each cross section and thereby readily showing the aforementioned trend for each cross section.

For specimens identified as having an EOF web crippling failure, the tested failure load, $(P_n)_{test}$ was also compared to the computed nominal web crippling load, $(P_n)_{comp}$ using AISI Eq.C3.4-1 multiplied by 1.85 to account for the factor of safety. The factor of safety is in accordance with (AISI 1986 and 1989), Section II (Commentary), Table 5.1. As indicated by the ratio $(P_n)_{test}/(P_n)_{comp}$ (Table 4), the specification generally yields a satisfactory estimate of the web crippling failure load for solid web specimens as indicated by the fact that $(P_n)_{test}/(P_n)_{comp}$ is approximately equal to or greater than unity. However, solid web specimens for cross sections EOF-SU-7 and 10, AISI Eq.C3.4-1 significantly overestimates the web crippling capacity as indicated by $(P_n)_{test}/(P_n)_{comp}$ values less than unity for the solid web specimens. Consequently, the $(P_n)_{test}/(P_n)_{comp}$ values from these cross sections with web openings were significantly less than unity. This particularly applies to specimens with α is equal to zero.

For N values greater than one inch, few tests were conducted as shown in Table 3. Many of these specimens failed in shear.

Development of the Reduction Factor Equation

Seventy-eight tests conducted at N equal to one inch failed in web crippling. A bivariate linear regression was performed with α and a/h as the independent variables and percent solid web strength, PSW, as the dependant variable. The resulting equation, with a maximum limit of 100 percent, is:

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

or,

$$PSW = 1.08-(0.63\frac{a}{h})+(0.12\alpha)\leq 1.00 \qquad \text{(Eq.2)}$$

The regression is the least y-squares plane (Fig. 10) for the 78 data points. A PSW value of 100 percent signifies that no strength reduction is required. The reduction factor equation yields, at 100 PSW:

$$\alpha \geq (5.25\ a/h) - 0.67 \geq 0 \qquad \text{(Eq.3)}$$

Equation 3 implies that, for any positive value of α, no strength reduction is required for any cross section with a/h values less than 0.13. The total joint region of α and a/h which requires no strength reduction is shown in Figure 10 as a horizontal plane with a PSW value of 100.

The parameters of α and a/h provided the only conclusive correlation with PSW. The additional parameters shown in Table 1, with the exception of the length of the hole, b, proportionally affected both of the aforementioned $(P_n)_{test}$ values which determine PSW. However, α and a/h influenced PSW since they are intrinsic only to specimens with web openings, and therefore they affected only the numerator of the PSW equation. The influence of b is addressed by imposing a maximum limit on b. See the section titled "Ranges of Applicability for the Reduction Factor Equation".

The correlation coefficient of the bivariate linear regression was 0.6442. A higher order regression will not significantly improve the correlation coefficient primarily because of the inconsistent influence of the a/h variable. As can be seen from Figures 9(a) and (b), cross sections with approximately the same a/h value often exhibit different PSW values at identical values of α. However, an overall trend does exist in that PSW is inversely proportional to a/h. This is demonstrated by the regression coefficient of negative 62.95 for the a/h term of the reduction factor equation.

Application of Reduction Factor

The allowable web crippling load for specimens with web openings can be obtained by applying the reduction factor, which is less than or equal to unity, to Eq.4 or Eq.5 taken from (AISI 1986, and 1989). Equation 4 corresponds to AISI Eq.C3.4-1, and Equation 5 corresponds to AISI Eq.C3.4-2. Equation 4 provides the allowable load for single-unreinforced webs with edge-stiffened flanges subjected to EOF loading. Equation 5 provides the allowable load for single-unreinforced webs with unstiffened flanges subjected to EOF loading.

$$P_a=t^2kC_3C_4C_\theta\left(179-0.33\frac{h}{t}\right)\left(1+0.01\frac{N}{t}\right), kips \qquad (Eq.\ 4)$$

$$P_a=t^2kC_3C_4C_\theta\left(117-0.15\frac{h}{t}\right)\left(1+0.01\frac{N}{t}\right), kips \qquad (Eq.\ 5)$$

Where: $k = F_y/33$
$C_3 = (1.33-0.33k)$
$C_4 = 0.50 < (1.15-0.15\ R/t) \leq 1.0$
$C_\theta = 0.7 + 0.30\ (\theta/90)^2$
F_y = Design yield stress of the web.
h = Depth of the flat portion of the web.
t = Web thickness, inches
R = Inside bend radius
θ = Angle between the plane of the web and the plane of the bearing surface ≥ 45°, but not more than 90°.

For Eq.4: When N/t>60, the factor [1+0.01(N/t)] may be increased to [0.71+0.015(N/t)]

Ranges of Applicability for Reduction Factor Equation

The reduction factor equation (Eq.2) developed in the current study is applicable to all cross sections that meet the ranges of applicability as follows:

1. Ranges based on applicability of Eq.4 and Eq.5: Although the testing was limited to specimens with edge-stiffened flanges (Eq.4 applies), the same percent reduction in strength is expected for sections with unstiffened flanges (Eq.5 applies). Therefore, Eq.2 is applicable to both conditions. If Eq.2 is used to reduce the allowable strength of Eq.4 or Eq.5, the limits on h/t, R/t, N/t, and N/h ratios stated in Section C3.4 of the AISI specification (1986, and 1989) must be met.

2. Ratio of a/h: Although the maximum a/h value tested which failed in web crippling was 0.47, Eq.2 is assumed to be valid for a/h less than or equal to 0.50. This limit corresponds to the maximum a/h employed by industry standard sections. As will be discussed, high a/h values increase the probability of a shear failure. Therefore, shear must be checked separately using results from the concurrent UMR study of shear behavior of sections with web openings.

3. End reaction length, N: Although Eq.2 is based on test data exclusively at N equal to one inch, it will be applicable for all N values. This occurs for two reasons. First, Eq.4 and Eq.5 incorporate the bearing length, N. Therefore, N influences the reduced nominal capacity although N is not included in Eq.2. Tables 3 and 4 show the effect of N on $(P_n)_{comp}$ for Eq.4. Second, the same trend in increasing web crippling strength with increasing Alpha values is expected at higher N values. Also, as will be discussed later, a cross section will change from web crippling to shear failure at a particular N value inherent to the cross section properties. Therefore, Eq.2 can be used in conjunction with Eq.4 and Eq.5 for all N values if shear strength is checked separately.

The test results strongly support the generalization of Eq.2 to all values of N. Table 3 shows seven test specimens which failed in web crippling for N values greater than one inch. The average $(P_n)_{test}/(P_n)_{comp}$, based on the reduced strength from Eq.2, was 1.333 for the seven tests. The average $(P_n)_{test}/(P_n)_{comp}$, based on the reduced strength from Eq.2 for the corresponding tests, i.e. at the same α value, at N equal to one inch was 1.347.

4. Depth of flat portion of the web, h: The tested range was 2.03 to 11.54 inches. However, all h values are valid if the h/t maximum limit of 200 is not exceeded.

5. Base metal thickness (t): The tested range was 0.033 to 0.077 inches. However, all t values are valid if the h/t maximum limit of 200 is not exceeded.

6. Yield Strength (F_y): The tested range was 34 to 93 ksi. Therefore, all F_y are valid for Eq.2. For cross sections with F_y greater than 66.5 ksi, 66.5 ksi should be used in Eq.4 and Eq.5. This limit is imposed because these equations were developed using specimens with F_y less than 66.5 ksi. Also, as can be seen from the product of the k and C_3 terms of the Eq.4 and Eq.5, the maximum value of P_a is obtained at 66.5 ksi.

7. Maximum opening height, a, and width, b:

a: No maximum limit is prescribed for a. However, the maximum allowable a/h ratio of 0.50 must be adhered to.

b: Although the maximum b value tested was four inches, it is recommended that the maximum limit for b be extended to the industry standard maximum of 4.5 inches. The parameter b is not included in the reduction factor equation, hence no variation in allowable load for b values between zero and 4.5 inches is recommended.

All web crippling failures were located between the region of the outer end of the web opening and the end of the specimen.

Only a minor portion of the horizontal length of the web opening appeared to influence the failure. Hence a small b value, i.e., less than the minimum tested value of two inches, will have the same effect as b values within the range of those tested.

The definitions of a and b for various shapes of web openings in given in Figure 11.

8. h/t: Although the maximum h/t ratio tested was 192, this can be extended to the maximum allowable prescribed for Eq.4 and Eq.5 of 200. No minimum h/t is prescribed although the minimum h/t tested was 34.

9. R/t: The tested range was 2.00 to 4.74. However, all R/t values less than or equal to 6.0 are valid for Eq.2, because this is the maximum limit imposed for Eq.4 and Eq.5.

10. θ: Theta equalled 90° for all tests. However, it is assumed that all θ values within the allowable limits of Eq.4 and Eq.5 of 45° to 90° are valid.

Comparison with Previous Studies for Specimens with Solid Webs

As shown in Table 4, most of the values for $(P_n)_{test}/(P_n)_{comp}$, using Eq.4, are significantly greater than unity. However, the values of $(P_n)_{test}/(P_n)_{comp}$ for cross sections EOF-SU-7 and 10 were less than one. Analysis of the cross section properties provides no trends which can predict the magnitude of the $(P_n)_{test}/(P_n)_{comp}$ value. Specifically, no trend exists which predicts the amount of the conservatism or unconservatism of Eq.4. Therefore, no recommendation is made to change the current AISI provisions for solid webs.

The 29 solid web test results (Tables 3, 4, and 5) were compared to Figure 34 of (Hetrakul and Yu, 1978) by using Figure 12 of this report. This reference serves as the basis for the current web crippling formulas in the AISI specification. As indicated by Figure 12, the conservative results obtained in the present study are consistent with results from previous studies. However, as can be seen from Figure 34 of (Hetrakul and Yu, 1978), the previous studies did not include specimens with $(P_n)_{comp}$ values lower than 0.5 kips. The higher $(P_n)_{test}/(P_n)_{comp}$ values from the current study were from cross sections with low $(P_n)_{comp}$ values. On Figure 12, these tests results plotted close to the origin. Therefore, $(P_n)_{test}/(P_n)_{comp}$ values which are conservative are from sections with low capacity. For example, the conservative results of $(P_n)_{test}/(P_n)_{comp}$ equal to 2.56 and 2.75 from specimens EOF-SU-13-(1 and 2) are attributed to a low $(P_n)_{comp}$ value of 217 lbs. Furthermore, $(P_n)_{comp}$ values were suppressed for sections with F_y values greater than 66.5 ksi, thereby artifically increasing the $(P_n)_{test}/(P_n)_{comp}$ ratio. These cross sections are noted in Table 4 by asteria.

Nominal Tested versus Computed Capacity

Table 3 shows the reduction values from the Sivakumaran and Zielonka study (Eq.1) and the current study (Eq.2) for each test specimen which had a web crippling failure. Table 4 shows the nominal web crippling strength from Eq.4, and the reduced strengths, based on Eq.4, multiplied by the two reduction factors. Table 4 also shows the $(P_n)_{test}/(P_n)_{comp}$ values using the three $(P_n)_{comp}$ values for all tests that failed in web crippling. Also listed on Table 4 are the required statistical values, mean and coefficient of variation, to compute the resistance factor Φ. The Φ factor based on each of the three $(P_n)_{comp}$ values was computed using Eq.F1-2 from the AISI specification, (1991):

$$\Phi = 1.5(M_m F_m P_m)\exp\left(-\beta_0\sqrt{V_M^2+V_F^2+C_P V_P^2+V_Q^2}\right) \quad (Eq.\ 6)$$

Where:

In general:

M_m = Mean value of the material factor for the type of component involved.
F_m = Mean value of the fabrication factor for the type of component involved.
P_m = Mean value of the tested-to-predicted load ratios.
β_o = Target reliability index = 2.5 for structural members and 3.5 for connections.
V_M = Coefficient of variation of the material factor for the type of component involved.
V_F = Coefficient of variation of the fabrication factor for the type of component involved.
C_P = Correction factor = (n-1)/(n-3)
V_P = Coefficient of variation of the tested-to-predicted load ratios.
n = number of tests values.
V_Q = Coefficient of variation of the load effect = 0.21

Specific values:

M_m, V_M, F_m, and V_F are from Table F1 of AISI 1991. For web crippling: M_m = 1.10, V_M = 0.10, F_m =1.00, and V_F =0.05.
P_m and V_P: from Table 4, based on the method used to determine $(P_n)_{comp}$.
β_o = 2.5

The Load and Resistance Factor Design, LRFD, factors of safety were computed using Eq.7 from Hsiao, Yu, and Galambos, (1988):

$$(F.S.)_{LRFD}=(1.2D_n/L_n+1.6)/[(\Phi(D_n/L_n+1)] \qquad (Eq.\ 7)$$

Where: $D_n/L_n = 1/5$.

Comparison of the results from Table 4 show that employing Eq.2 will increase the conservatism exhibited by the solid web specimens for some cross sections. However, for other cross sections, disregarding Eq.2 will increase the existing unconservatism inherent in the solid web cross section. This is demonstrated by cross sections EOF-SU-7 and 10. Also, three cross sections, EOF-SU-2, 4, and 9 had $(P_n)_{test}/(P_n)_{comp}$ values greater than one for the solid web specimens, but $(P_n)_{test}/(P_n)_{comp}$ values less than one at low α values. Therefore, of the ten cross sections with web openings that exhibited web crippling failures, five require the use of Eq.2 to ensure that a portion of the safety factor of 1.85 is not unsafely depreciated solely by the existence of web openings.

The strength reduction given by Eq.2 is generally less conservative than the Sivakumaran and Zielonka reduction, Eq.1. Exceptions to this are found when a/h is small: Eq.2 is equal to one, while Eq.1 is always less than unity, but the test results indicate that for small a/h a reduction is not warranted. Equation 1 was developed based on the web opening being centered on the load. Therefore, Eq.1 produced more conservative results than Eq.2. As can be seen from Table 3, Eq.1 is a constant for all specimens with web openings from the same cross section since it does not consider the location of the web opening with respect to the load.

The $(F.S.)_{LRFD}$ values from Table 4 show the factors of safety required to satisfy the target reliability index, β_o, of 2.5. A notable observation is that the $(F.S.)_{LRFD}$ value resulting from Eq.2 equals 1.8623 when all specimens, regardless of yield strength, are considered. This is approximately equal to the desired factor of safety of 1.85 which is currently applied to Eq.4 and Eq.5. The $(F.S.)_{LRFD}$ value based on the unreduced $(P_n)_{comp}$ value was 2.1661. This is 16 percent less conservative than the $(F.S.)_{LRFD}$ resulting from Eq.2 and the desired value of 1.85. Additionally, Eq.2 reduces the coefficient of variation of the $(P_n)_{test}/(P_n)_{comp}$ values.

Shear

Thirty test specimens failed in shear. The shear failures were very pronounced at the location of the web opening. The shear failures formed flange hinge mechanisms described by Figure 1 of (Narayanan and Der-Avanessian, 1985). Shear failures usually occurred with little or no web crippling deformation at the end reaction.

Shear Observations

Shear failures generally occurred at higher end bearing lengths, N, because an increase in N provides an increase in the web crippling strength of the section, as can be seen from the values of $(P_n)_{comp}$ in Table 3. However, as can be seen by AISI

Section C3.2 (AISI, 1986 and 1989) shear capacity is independent of N.

To determine the web crippling - shear failure transition, tests were conducted on cross section EOF-SU-9, with varying values of N. For the EOF-SU-9 cross section, the transition occurred distinctly between N equal to 4 and 5 inches. Alpha was arbitrarily maintained at a constant value of 0.50 for these tests. In other cross sections or possibly at other α values this transition will occur at different N values. For example, for the EOF-SU-4 cross section, the transition occurred between N equal to 1 and 3 inches. These tests were also conducted at α equals 0.50.

Shear failures also occurred at high a/h values. The specimen series EOF-SU-5 and series EOF-SU-6 demonstrate this phenomenon for a/h ratios of 0.74 and 0.73 respectively. These high a/h ratios failed in shear at N equal to one inch for all test specimens with web openings.

Because of the pronounced shear deformation, shear failures were readily identified, and the data is valid for studies on sections with web openings subjected to shear. An additional observation is that many of the specimens that failed due to web crippling had a slight amount of shear deformation. The location of the shear "bulges" protruding from the diagonal compression corners of the web opening were the same as distinct shear failures, but the magnitude of the deformation was very slight. Failure modes were identified as either web crippling or shear.

No attempt has been made to establish the interaction of shear and web crippling.

Rate of loading

UMR Civil Engineering Study 78-4 (Hetrakul and Yu, 1978) states that the specimens of this previous study were loaded in 15% increments of the expected failure load, and the load maintained for five minutes at each increment. However, all tests for the present were loaded at a constant and gradual rate. To ascertain the difference between these two loading methods, six identical specimens were tested. Three specimens were tested under each loading condition. The results are shown in Table 5 for cross section EOF-SU-11. Both loading rates resulted in web crippling failure loads within the realm of experimental error. Thus, both loading rates are acceptable.

Specimen length

As previously stated, the minimum length of each specimen was determined to satisfy the requirement for one flange loading, i.e., a clear distance between end bearing plate and mid-span loading plate greater than or equal to 1.5h. Most specimens were longer than the minimum to allow for the desired clear distance, x, between the end plate and the web opening (Fig. 1).

The length of the specimen, L, and the horizontal clear distance of the web opening to the mid-span loading plate, x′, are extraneous to EOF web crippling behavior. Therefore, diagnostic tests were conducted to ensure variations in L and x′ did not affect the web crippling strength. Diagnostic tests were performed by using test specimens which were identical except for L and x′. Specimens EOF-SU-9-12a,b, and c exhibited no significant difference with the variance of only L and x′ as shown in Table 5. Also specimens EOF-SU-9-5(1 and 2) and EOF-SU-6 (1 and 2) exhibited no significant difference as shown in Table 3.

Several specimens failed at mid-span because of either yielding in the flanges or compression flange buckling. These specimens were of excessive length and therefore resulted in a high bending moment at mid-span. These mid-span failure modes were readily identified and are not included as part of the web crippling data.

Deformation at Failure

At failure, most specimens were severely deformed and would be considered unserviceable under most applications. See Figures 4 thru 7, which were taken while the failure load was still applied. This is an important consideration in the selection of the design safety factor since the AISI specification does not place a serviceability limit on web crippling. This phenomenon adds credibility to the use of the AISI web crippling design safety factor of 1.85, which, as mentioned previously, is generally conservative from a strength aspect.

Bending Moment Interaction

Web crippling and bending moment interaction was not considered in this study. The bending moments created in the region of web crippling failure by the EOF loading condition were insignificant.

Summary

A total of 157 specimens were tested for the EOF loading condition. Analysis of EOF test data provides a simple and practical reduction factor (Eq.2) for AISI Eq.C3.4-1 (Eq.4) and AISI Eq.C3.4-2 (Eq.5). The reduction factor equation is a function of α and a/h. A joint region of α and a/h was identified that requires no strength reduction. The reduction factor is valid for all bearing lengths, N, and for all sections that satisfy the ranges of applicability stated herein. Other failure modes, i.e. shear, flexure, and combinations thereof, must be checked separately.

Future work

The research reported herein is one phase of a comprehensive study of web elements with web openings. Future phases may address:

(1) Further analysis of the EOF results will be performed.

(2) IOF test results will be analyzed.

(3) Use of stiffeners with the web opening partially within the bearing length (Fig.13).

(4) Use of stiffeners with the web opening not within the bearing length (Fig.13)

(5) Type of stiffener (Fig.14).

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Table 1: Cross Section Properties

Cross Section	D(in.)	t(in.)	R(in.) nominal	h(in.)	B(in.)	d(in.)	a(in.)	b(in.)	Fy (ksi) actual	Fy (ksi) used	h/t	a/h	R/t
EOF-SU- 1	11.97	0.060	0.156	11.54	1.63	0.52	1.50	4.00	60	60	192	0.130	2.604
EOF-SU- 2	3.62	0.044	0.156	3.22	1.64	0.51	1.50	4.00	53	53	73	0.466	3.551
EOF-SU- 3	3.61	0.036	0.156	3.22	1.63	0.47	1.50	4.00	64	64	90	0.465	4.340
EOF-SU- 4	3.63	0.071	0.156	3.18	1.63	0.51	1.50	4.00	81	66.5	45	0.472	2.201
EOF-SU- 5	2.46	0.059	0.156	2.03	1.62	0.49	1.50	4.00	54	54	34	0.738	2.648
EOF-SU- 6	2.42	0.033	0.156	2.05	1.63	0.46	1.50	4.00	67	66.5	62	0.733	4.735
EOF-SU- 7	2.52	0.062	0.156	2.08	1.62	0.43	0.75	2.00	37	37	34	0.361	2.520
EOF-SU- 8	2.50	0.039	0.156	2.11	1.60	0.41	0.75	2.00	34	34	54	0.355	4.006
EOF-SU- 9	3.67	0.044	0.156	3.27	1.58	0.56	1.50	4.00	47	47	74	0.459	3.551
EOF-SU- 10	3.71	0.077	0.156	3.24	1.63	0.54	1.50	4.00	64	64	42	0.462	2.029
EOF-SU- 11	3.65	0.044	0.156	3.25	1.64	0.49	0.00	0.00	63	63	74	0.000	3.551
EOF-SU- 12	5.92	0.033	0.156	5.54	1.58	0.44	1.50	4.00	93	66.5	168	0.271	4.735
EOF-SU- 13	7.94	0.045	0.156	7.54	1.59	0.47	1.50	4.00	72	66.5	168	0.199	3.472

Notes:
1. See Figures 1 and 2 for definitions of dimensions.
2. Cross section designations:
   EOF: End-One-Flange (loading)
   SU: Single Unreinforced (web)
3. AISI Eq. C3.4-1 obtains a maximum value at Fy = 66.5 Ksi, therefore, 66.5 Ksi was used to calculate the nominal computed strength for all cross sections with a Fy exceeding 66.5 Ksi.

Table 2: Ranges of Parameters and Aspect Ratios

	min.	max.
h(in.)	2.03	11.54
t(in.)	0.033	0.077
Fy(ksi)	34	93
N(in.)	1.00	6.00
Alpha	0.00	1.50
a(in.)	0.75	1.50
b(in.)	2.00	4.00
a/h	0.13	0.74
h/t	34	192
R/t	2.03	4.74

Note: a, b, and a/h for solid web test specimens is equal to zero.

Table 3: Test Results

							REDUCTION FACTORS	
SPECIMEN NO.	L(in.)	N(in.)	ALPHA	(Pn) test, per web (lbs.)	PERCENT of SOLID WEB AVERAGE STRENGTH (for web crippling failures at N=1")	FAILURE MODE	Sivakumaran & Zielonka (Eq. 1)	Current Study (Eq. 2)
EOF-SU- 1-1-1	39.64	1.0	solid	994	97.3	crippling	1.000	1.000
EOF-SU- 1-1-2	39.64	1.0	solid	1050	102.7	crippling	1.000	1.000
EOF-SU- 1-2-1	39.64	1.0	0.00	1175	115.0	crippling	0.980	0.997
EOF-SU- 1-2-2	39.64	1.0	0.00	1100	107.6	crippling	0.980	0.997
EOF-SU- 2-1-1	20.00	1.0	solid	706	100.9	crippling	1.000	1.000
EOF-SU- 2-1-2	20.00	1.0	solid	694	99.1	crippling	1.000	1.000
EOF-SU- 2-2-1	22.66	1.0	0.00	488	69.7	crippling	0.695	0.786
EOF-SU- 2-2-2	22.66	1.0	0.00	506	72.3	crippling	0.695	0.786
EOF-SU- 2-3-1	22.66	1.0	0.50	581	83.0	crippling	0.695	0.846
EOF-SU- 2-3-2	22.66	1.0	0.50	588	84.0	crippling	0.695	0.846
EOF-SU- 2-4-1	22.66	1.0	0.70	600	85.7	crippling	0.695	0.870
EOF-SU- 2-4-2	22.66	1.0	0.70	613	87.6	crippling	0.695	0.870
EOF-SU- 2-5-1	22.66	1.0	1.00	663	94.7	crippling	0.695	0.907
EOF-SU- 2-5-2	22.66	1.0	1.00	650	92.9	crippling	0.695	0.907
EOF-SU- 2-6-1	22.66	1.0	1.50	688	98.3	crippling	0.695	0.967
EOF-SU- 2-6-2	22.66	1.0	1.50	681	97.3	crippling	0.695	0.967
EOF-SU- 2-7-1	26.66	3.0	0.50	831		crippling	0.870	0.846
EOF-SU- 2-7-2	26.66	3.0	0.50	775		crippling	0.870	0.846
EOF-SU- 3-1-1	20.00	1.0	solid	463	100.7	crippling	1.000	1.000
EOF-SU- 3-1-2	20.00	1.0	solid	456	99.1	crippling	1.000	1.000
EOF-SU- 3-2-1	22.66	1.0	0.00	363	78.9	crippling	0.695	0.786
EOF-SU- 3-2-2	22.66	1.0	0.00	338	73.5	crippling	0.695	0.786
EOF-SU- 3-3-1	22.66	1.0	0.50	431	93.7	crippling	0.695	0.846
EOF-SU- 3-3-2	22.66	1.0	0.50	406	88.3	crippling	0.695	0.846
EOF-SU- 3-4-1	22.66	1.0	1.00	444	96.5	crippling	0.695	0.907
EOF-SU- 3-4-2	22.66	1.0	1.00	444	96.5	crippling	0.695	0.907
EOF-SU- 4-1-1	19.75	1.0	solid	2413	100.4	crippling	1.000	1.000
EOF-SU- 4-1-2	19.75	1.0	solid	2394	99.6	crippling	1.000	1.000
EOF-SU- 4-2-1	22.54	1.0	0.00	1763	73.3	crippling	0.685	0.782
EOF-SU- 4-2-2	22.54	1.0	0.00	1775	73.8	crippling	0.685	0.782
EOF-SU- 4-3-1	22.54	1.0	0.50	2038	84.8	crippling	0.685	0.842
EOF-SU- 4-3-2	22.54	1.0	0.50	2019	84.0	crippling	0.685	0.842
EOF-SU- 4-4-1	22.54	1.0	0.70	2100	87.4	crippling	0.685	0.866
EOF-SU- 4-4-2	22.54	1.0	0.70	2062	85.8	crippling	0.685	0.866
EOF-SU- 4-5-1	22.54	1.0	1.00	2219	92.3	crippling	0.685	0.903
EOF-SU- 4-5-2	22.54	1.0	1.00	2256	93.8	crippling	0.685	0.903
EOF-SU- 4-6-1	22.54	1.0	1.50	2269	94.4	crippling	0.685	0.963
EOF-SU- 4-6-2	22.54	1.0	1.50	2350	97.8	crippling	0.685	0.963
EOF-SU- 4-7-1	26.54	3.0	0.50	2738		shear		
EOF-SU- 4-7-2	26.54	3.0	0.50	2781		shear		

Table 3: Test Results (cont.)

SPECIMEN NO.	L(in.)	N(in.)	ALPHA	(Pn) test, per web (lbs.)	PERCENT of SOLID WEB AVERAGE STRENGTH (for web crippling failures at N=1")	FAILURE MODE	REDUCTION FACTORS	
							Sivakumaran & Zielonka (Eq. 1)	Current Study (Eq. 2)
EOF-SU- 5-1-1	19.10	1.0	solid	1331	102.9	crippling	1.000	1.000
EOF-SU- 5-1-2	19.10	1.0	solid	1256	97.1	crippling	1.000	1.000
EOF-SU- 5-2-1	19.10	1.0	0.00	781		shear		
EOF-SU- 5-2-2	19.10	1.0	0.00	781		shear		
EOF-SU- 5-3-1	19.10	1.0	0.50	813		shear		
EOF-SU- 5-3-2	19.10	1.0	0.50	788		shear		
EOF-SU- 5-4-1	19.10	1.0	0.70	775		shear		
EOF-SU- 5-4-2	19.10	1.0	0.70	781		shear		
EOF-SU- 5-5-1	19.10	1.0	1.00	769		shear		
EOF-SU- 5-5-2	19.10	1.0	1.00	781		shear		
EOF-SU- 5-6-1	19.10	1.0	1.50	781		shear		
EOF-SU- 5-6-2	19.10	1.0	1.50	769		shear		
EOF-SU- 5-7-1	23.10	3.0	0.50	731		shear		
EOF-SU- 5-7-2	23.10	3.0	0.50	781		shear		
EOF-SU- 6-1-1	19.16	1.0	solid	475	100.0	crippling	1.000	1.000
EOF-SU- 6-1-2	19.16	1.0	solid	475	100.0	crippling	1.000	1.000
EOF-SU- 6-2-1	19.16	1.0	0.00	288		shear		
EOF-SU- 6-2-2	19.16	1.0	0.00	288		shear		
EOF-SU- 6-3-1	19.16	1.0	0.50	331		shear		
EOF-SU- 6-3-1	19.16	1.0	0.50	344		shear		
EOF-SU- 6-4-1	19.16	1.0	0.70	356		shear		
EOF-SU- 6-4-2	19.16	1.0	0.70	325		shear		
EOF-SU- 6-5-1	19.16	1.0	1.00	331		shear		
EOF-SU- 6-5-2	19.16	1.0	1.00	325		shear		
EOF-SU- 6-6-1	19.16	1.0	1.50	325		shear		
EOF-SU- 6-6-2	19.16	1.0	1.50	325		shear		
EOF-SU- 6-7-1	19.16	3.0	0.50	356		shear		
EOF-SU- 6-7-2	19.16	3.0	0.50	331		shear		
EOF-SU- 7-1-1	11.24	1.0	solid	994	96.6	crippling	1.000	1.000
EOF-SU- 7-1-2	11.24	1.0	solid	1063	103.3	crippling	1.000	1.000
EOF-SU- 7-2-1	15.24	1.0	0.00	850	82.6	crippling	0.883	0.852
EOF-SU- 7-2-2	15.24	1.0	0.00	800	77.7	crippling	0.883	0.852
EOF-SU- 7-3-1	15.24	1.0	0.50	994	96.6	crippling	0.883	0.912
EOF-SU- 7-3-2	15.24	1.0	0.50	944	91.7	crippling	0.883	0.912
EOF-SU- 7-4-1	15.24	1.0	0.70	988	96.0	crippling	0.883	0.936
EOF-SU- 7-4-2	15.24	1.0	0.70	956	92.9	crippling	0.883	0.936
EOF-SU- 7-5-1	15.24	1.0	1.00	963	93.6	crippling	0.883	0.973
EOF-SU- 7-5-2	15.24	1.0	1.00	994	96.6	crippling	0.883	0.973
EOF-SU- 7-6-1	15.24	1.0	1.50	988	96.0	crippling	0.883	1.000
EOF-SU- 7-6-2	15.24	1.0	1.50	988	96.0	crippling	0.883	1.000

Table 3: Test Results (cont.)

SPECIMEN NO.	L(in.)	N(in.)	ALPHA	(Pn) test, per web (lbs.)	PERCENT of SOLID WEB AVERAGE STRENGTH (for web crippling failures at N=1")	FAILURE MODE	REDUCTION FACTORS	
							Sivakumaran & Zielonka (Eq. 1)	Current Study (Eq. 2)
EOF-SU- 8-1-1	15.33	1.0	solid	406	98.3	crippling	1.000	1.000
EOF-SU- 8-1-2	15.33	1.0	solid	419	101.5	crippling	1.000	1.000
EOF-SU- 8-2-1	15.33	1.0	0.00	388	93.9	crippling	0.887	0.856
EOF-SU- 8-2-2	15.33	1.0	0.00	394	95.4	crippling	0.887	0.856
EOF-SU- 8-3-1	15.33	1.0	0.50	400	96.9	crippling	0.887	0.916
EOF-SU- 8-3-2	15.33	1.0	0.50	406	98.3	crippling	0.887	0.916
EOF-SU- 8-4-1	15.33	1.0	0.70	419	101.5	crippling	0.887	0.940
EOF-SU- 8-4-2	15.33	1.0	0.70	419	101.5	crippling	0.887	0.940
EOF-SU- 8-5-1	15.33	1.0	1.00	406	98.3	crippling	0.887	0.976
EOF-SU- 8-5-2	15.33	1.0	1.00	406	98.3	crippling	0.887	0.976
EOF-SU- 8-6-1	15.33	1.0	1.50	400	96.9	crippling	0.887	1.000
EOF-SU- 8-6-2	15.33	1.0	1.50	406	98.3	crippling	0.887	1.000
EOF-SU- 8-7-1	19.33	3.0	0.50	550		crippling	0.949	0.916
EOF-SU- 8-7-2	19.33	3.0	0.50	538		crippling	0.949	0.916
EOF-SU- 9-1-1	19.54	1.0	solid	669	99.1	crippling	1.000	1.000
EOF-SU- 9-1-2	19.54	1.0	solid	681	100.9	crippling	1.000	1.000
EOF-SU- 9-2-1	19.54	1.0	0.00	481	71.3	crippling	0.705	0.790
EOF-SU- 9-2-2	19.54	1.0	0.00	475	70.4	crippling	0.705	0.790
EOF-SU- 9-3-1	19.54	1.0	0.50	585	86.7	crippling	0.705	0.851
EOF-SU- 9-3-2	19.54	1.0	0.50	619	91.7	crippling	0.705	0.851
EOF-SU- 9-4-1	19.54	1.0	0.70	619	91.7	crippling	0.705	0.875
EOF-SU- 9-4-2	19.54	1.0	0.70	619	91.7	crippling	0.705	0.875
EOF-SU- 9-5-1	19.54	1.0	1.00	681	100.9	crippling	0.705	0.911
EOF-SU- 9-5-2	19.54	1.0	1.00	656	97.2	crippling	0.705	0.911
EOF-SU- 9-6-1	24.81	1.0	1.00	638	94.5	crippling	0.705	0.911
EOF-SU- 9-6-2	24.81	1.0	1.00	675	100.0	crippling	0.705	0.911
EOF-SU- 9-7-1	24.81	1.0	1.50	681	100.9	crippling	0.705	0.971
EOF-SU- 9-7-2	24.81	1.0	1.50	619	91.7	crippling	0.705	0.971
EOF-SU- 9-8-1	23.54	3.0	0.50	819		crippling	0.873	0.851
EOF-SU- 9-8-2	23.54	3.0	0.50	831		crippling	0.873	0.851
EOF-SU- 9-9-1	25.54	4.0	0.50	919		crippling	0.900	0.851
EOF-SU- 9-10-1	27.54	5.0	0.50	1125		shear		
EOF-SU- 9-11-1	29.54	6.0	0.50	919		shear		
EOF-SU- 9-11-2	29.54	6.0	0.50	938		shear		

Table 3: Test Results (cont.)

SPECIMEN NO.	L(in.)	N(in.)	ALPHA	(Pn) test, per web (lbs.)	PERCENT of SOLID WEB AVERAGE STRENGTH (for web crippling failures at N=1")	FAILURE MODE	REDUCTION FACTORS	
							Sivakumaran & Zielonka (Eq. 1)	Current Study (Eq. 2)
EOF-SU- 10-1-1	19.54	1.0	solid	2000	100.0	crippling	1.000	1.000
EOF-SU- 10-2-1	24.81	1.0	0.00	1338	66.9	crippling	0.699	0.788
EOF-SU- 10-2-2	24.81	1.0	0.00	1350	67.5	crippling	0.699	0.788
EOF-SU- 10-3-1	24.81	1.0	0.50	1606	80.3	crippling	0.699	0.848
EOF-SU- 10-3-2	24.81	1.0	0.50	1650	82.5	crippling	0.699	0.848
EOF-SU- 10-4-1	24.81	1.0	0.70	1888	94.4	crippling	0.699	0.872
EOF-SU- 10-4-2	24.81	1.0	0.70	1706	85.3	crippling	0.699	0.872
EOF-SU- 10-5-1	34.81	6.0	0.00	2406		shear		
EOF-SU- 10-6-1	34.81	6.0	0.50	2750		shear		
EOF-SU- 10-6-2	34.81	6.0	0.50	2750		shear		
EOF-SU- 10-7-1	34.81	6.0	1.00	2506		shear		
EOF-SU- 10-7-2	34.81	6.0	1.00	2606		shear		
EOF-SU- 12-1-1	21.62	1.0	solid	556	96.4	crippling	1.000	1.000
EOF-SU- 12-1-2	21.62	1.0	solid	598	103.6	crippling	1.000	1.000
EOF-SU- 12-2-1	21.62	1.0	0.00	531	92.0	crippling	0.907	0.909
EOF-SU- 12-2-2	21.62	1.0	0.00	506	87.7	crippling	0.907	0.909
EOF-SU- 12-3-1	21.62	1.0	0.50	544	94.3	crippling	0.907	0.969
EOF-SU- 12-3-2	21.62	1.0	0.50	556	96.4	crippling	0.907	0.969
EOF-SU- 12-4-1	24.20	1.0	1.00	556	96.4	crippling	0.907	1.000
EOF-SU- 12-4-2	24.20	1.0	1.00	563	97.6	crippling	0.907	1.000
EOF-SU- 12-5-1	30.00	1.0	1.50	581	100.7	crippling	0.907	1.000
EOF-SU- 12-5-2	30.00	1.0	1.50	569	98.6	crippling	0.907	1.000
EOF-SU- 13-1-1	27.62	1.0	solid	850	100.4	crippling	1.000	1.000
EOF-SU- 13-1-2	27.62	1.0	solid	844	99.6	crippling	1.000	1.000
EOF-SU- 13-2-1	27.62	1.0	0.00	800	94.5	crippling	0.951	0.954
EOF-SU- 13-2-2	27.62	1.0	0.00	794	93.7	crippling	0.951	0.954
EOF-SU- 13-3-1	27.62	1.0	0.50	831	98.1	crippling	0.951	1.000
EOF-SU- 13-3-2	27.62	1.0	0.50	844	99.6	crippling	0.951	1.000

Note: The centerline bearing length for all test specimens is equal to three inches.

Table 4: Analysis of Test Results

	NOMINAL CAPACITY (Pn)comp, per web (lbs.)			(Pn)test/(Pn)comp:		
		AISI Eq.C3.4-1 REDUCED			AISI Eq.C3.4-1 REDUCED	
SPECIMEN NO.	AISI Eq.C3.4-1 x SF of 1.85	Sivakumaran & Zielonka (Eq. 1)	Current Study (Eq. 2)	AISI Eq.C3.4-1	Sivakumaran & Zielonka (Eq. 1)	Current Study (Eq. 2)
EOF-SU- 1-1-1	905	905	905	1.10	1.10	1.10
EOF-SU- 1-1-2	905	905	905	1.16	1.16	1.16
EOF-SU- 1-2-1	905	887	902	1.30	1.32	1.30
EOF-SU- 1-2-2	905	887	902	1.22	1.24	1.22
EOF-SU- 2-1-1	540	540	540	1.31	1.31	1.31
EOF-SU- 2-1-2	540	540	540	1.29	1.29	1.29
EOF-SU- 2-2-1	540	375	424	0.90	1.30	1.15
EOF-SU- 2-2-2	540	375	424	0.94	1.35	1.19
EOF-SU- 2-3-1	540	375	457	1.08	1.55	1.27
EOF-SU- 2-3-2	540	375	457	1.09	1.57	1.29
EOF-SU- 2-4-1	540	375	470	1.11	1.60	1.28
EOF-SU- 2-4-2	540	375	470	1.14	1.63	1.30
EOF-SU- 2-5-1	540	375	489	1.23	1.77	1.35
EOF-SU- 2-5-2	540	375	489	1.20	1.73	1.33
EOF-SU- 2-6-1	540	375	522	1.27	1.83	1.32
EOF-SU- 2-6-2	540	375	522	1.26	1.82	1.30
EOF-SU- 2-7-1	740	644	626	1.12	1.29	1.33
EOF-SU- 2-7-2	740	644	626	1.05	1.20	1.24
EOF-SU- 3-1-1	306	306	306	1.51	1.51	1.51
EOF-SU- 3-1-2	306	306	306	1.49	1.49	1.49
EOF-SU- 3-2-1	306	213	241	1.18	1.71	1.51
EOF-SU- 3-2-2	306	213	241	1.10	1.59	1.40
EOF-SU- 3-3-1	306	213	259	1.41	2.02	1.66
EOF-SU- 3-3-2	306	213	259	1.33	1.91	1.57
EOF-SU- 3-4-1	306	213	278	1.45	2.09	1.60
EOF-SU- 3-4-2	306	213	278	1.45	2.09	1.60
* EOF-SU- 4-1-1	1920	1920	1920	1.26	1.26	1.26
* EOF-SU- 4-1-2	1920	1920	1920	1.25	1.25	1.25
* EOF-SU- 4-2-1	1920	1316	1501	0.92	1.34	1.17
* EOF-SU- 4-2-2	1920	1316	1501	0.92	1.35	1.18
* EOF-SU- 4-3-1	1920	1316	1617	1.06	1.55	1.26
* EOF-SU- 4-3-2	1920	1316	1617	1.05	1.53	1.25
* EOF-SU- 4-4-1	1920	1316	1663	1.09	1.60	1.26
* EOF-SU- 4-4-2	1920	1316	1663	1.07	1.57	1.24
* EOF-SU- 4-5-1	1920	1316	1733	1.16	1.69	1.28
* EOF-SU- 4-5-2	1920	1316	1733	1.18	1.71	1.30
* EOF-SU- 4-6-1	1920	1316	1849	1.18	1.72	1.23
* EOF-SU- 4-6-2	1920	1316	1849	1.22	1.79	1.27
* EOF-SU- 4-7-1	Shear Failure					
* EOF-SU- 4-7-2	Shear Failure					

Table 4: Analysis of Test Results (cont.)

	NOMINAL CAPACITY (Pn)comp, per web (lbs.)			(Pn)test/(Pn)comp:		
		AISI Eq.C3.4-1 REDUCED			AISI Eq.C3.4-1 REDUCED	
SPECIMEN NO.	AISI Eq.C3.4-1 x SF of 1.85	Sivakumaran & Zielonka (Eq. 1)	Current Study (Eq. 2)	AISI Eq.C3.4-1	Sivakumaran & Zielonka (Eq. 1)	Current Study (Eq. 2)
EOF-SU- 5-1-1	1229	1229	1229	1.08	1.08	1.08
EOF-SU- 5-1-2	1229	1229	1229	1.02	1.02	1.02
EOF-SU- 5-2-1	Shear Failure					
EOF-SU- 5-2-2	Shear Failure					
EOF-SU- 5-3-1	Shear Failure					
EOF-SU- 5-3-2	Shear Failure					
EOF-SU- 5-4-1	Shear Failure					
EOF-SU- 5-4-2	Shear Failure					
EOF-SU- 5-5-1	Shear Failure					
EOF-SU- 5-5-2	Shear Failure					
EOF-SU- 5-6-1	Shear Failure					
EOF-SU- 5-6-2	Shear Failure					
EOF-SU- 5-7-1	Shear Failure					
EOF-SU- 5-7-2	Shear Failure					
* EOF-SU- 6-1-1	279	279	279	1.70	1.70	1.70
* EOF-SU- 6-1-2	279	279	279	1.70	1.70	1.70
* EOF-SU- 6-2-1	Shear Failure					
* EOF-SU- 6-2-2	Shear Failure					
* EOF-SU- 6-3-1	Shear Failure					
* EOF-SU- 6-3-1	Shear Failure					
* EOF-SU- 6-4-1	Shear Failure					
* EOF-SU- 6-4-2	Shear Failure					
* EOF-SU- 6-5-1	Shear Failure					
* EOF-SU- 6-5-2	Shear Failure					
* EOF-SU- 6-6-1	Shear Failure					
* EOF-SU- 6-6-2	Shear Failure					
* EOF-SU- 6-7-1	Shear Failure					
* EOF-SU- 6-7-2	Shear Failure					
EOF-SU- 7-1-1	1152	1152	1152	0.86	0.86	0.86
EOF-SU- 7-1-2	1152	1152	1152	0.92	0.92	0.92
EOF-SU- 7-2-1	1152	1018	982	0.74	0.84	0.87
EOF-SU- 7-2-2	1152	1018	982	0.69	0.79	0.81
EOF-SU- 7-3-1	1152	1018	1051	0.86	0.98	0.95
EOF-SU- 7-3-2	1152	1018	1051	0.82	0.93	0.90
EOF-SU- 7-4-1	1152	1018	1079	0.86	0.97	0.92
EOF-SU- 7-4-2	1152	1018	1079	0.83	0.94	0.89
EOF-SU- 7-5-1	1152	1018	1121	0.84	0.95	0.86
EOF-SU- 7-5-2	1152	1018	1121	0.86	0.98	0.89
EOF-SU- 7-6-1	1152	1018	1152	0.86	0.97	0.86
EOF-SU- 7-6-2	1152	1018	1152	0.86	0.97	0.86

Table 4: Analysis of Test Results (cont.)

	NOMINAL CAPACITY (Pn)comp, per web (lbs.)			(Pn)test/(Pn)comp:		
SPECIMEN NO.	AISI Eq.C3.4-1 x SF of 1.85	AISI Eq.C3.4-1 Sivakumaran & Zielonka (Eq. 1)	REDUCED Current Study (Eq. 2)	AISI Eq.C3.4-1	AISI Eq.C3.4-1 Sivakumaran & Zielonka (Eq. 1)	REDUCED Current Study (Eq. 2)
EOF-SU- 8-1-1	319	319	319	1.27	1.27	1.27
EOF-SU- 8-1-2	319	319	319	1.31	1.31	1.31
EOF-SU- 8-2-1	319	283	273	1.22	1.37	1.42
EOF-SU- 8-2-2	319	283	273	1.24	1.39	1.44
EOF-SU- 8-3-1	319	283	292	1.25	1.41	1.37
EOF-SU- 8-3-2	319	283	292	1.27	1.44	1.39
EOF-SU- 8-4-1	319	283	300	1.31	1.48	1.40
EOF-SU- 8-4-2	319	283	300	1.31	1.48	1.40
EOF-SU- 8-5-1	319	283	311	1.27	1.44	1.30
EOF-SU- 8-5-2	319	283	311	1.27	1.44	1.30
EOF-SU- 8-6-1	319	283	319	1.25	1.41	1.25
EOF-SU- 8-6-2	319	283	319	1.27	1.44	1.27
EOF-SU- 8-7-1	449	426	411	1.22	1.29	1.34
EOF-SU- 8-7-2	449	426	411	1.20	1.26	1.31
EOF-SU- 9-1-1	513	513	513	1.30	1.30	1.30
EOF-SU- 9-1-2	513	513	513	1.33	1.33	1.33
EOF-SU- 9-2-1	513	362	406	0.94	1.33	1.19
EOF-SU- 9-2-2	513	362	406	0.93	1.31	1.17
EOF-SU- 9-3-1	513	362	437	1.14	1.62	1.34
EOF-SU- 9-3-2	513	362	437	1.21	1.71	1.42
EOF-SU- 9-4-1	513	362	449	1.21	1.71	1.38
EOF-SU- 9-4-2	513	362	449	1.21	1.71	1.38
EOF-SU- 9-5-1	513	362	468	1.33	1.88	1.46
EOF-SU- 9-5-2	513	362	468	1.28	1.81	1.40
EOF-SU- 9-6-1	513	362	468	1.24	1.76	1.36
EOF-SU- 9-6-2	513	362	468	1.31	1.87	1.44
EOF-SU- 9-7-1	513	362	499	1.33	1.88	1.37
EOF-SU- 9-7-2	513	362	499	1.21	1.71	1.24
EOF-SU- 9-8-1	704	614	598	1.16	1.33	1.37
EOF-SU- 9-8-2	704	614	598	1.18	1.35	1.39
EOF-SU- 9-9-1	799	719	679	1.15	1.28	1.35
EOF-SU- 9-10-1	Shear Failure					
EOF-SU- 9-11-1	Shear Failure					
EOF-SU- 9-11-2	Shear Failure					

Table 4: Analysis of Test Results (cont.)

	NOMINAL CAPACITY (Pn)comp, per web (lbs.)			(Pn)test/(Pn)comp:		
	AISI	AISI Eq.C3.4-1 REDUCED			AISI Eq.C3.4-1 REDUCED	
SPECIMEN NO.	Eq.C3.4-1 x SF of 1.85	Sivakumaran & Zielonka (Eq. 1)	Current Study (Eq. 2)	AISI Eq.C3.4-1	Sivakumaran & Zielonka (Eq. 1)	Current Study (Eq. 2)
EOF-SU- 10-1-1	2315	2315	2315	0.86	0.86	0.86
EOF-SU- 10-2-1	2315	1619	1824	0.58	0.83	0.73
EOF-SU- 10-2-2	2315	1619	1824	0.58	0.83	0.74
EOF-SU- 10-3-1	2315	1619	1964	0.69	0.99	0.82
EOF-SU- 10-3-2	2315	1619	1964	0.71	1.02	0.84
EOF-SU- 10-4-1	2315	1619	2020	0.82	1.17	0.93
EOF-SU- 10-4-2	2315	1619	2020	0.74	1.05	0.84
EOF-SU- 10-5-1	Shear Failure					
EOF-SU- 10-6-1	Shear Failure					
EOF-SU- 10-6-2	Shear Failure					
EOF-SU- 10-7-1	Shear Failure					
EOF-SU- 10-7-2	Shear Failure					
* EOF-SU- 12-1-1	217	217	217	2.56	2.56	2.56
* EOF-SU- 12-1-2	217	217	217	2.75	2.75	2.75
* EOF-SU- 12-2-1	217	197	198	2.44	2.69	2.69
* EOF-SU- 12-2-2	217	197	198	2.33	2.57	2.56
* EOF-SU- 12-3-1	217	197	211	2.50	2.76	2.58
* EOF-SU- 12-3-2	217	197	211	2.56	2.82	2.64
* EOF-SU- 12-4-1	217	197	217	2.56	2.82	2.56
* EOF-SU- 12-4-2	217	197	217	2.59	2.86	2.59
* EOF-SU- 12-5-1	217	197	217	2.67	2.95	2.67
* EOF-SU- 12-5-2	217	197	217	2.62	2.89	2.62
* EOF-SU- 13-1-1	478	478	478	1.78	1.78	1.78
* EOF-SU- 13-1-2	478	478	478	1.77	1.77	1.77
* EOF-SU- 13-2-1	478	454	456	1.67	1.76	1.76
* EOF-SU- 13-2-2	478	454	456	1.66	1.75	1.74
* EOF-SU- 13-3-1	478	454	478	1.74	1.83	1.74
* EOF-SU- 13-3-2	478	454	478	1.77	1.86	1.77
		STATISTICAL DATA BASED ON ALL SPECIMENS				
		Average		1.2928	1.5455	1.3917
		Standard Deviation		0.4759	0.4995	0.4608
		Coefficient of Variation		0.3681	0.3232	0.3311
		PHI		0.7079	0.9293	0.8234
		(F.S.)lrfd		2.1661	1.6500	1.8623
		STATISTICAL DATA BASED ON Fy <= 66.5 ksi				
		Average		1.1139	1.3686	1.2202
		Standard Deviation		0.2211	0.3330	0.2320
		Coefficient of Variation		0.1985	0.2433	0.1901
		PHI		0.8435	0.9589	0.9366
		(F.S.)lrfd		1.8178	1.5990	1.6371
		STATISTICAL DATA BASED ON SOLID WEB SPECIMENS WITH Fy <= 66.5 ksi.				
		Average		1.1881	1.1881	1.1881
		Standard Deviation		0.2004	0.2004	0.2004
		Coefficient of Variation		0.1687	0.1687	0.1687
		PHI		0.9268	0.9268	0.9268
		(F.S.)lrfd		1.6545	1.6545	1.6545

Note: * signifies specimens with Fy greater than 66.5 ksi. See Table 1, note 3.

Table 5: Diagnostic Tests

Specimen no.	L(in.)	N(in.)	ALPHA	(Pn)test, per web (lbs.)				
L &x' STUDY:				test 1	test 2	avg.		
EOF-SU 9-12a	16.28	1.0	0.50	669	656	663		x'= 0.00 inches.
EOF-SU 9-12b	19.54	1.0	0.50	675		675		x'= 1.67 inches = h/2
EOF-SU 9-12c	22.81	1.0	0.50	663	644	654		x'= 3.27 inches = h
LOAD RATE STUDY:				test 1	test 2	test 3	avg.	
EOF-SU 11-1a	18.00	1.0	solid	750	738	725	738	Constant-Gradual Rate
EOF-SU 11-1b	18.00	1.0	solid	806	738	825	790	"5 minute-15 % incr.rate"

Notes:

1. The centerline bearing length for all test specimens is equal to three inches.
2. For specimens EOF-SU-11-1b: The specimens were loaded in 15 percent increments of the expected failure load and maintained for five minutes at each increment. The expected failure load was equal to the average of the three specimens loaded at a constant and gradual rate.

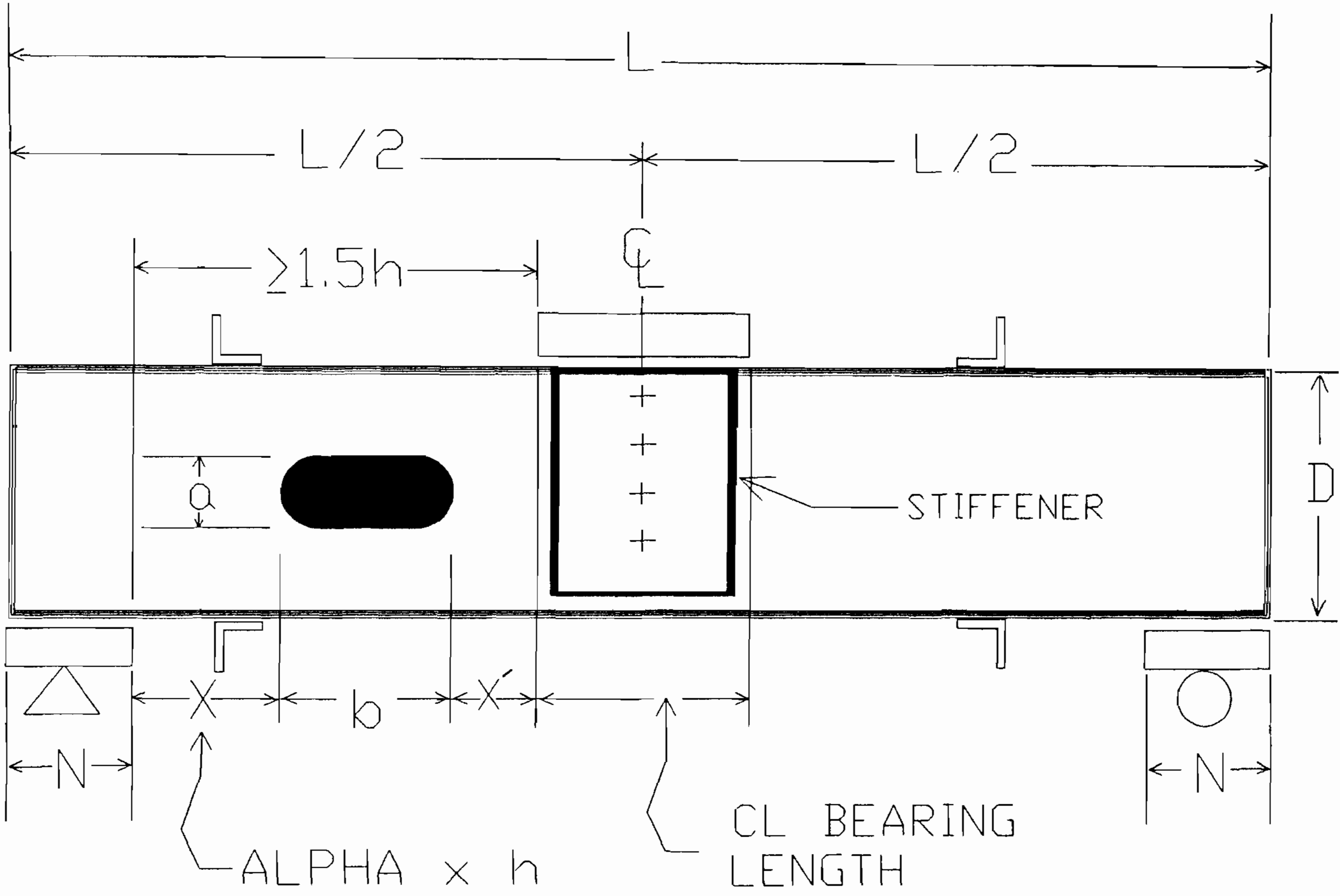


FIGURE 1: SPECIMEN PARAMETERS LONGITUDINAL VIEW

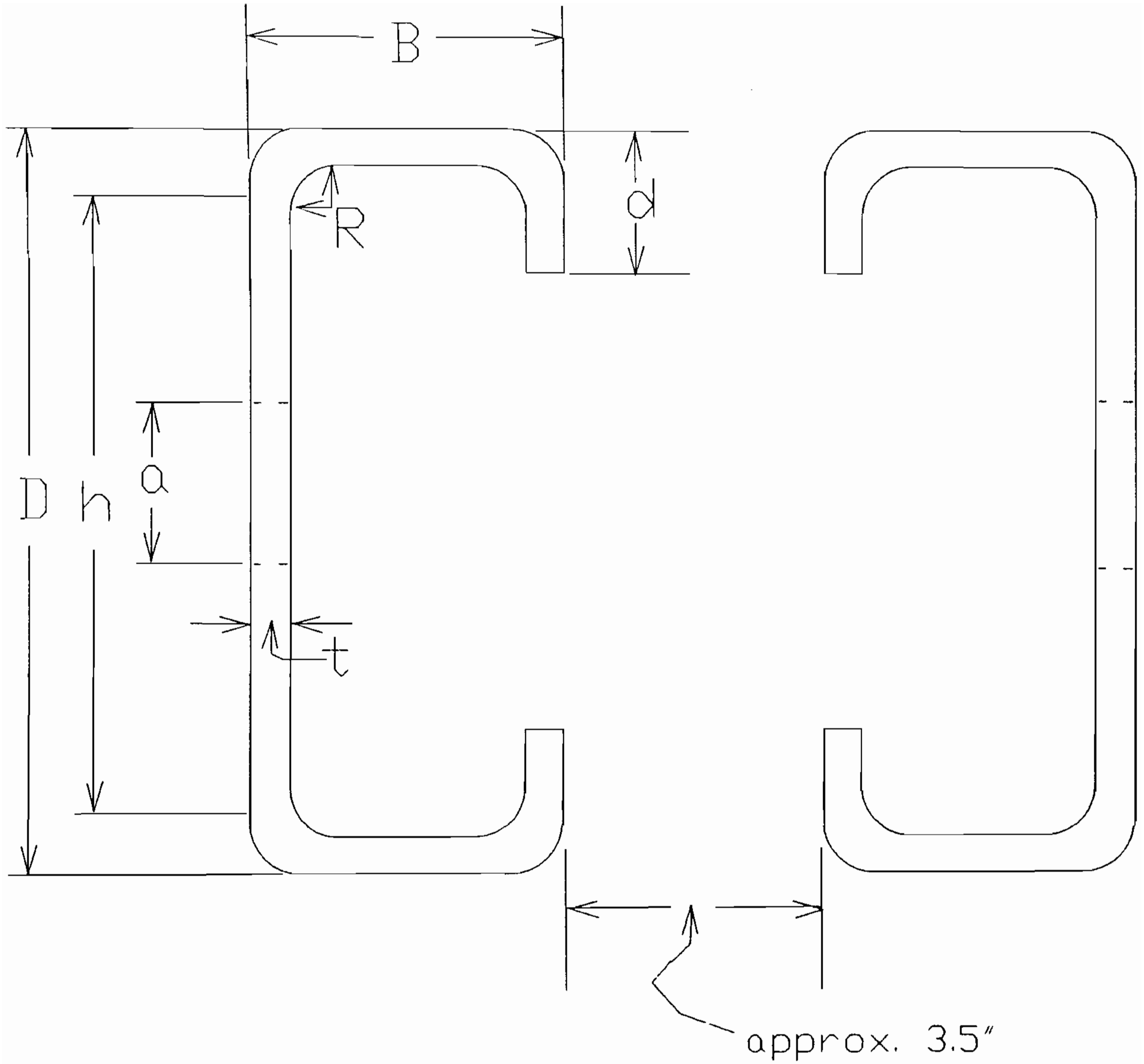
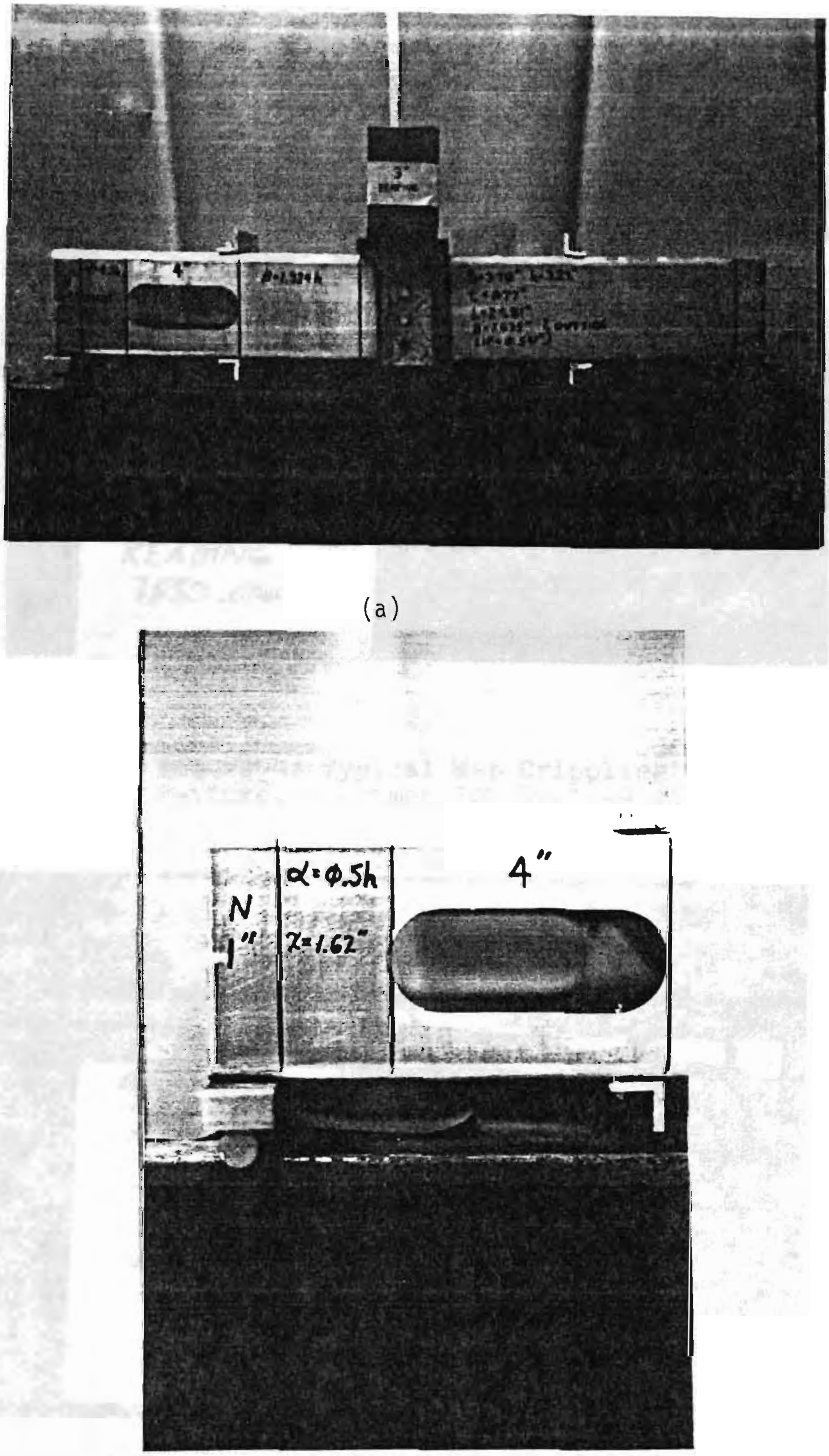


FIGURE 2: SPECIMEN PARAMETERS
END VIEW



(a)

(b)

Figure 3a and b: Typical Specimen Parameters, Specimen EOF-SU-10-3(#1)

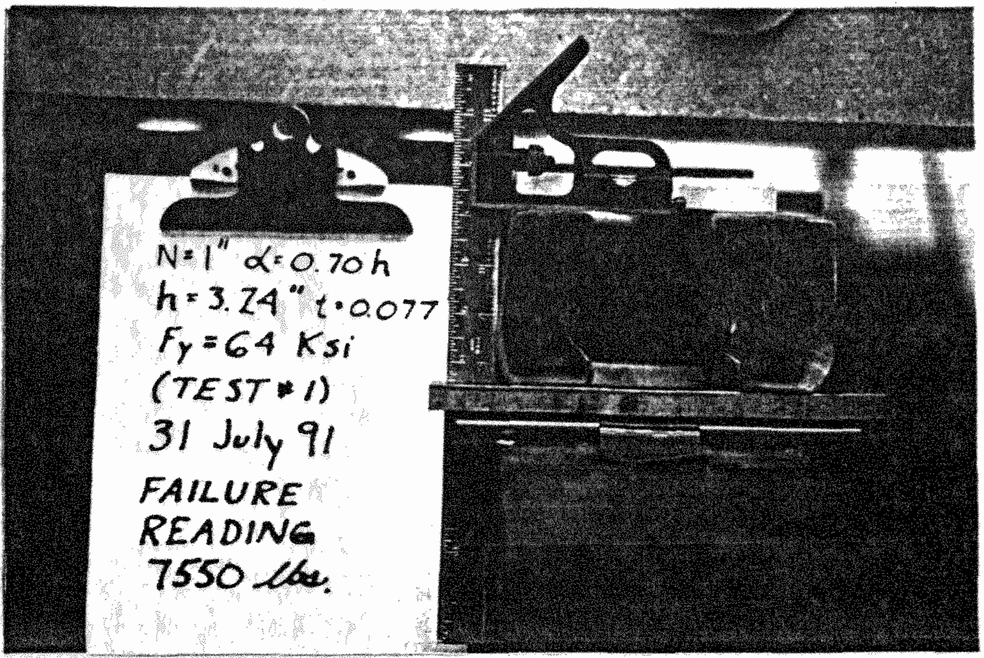


Figure 4: Typical Web Crippling Failure, Specimen EOF-SU-10-4(#1)

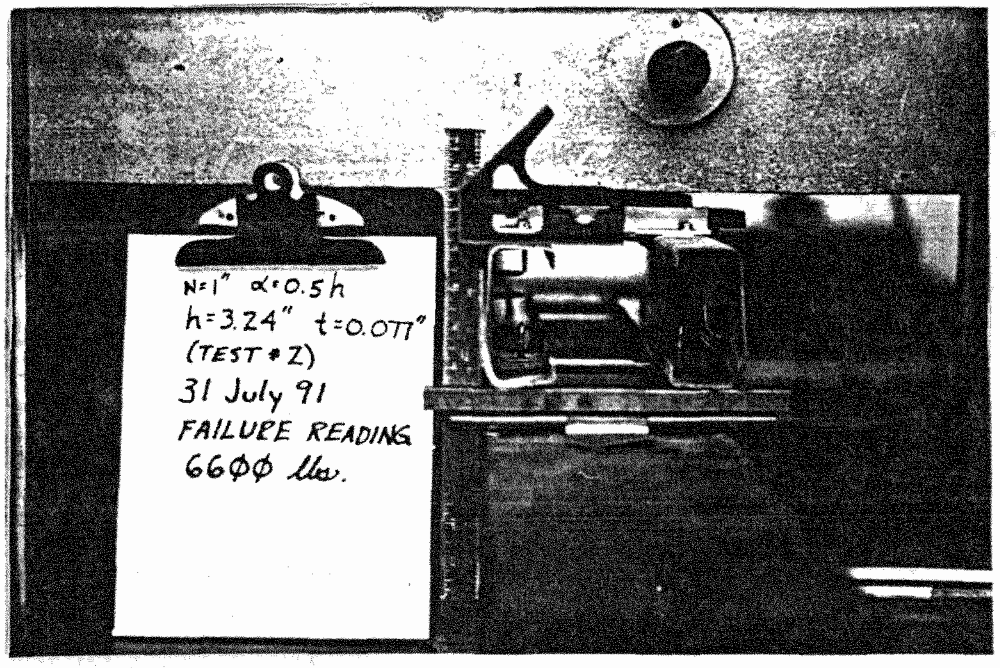
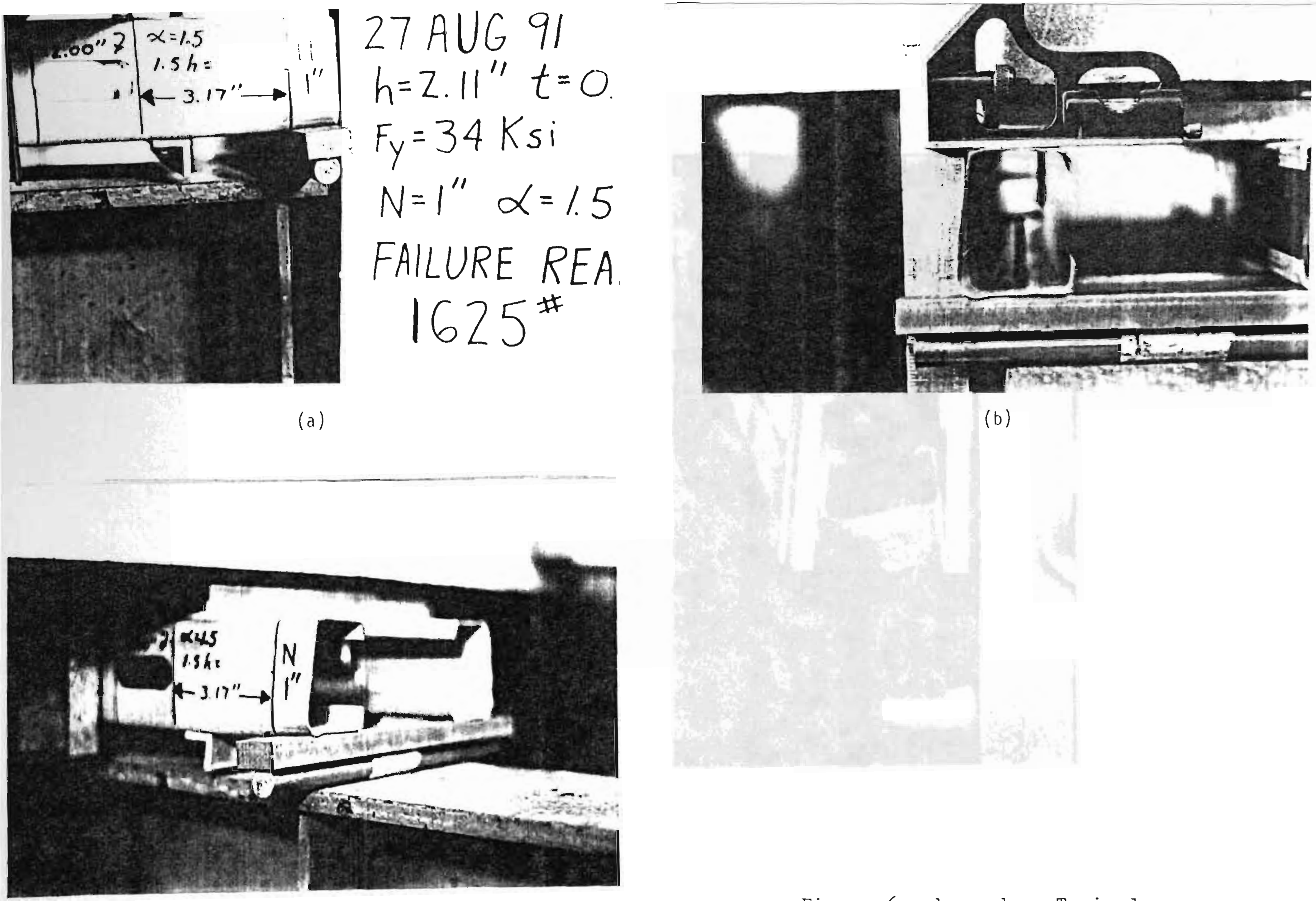


Figure 5: Typical Web Crippling Failure, Specimen EOF-SU-10-3(#2)



27 AUG 91
h=2.11" t=0.
F_y=34 Ksi
N=1" α=1.5
FAILURE REA.
1625#

(a)

(b)

(c)

Figure 6a, b, and c: Typical Web Crippling Failure, Specimen EOF-SU-8-6 (#2)

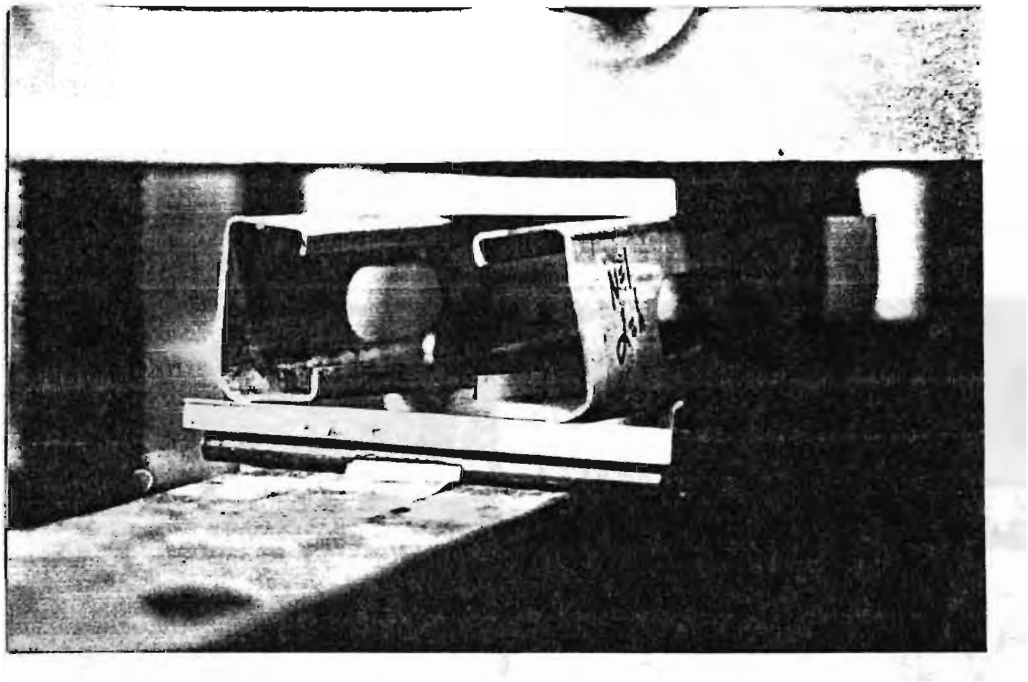


Figure 7: Typical Web Crippling Failure, Specimen EOF-SU-4-5(#1)

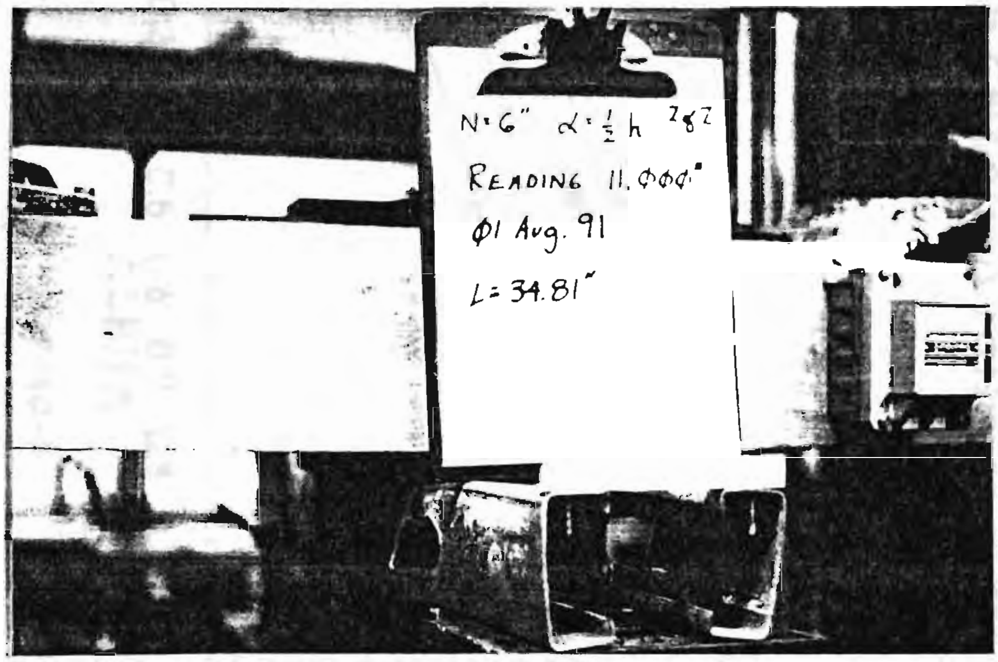


Figure 8: Typical Shear Failure,
Specimen EOF-SU-10-6(#2)

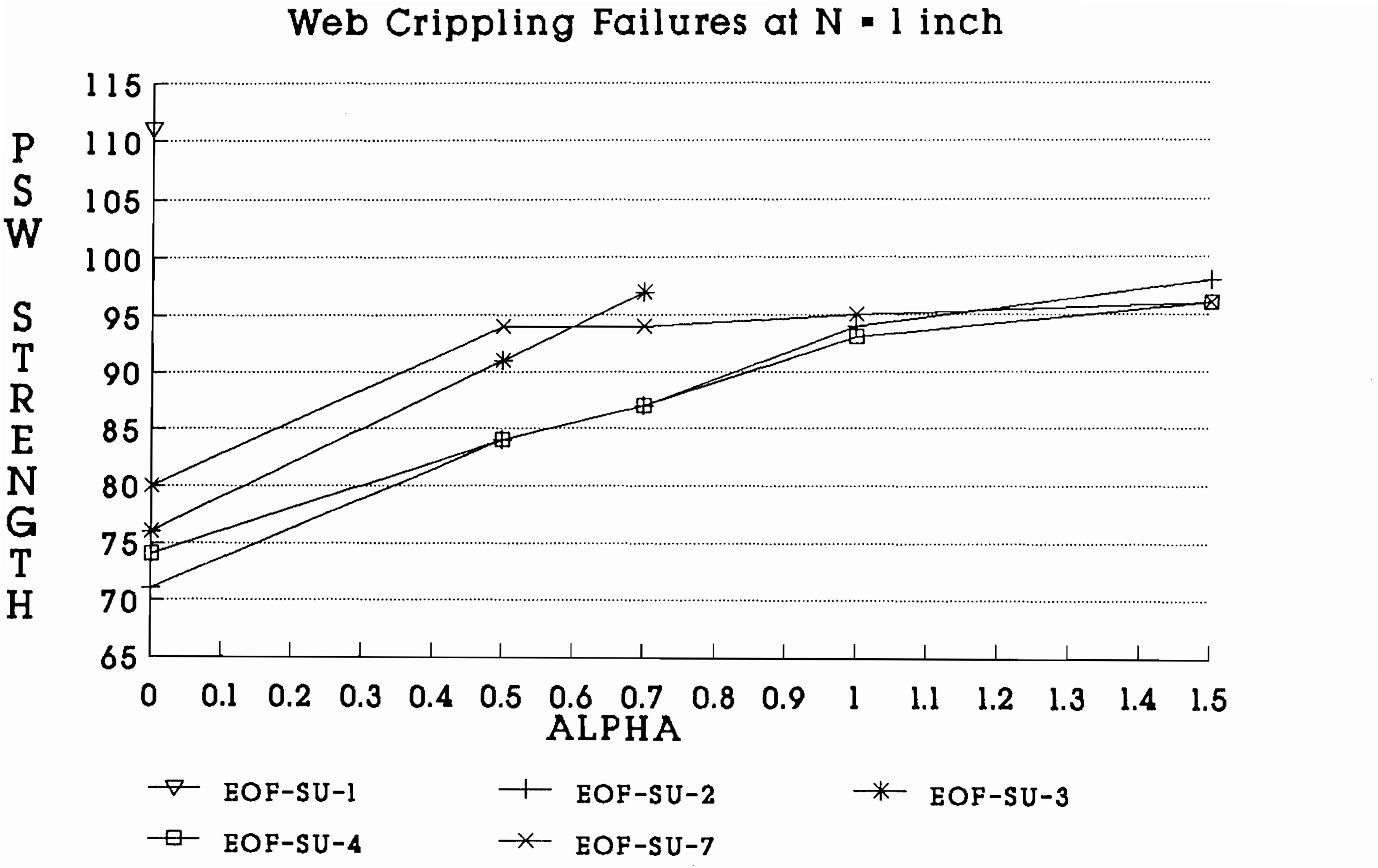


Figure 9a: Alpha vs. Percent of Solid Web Strength

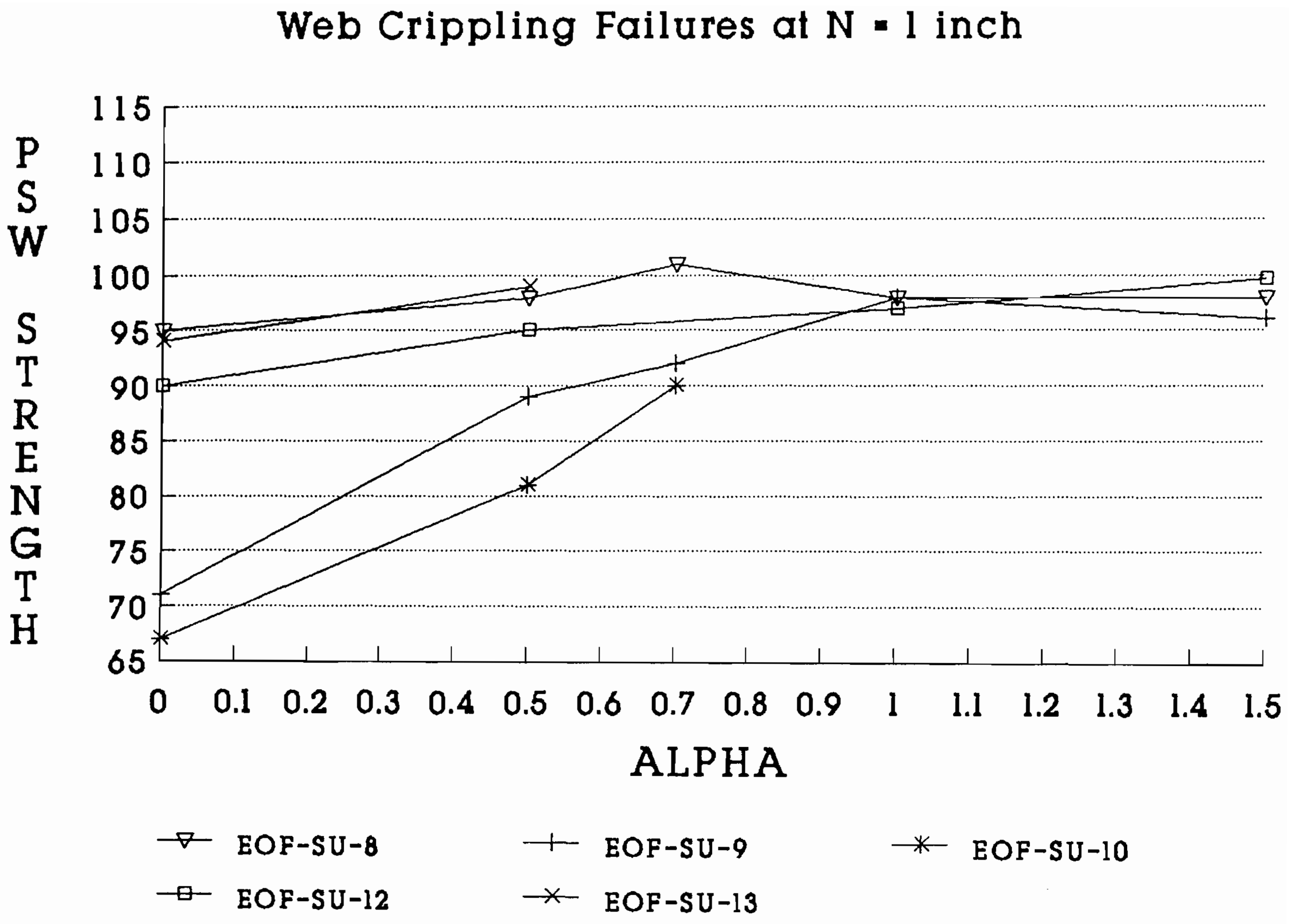


Figure 9b: Alpha vs. Percent of Solid Web Strength

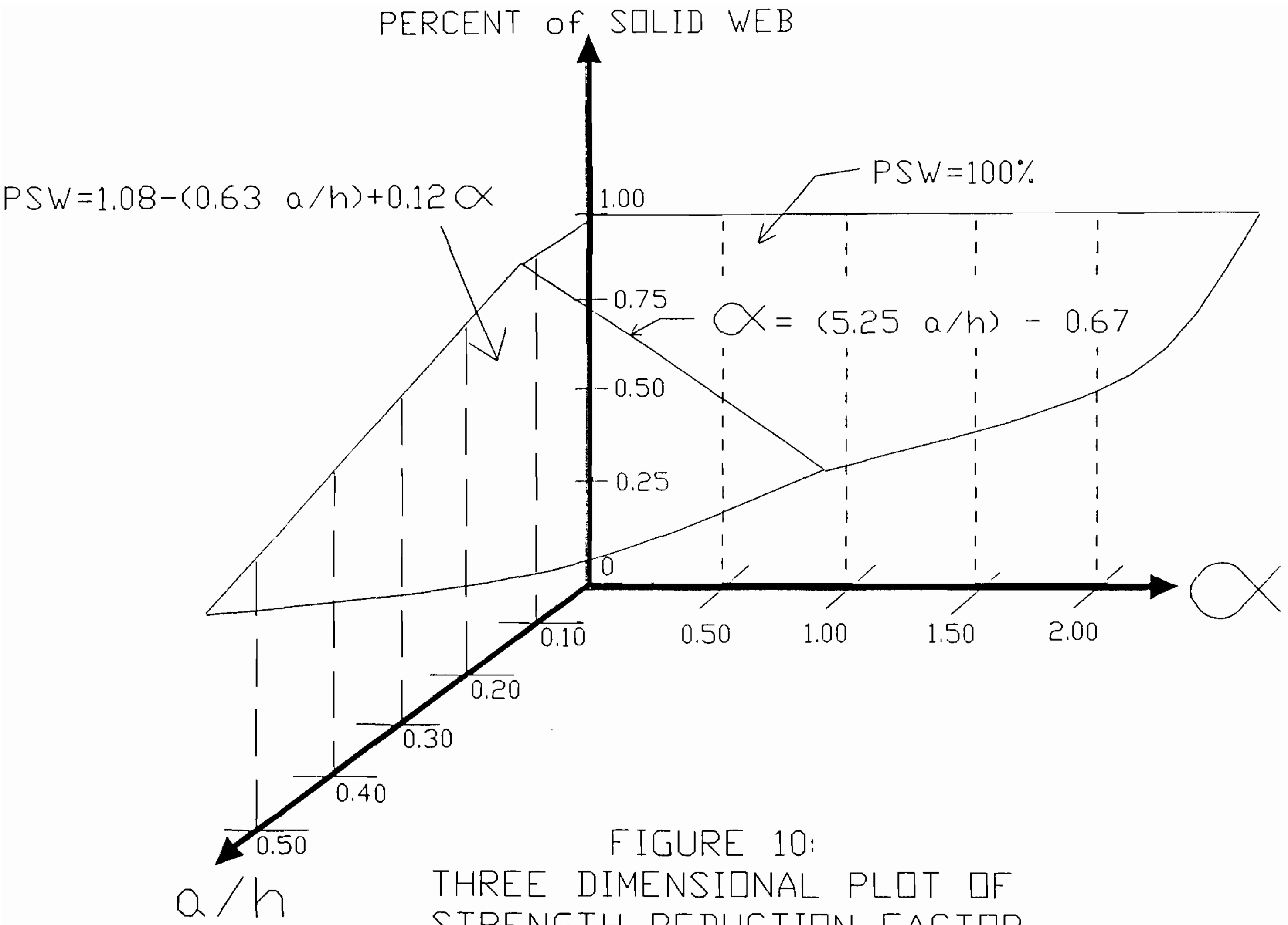


FIGURE 10:
THREE DIMENSIONAL PLOT OF
STRENGTH REDUCTION FACTOR

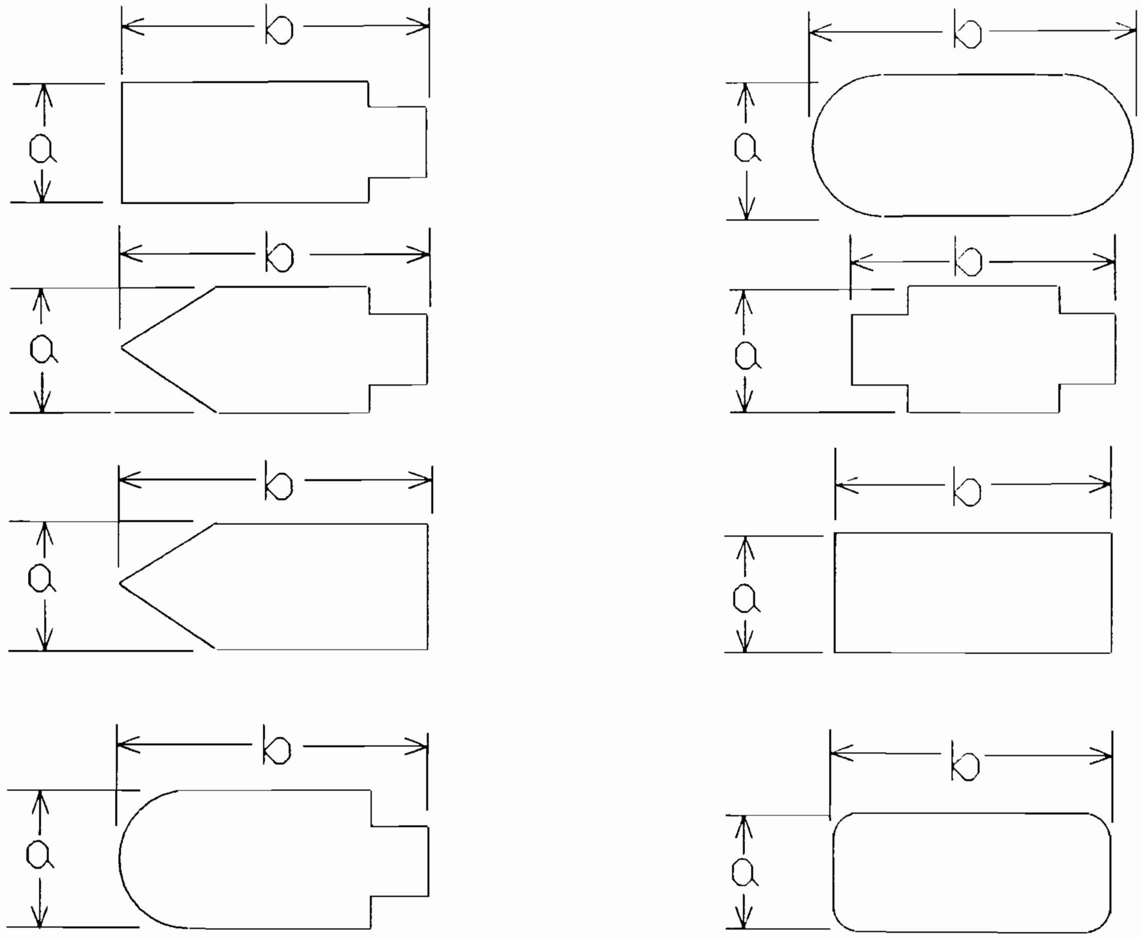
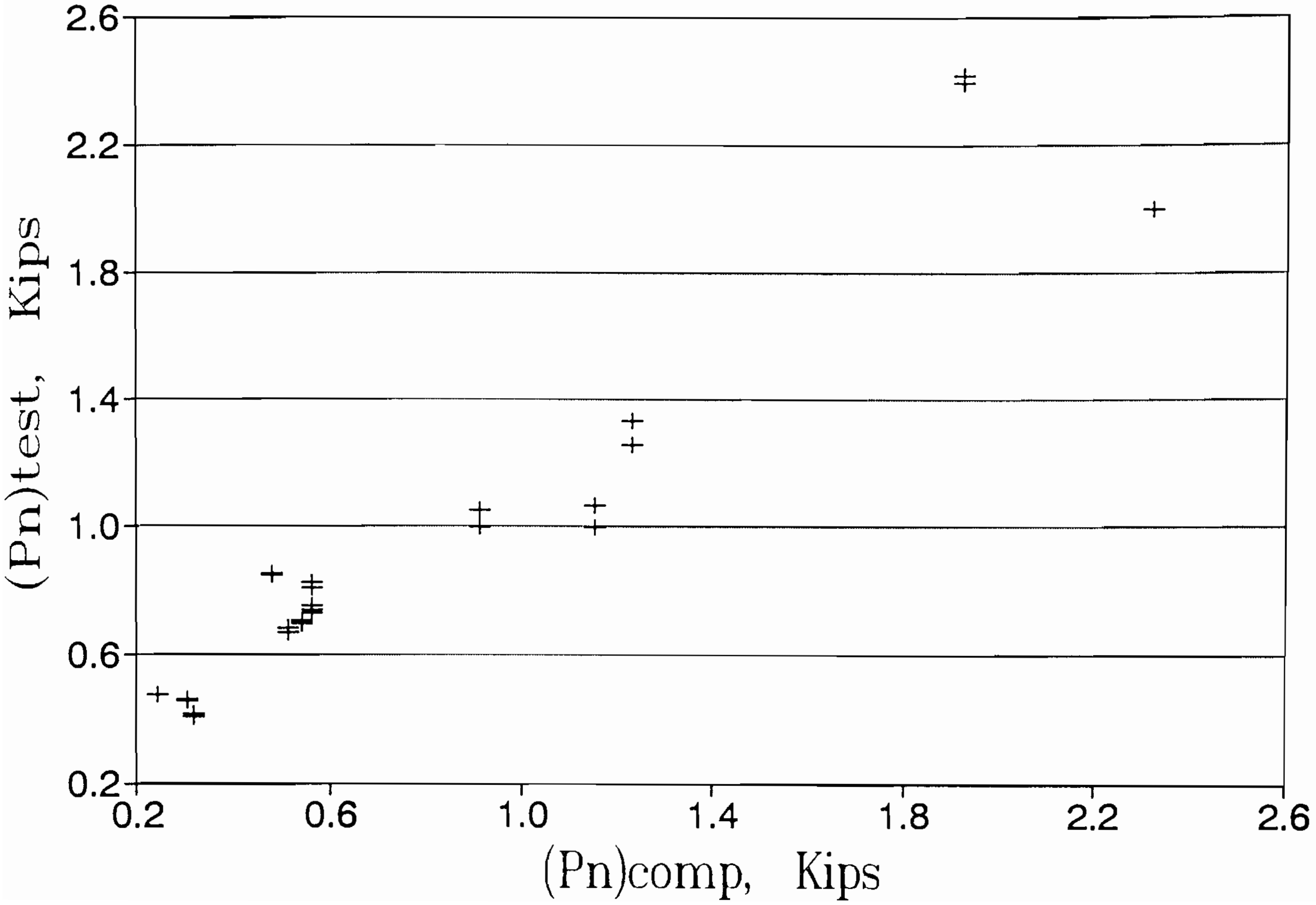


FIGURE 11: a and b DEFINITIONS
FOR INDUSTRY STANDARD WEB OPENINGS

Figure 12: (Pn)comp vs. (Pn)test
for Solid Web Tests



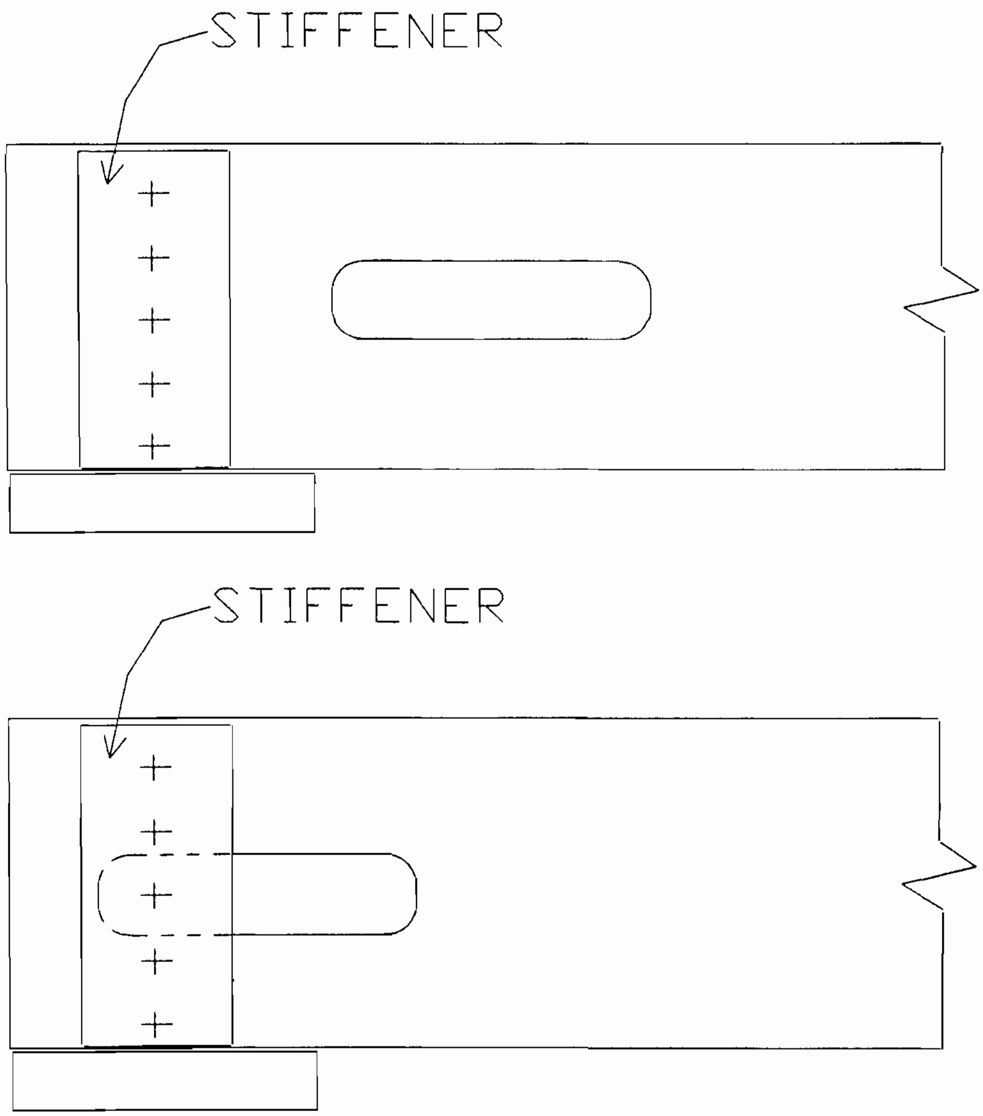


FIGURE 13: WEB OPENING AND STIFFENER LOCATIONS FOR FUTURE WORK

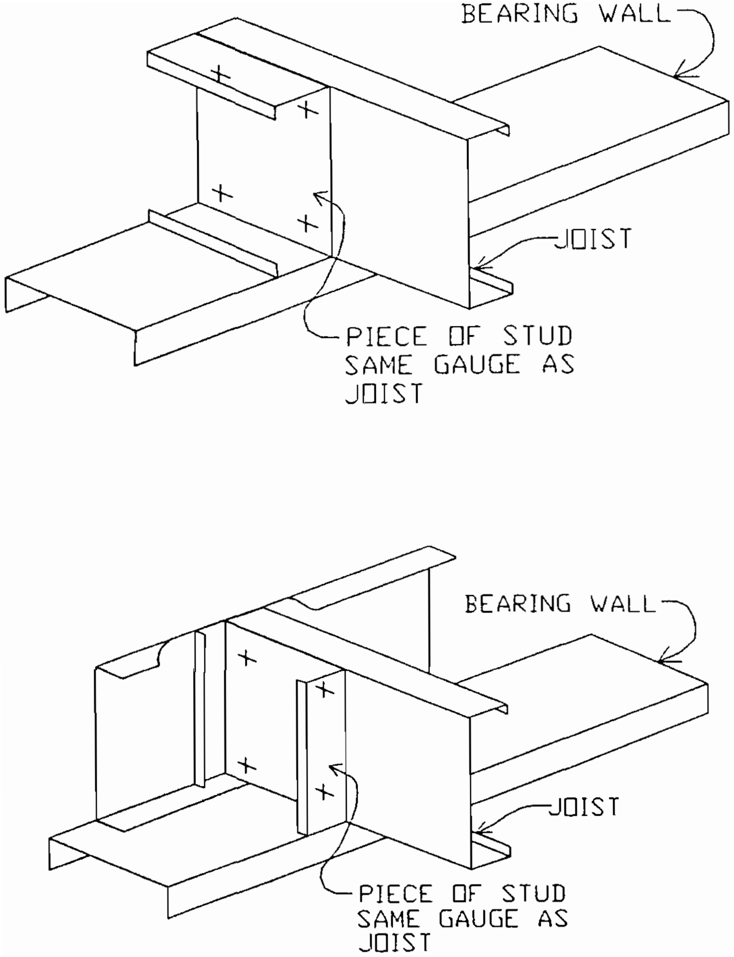


FIGURE 14: STIFFENER TYPES FOR FUTURE WORK

Fourth Progress Report
Web Crippling Behavior of Sections with Web Openings

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January 25, 1993

Foreword

A comprehensive study of the behavior of web elements with openings subjected to bending, shear, and web crippling, and combinations thereof is being conducted at UMR.

This is the fourth report in the investigation of the effect of web crippling behavior of single unreinforced webs with web openings at mid-height of the web. Report 1 (Langan, LaBoube, and Yu, 1991) provided test results from End-One-Flange (EOF) loading. Report 2 (Langan, LaBoube, and Yu, 1992a) provided test results from Interior-One-Flange (IOF) loading. Report 3 (Langan, LaBoube, and Yu 1992b) superseded Report 1 in its entirety due to the performance of additional tests and analysis of results. Therefore, Report 3 is the sole source for the current UMR study of web crippling behavior for sections with web openings subjected to EOF loading. This report supersedes Report 2 in its entirety due to the performance of additional IOF tests and analysis. Therefore, this is the sole source for the current UMR study of web crippling behavior for sections with web openings subjected to IOF loading.

Introduction

The terms "solid web", "no web opening(s)", and "without web opening(s)" are used synonymously throughout this report.

The purpose of this phase of the research was to investigate the web crippling behavior of single unreinforced webs with web openings subjected to IOF loading. The web openings were centered at the mid-height of the web. Tests were limited to C-shaped sections with edge-stiffened flanges. The major parameter varied within each common cross section was the horizontal clear distance of the opening from the near edge of the loading plate, x, (Fig. 1).

The primary goals of this study were (1) to examine the web crippling behavior as x was varied, (2) to evaluate the adequacy of the AISI provisions, based on no web openings, for predicting the web crippling strength for web elements with web openings, and (3) to develop appropriate design recommendations. All three goals will be discussed in this report.

Literature Review: Previous Research on Sections with Web Openings

Only two previous studies for web crippling behavior of thin-walled members with web openings have been documented.

Yu and Davis (1973) reported the results of 20 IOF tests conducted on cold-formed steel members. The tests were conducted on specimens composed of two channels with square or circular web openings. The channels were connected either back-to-back or through the edge stiffeners.

Sivakumaran and Zielonka (1989) developed a reduction factor for sections with web openings subjected to IOF loading:

$$RF = \left(1-0.197\left(\frac{a}{h}\right)^2\right)\left(1-0.127\left(\frac{b}{n_1}\right)^2\right) \qquad \text{(Eq. 1)}$$

where: $n_1 = N + h - a$
N = bearing load length
h = flat height of web
a = height of web opening
b = longitudinal length of web opening
limits: $b/n_1 \leq 2.0$
$a/h \leq 0.75$

Equation 1 is Eq.7 of their report. The computed strength reduction is accomplished by multiplying the solid web strength, computed using AISI equations, by the Sivakumaran and Zielonka reduction factor (Eq.1), which is always less than unity for sections with web openings. This reduction factor was developed based on the results of 103 tests with the web opening centered on the load plate. This experimental research was performed on C-shaped, edge-stiffened, channel sections subjected to IOF loading having rectangular web openings at mid-height of the web. Sivakumaran and Zielonka state, "The bending moments associated with the present tests were calculated and were compared to the corresponding moment capacity of the section and the effects were found negligible."

LaBoube (1990) proposed using a simplified form of the Sivakumaran and Zielonka reduction factor as an interim design recommendation to account for web openings. The effectiveness of the Sivakumaran and Zielonka reduction factor as applied to the current IOF study is discussed herein.

The current UMR investigation is therefore the first known research performed on C-shaped sections using IOF loading which considers the effect of the web opening location when it is not centered on the loading plate.

Test Specimens

The test specimens were fabricated from industry standard C-sections. See Figures 1 and 2 for the geometric parameters of each test specimen. Figures 3(a) through (f) show typical test specimens.

The sections were cut to the desired length to ensure that the web opening in each section was at the desired distance x from the mid-span loading plate. Ten cross sections were tested with cross section dimensions and yield strength as listed in Table 1. The range of major parameters and aspect ratios, i.e. a/h, h/t, and R/t are given in Table 2. Inside bend radius was nominally 5/32 inch. Two sizes of web openings were used in this test program, 0.75 x 4 inches (Figs. 3(a) thru (d)) and 1.50 x 4 inches (Figs. 3(e) and (f)), and are designated by dimensions a and b of Figure 1. The web openings were rectangular with fillet corners.

The major parameter varied within each cross section was the distance x. This was varied as a percent of section depth, $\alpha = x/h$. Tests were conducted for α values in increments of 0, 0.5, 0.7, 1.0, and 1.5. Figure 3 shows specimens with α equal to zero and one.

As depicted by Figure 1, the minimum length of each specimen was chosen to satisfy the requirement for one-flange loading. This minimum length is defined as a clear distance between the end bearing reaction plate and mid-span loading plate greater than or equal to 1.5h. Table 3 contains a summary of the overall specimen length, L, bearing length, N, and α of each specimen.

Test Setup

To stabilize the specimens against lateral-torsional buckling, each test specimen consisted of two C-shaped sections inter-connected by 3/4 x 3/4 x 1/8 inch angles using self-drilling screws. To prevent web crippling at the ends of the span due to an EOF loading, stiffeners were attached vertically on the webs of both sections at the ends of the span. Using a Tinius-Olson testing machine, a concentrated load was applied at mid-span to the loading plate of length N in contact with the top flanges of the test specimen. The end-of-span reactions were introduced to the specimen by three inch bearing plates flush with the ends of the specimen. Rollers were placed at the centerline of the bearing reactions to achieve a simple support condition.

Test Procedure

The load was applied to the test specimens at a constant and gradual rate until the specimen failed. Failure was defined when the specimen could carry no additional load. For many tests, the load was maintained for a duration after failure, as the testing machine continued to cause the specimen to deflect. None of the tests exhibited any increase in load capacity due to a combination of additional post-buckling strength or strain hardening. Two identical tests were conducted for all test specimens. Duplicate tests on identical specimens are identified by the specimen number designations in Tables 3 and 4.

Test Results

One hundred forty-eight tests were conducted to date. Of these, 138 are valid for web crippling analysis and 10 failed in shear. No specimens failed in pure bending.

The tested failure load, $(P_n)_{test}$, per web, for all tests are given in Table 3. The tested failure load per web is 1/2 of the applied mid-span load at failure.

Figures 3(c) and (d) show a typical web crippling failure of specimen IOF-SU-3-8-1 with the failure load still applied. The path of severe out-of-plane web deformation is highlighted. Figures 3(a) and (b) show a typical shear failure of specimen IOF-SU-2-8-1 with the failure load still applied. The shear "bulges" are outlined.

Definitions

The following definitions are used in the discussion of the observations and analysis of results:

1. Failure loads, (P_n):

    a. Tested failure load, $(P_n)_{test}$: As stated previously, this is one-half of the applied mid-span load at failure. See Table 3 for the $(P_n)_{test}$ value of each test specimen.

b. Adjusted tested failure load $(P_n)_{test\ adj.}$: This is determined from:

$$(P_n)_{test,adj.} = \left(\frac{1.07}{1.42 - \frac{M_t}{(M_n)_{comp}}} \right) (P_n)_{test} \geq (P_n)_{test} \qquad (Eq.2)$$

This equation is used to account for the degradation of the web crippling strength of the specimens due to bending moment interaction. Equation 2 provides the strength of the specimen that would have been realized if the bending moment interaction was insignificant and therefore caused no degradation of web crippling strength. The use of the inequality is implemented if $M_t/(M_n)_{comp}$ is less than 0.35. This is the range at which $M_t/(M_n)_{comp}$ is considered to not degrade web crippling strength, as illustrated by the value of $1.07/(1.42-M_t/(M_n)_{comp})$ being less than unity. The derivation of Eq.2, and the reasons for requiring its implementation are discussed in subsequent sections. See Table 3 for the $(P_n)_{test\ adj.}$ value of each test specimen.

2. Percent (of) Solid Web (average) strength, PSW: This percentage is the value of $(P_n)_{test}$ or $(P_n)_{test\ adj.}$ for a specimen with a web opening divided by the average $(P_n)_{test}$ or $(P_n)_{test\ adj.}$ for all solid web specimens from the same cross section tested at the same N length. Three PSW values are used herein.

a. Apparent PSW, PSW_{app}: This percentage is the value of $(P_n)_{test}$ for a specimen with a web opening divided by the average

$(P_n)_{test}$ for all solid web specimens from the same cross section tested at the same N length. Hence, according to the aforementioned definition of $(P_n)_{test}$, the apparent PSW value for each specimen does not account for the degradation of web crippling strength due to bending moment interaction.

b. Solid web adjusted PSW, $PSW_{S\ adj}$: This percentage is the value of $(P_n)_{test}$ for a specimen with a web opening divided by the average $(P_n)_{test\ adj.}$ for all solid web specimens from the same cross section tested at the same N length. Hence, the adjusted PSW value accounts for the degradation of web crippling strength due to bending moment interaction for the solid web specimens only.

c. All adjusted PSW, $PSW_{A\ adj}$: This percentage is the value of $(P_n)_{test\ adj.}$ for a specimen with a web opening divided by the average $(P_n)_{test\ adj.}$ for all solid web specimens from the same cross section tested at the same N length. Hence the adjusted PSW value accounts for the degradation of web crippling strength due to bending moment interaction for both the solid web specimens and specimens with web openings.

Observations

Based on the results of the specimens tested in this study, the following observations can be drawn.

A notable trend exists within the test results. As α increased, the PSW_{app} value did not increase to 100 percent as was demonstrated by the EOF results (Langan, LaBoube,and Yu 1992b).

This is shown in Table 3, and in Figure 4. Figure 4 shows α vs. the average PSW_{app} for a typical cross section, IOF-SU-5 at N is equal to 3 inches. Figure 4 is in contrast to the results of the EOF tests shown in Figures 9a and b of Report 3 (Langan, LaBoube, and Yu, 1992b), which showed PSW to converge to 100 percent as α increased for the EOF tests.

The reason for the decrease in PSW_{app} at high α values for the IOF results is believed to be due to the moment degradation of the web crippling strength of the specimens as α increased. As can be seen from Table 3, specimens with high α values generally had higher L values and greater bending moments. As will be shown herein and in Table 3, this trend is corrected by using $PSW_{A\,adj.}$. $PSW_{A\,adj.}$ is postulated to remove bending moment interaction from the PSW_{app} results, and provides a trend of α vs. PSW similar to that demonstrated by the EOF tests.

Bending Moment

The specimens acted as simply supported beams with the span length equal to the distance between the reaction plate rollers. Since the end reaction plates were always three inches, the span length, L_{span}, is equal to $L_{specimen}$ - 3". The bending moment at failure, M_t, at mid-span is equal to one-half the failure load times one-half the span length, or:

$$M_t = (L_{span})((P_n)_{test})/4 \qquad \text{(Eq.3)}$$

where: $L_{span} = L_{specimen} - 3$ in.

$(P_n)_{test}$ is as defined previously.

The ultimate moment capacity, $(M_n)_{comp}$, of the specimens was determined by using AISI (1986, 1989), Section C3.1.1 Nominal Section Strength, Paragraph (a) Procedure I-Based on Initiation of Yielding. The $(M_n)_{comp}$ values for each cross section are given in Table 1.

The ratio $M_t/(M_n)_{comp}$ Table 3, is therefore the bending moment at the failure load, as defined earlier, divided by the ultimate moment based on initiation of yielding.

Preliminary results from a simultaneous University of Missouri-Rolla study on the effect of web openings on the bending moment capacity of sections indicate that the moment capacity reduction may be only as much as ten percent due to the web openings. The bending moment study for sections with web openings uses third point loading geometry, which provides a long span region with constant-maximum moment. Therefore, several web openings are located within the constant-maximum moment region. For the IOF web crippling study, no reduction in $(M_n)_{comp}$ was used for specimens with web openings because: (1) as stated, web openings do not significantly decrease the moment capacity of the sections, and (2) the point of maximum moment for the web crippling study, at mid-span, does not coincide with the location of the web opening. For this study, an idealized triangular bending moment diagram for simply supported beams was used. As a minimum, the location of the web opening, for Alpha is equal to zero, is at N/2 from mid-span.

Bending Moment Interaction

The length of the specimen, L, was a parameter that affected the $(P_n)_{test}$ value of the specimens because of its effect on bending moment and therefore on the interaction of bending moment and IOF web crippling. As stated previously the specimen had to be of sufficient length to accommodated the various constituent lengths and requirements of:

(1) clear distance between bearing plates of greater than or equal to 1.5h, as required for one-flange-loading.

(2) distance x′ of Fig. 1 had to be greater than or equal to zero. This requirement increased L by the amount 2(b+x-1.5h). The factor of two results from maintenance of symmetry of span length about the center of the loading plate.

(3) length N of the mid-span loading plate, and the three inch lengths of the two end-of-span bearing plates.

The second requirement was not a factor in the previous investigations discussed in the literature review. In the current study, this requirement often constituted a significant portion of overall specimen length. Therefore, the length of the specimens and the resulting effect of bending moment on specimens with web openings was often significantly greater than for those used in previous IOF studies without web openings (Hetrakul and Yu, 1978). Likewise, the effect of bending moment was greater than for the Sivakumaran and Zielonka tests (1989), since the tests were conducted with the web opening centered on the load plate. As stated by Sivakumaran and Zielonka, the bending moments were insignificant.

In practice, significant bending moment may typically exist at locations of IOF loading. A common example is the IOF reaction resulting from a continuous wall stud subjected to a distributed wind load which spans a girt or intermediate support. As stated in (Yu, 1991) pgs. 234 to 236:

> The AISI (web crippling) design formulas were used to prevent any localized failure of webs resulting from the bearing pressure due to reactions or concentrated loads without consideration of the effect of other stresses. In practical applications a high bending moment may occur at the location of the applied concentrated load in simple span beams. For continuous beams, the reactions at supports may be combined with high bending moments and/or high shear. Under these conditions, the web crippling strength as determined by (AISI (1986, 1989) Section 3.4 Web Crippling Strength) may be reduced significantly due to the effect of bending moments. The interaction relationship for the combination of bearing pressure and bending stress has been studied by numerous researchers. ... Based on the results of beam tests with combined web crippling and bending, interaction formulas have been developed for use in several design specifications.

The design interaction equation used by AISI (1986, 1989) for sections having flat-single unreinforced webs, is AISI Eq.C3.5-1:

$$1.2(P/P_a) + (M/M_{axo}) \leq 1.5 \qquad \text{(Eq.4)}$$

M_{axo} is the allowable moment based on AISI (1986, 1989), Sect. C3.1.1 Nominal Section Strength for Bending. Therefore, this does not apply to sections with the maximum allowable moment controlled by lateral stability.

AISI Equation C3.5-1 was adopted from Hetrakul and Yu (1978) Eq.74:

$$1.22(P/P_{max}) + (M/M_{max}) \le 1.53 \qquad \text{(Eq.5)}$$

which was derived from Hetrakul and Yu (1978) Eq.61:

$$1.07\frac{(P)_{test}}{(P_u)_{comp}} + \frac{(M)_{test}}{(M_u)_{comp}} = 1.42 \qquad \text{(Eq. 6)}$$

AISI Eq.C3.5-1 (Eq.4) incorporates the safety factors of 1.85 for web crippling and 1.67 for bending. The factors of safety are from AISI (1986, 1989), Sect. II (Commentary), Table A5.1.

Equation 2 was derived from Eq.6 by substituting $(P_n)_{test}$ for $(P)_{test}$ and $(P_n)_{test\ adj}$ for $(P_u)_{comp}$, and by noting that $(M_u)_{comp}$ and $(M_n)_{comp}$ have the same meaning.

The derivation of Eq.6 can readily be seen from (Hetrakul and Yu, 1978) in their Fig.94, which is a graph of $(P)_{test}/(P_u)_{comp}$ vs. $M_t/(M_n)_{comp}$ values. Equation 6 is primarily a regression factor equation for the widely scattered data associated with the interaction phenomenon. Therefore, use of Eq.6 to account for the effect of bending moment interaction is not exact. However, it is the best model available. Furthermore, it succeeds in rectifying the erroneous trend of decreasing web crippling strength as the distance between the load and the web opening increase.

It is assumed that the location of interaction between web crippling and bending moment was at mid-span of the test specimens, regardless of the location of the web opening. This is based on the assumption that the web crippling failures occurred at mid-span, as is exhibited by solid web specimens.

For specimens with web openings, a large longitudinal region of the web is deformed (Figs. 3(c) and (d)). However, the web opening was assumed to influence the web crippling resistance of the specimen at mid-span by reducing the mid-span region's capability to transfer load longitudinally along the section.

Development of the Reduction Factor Equation

Ninety tests were conducted on specimens with web openings that failed in web crippling. Several multi-variable linear regression analyses were performed on the 90 test results to develop reduction factor equations. The recommended reduction factor equation is described in this section. The development of an alternative reduction factor equation is given in Appendix 1.

A bivariate linear regression was performed with α and a/h as the independent variables and $PSW_{A\,adj.}$, as the dependant variable. The resulting reduction factor equation, with a maximum of 100 percent is:

$$PSW = 96.44-(27.20\frac{a}{h})+(6.31\alpha)\leq 100\% \qquad (Eq.7)$$

or,

$$PSW = 0.964-(0.272\frac{a}{h})+(0.0631\alpha) \leq 1.00 \qquad (Eq.8)$$

The regression is the least y-squares plane (Fig. 5) for the 90 data points. A PSW value of 100 percent signifies that no strength reduction is required. The reduction factor equation indicates that at 100 PSW:

$$\alpha \geq (4.31\ a/h) + 0.571 \geq 0 \qquad \text{(Eq.9)}$$

Equation 9 implies that for a web opening of infinitesimal size, α must be greater than or equal to 0.571 for no reduction of the solid web strength. Intuitively, the strength should not require reduction for an infinitesimal web opening even at the minimum α value of zero. However, Eq.8 yields a satisfactory value of approximately unity, 0.964, when α is equal to zero and a/h is slightly greater than zero. The region of α and a/h which requires no strength reduction is shown in Fig. 5 as a horizontal plane with a PSW value of 1.00.

The parameters of α and a/h provided the only conclusive correlation with $PSW_{A\ adj.}$. The additional parameters shown in Table 1, with the exception of b, proportionally affected both of the aforementioned $(P_n)_{test\ adj.}$ values which determine $PSW_{A\ adj.}$. However, only α and a/h influenced $PSW_{A\ adj.}$ since they are intrinsic only to specimens with web openings, and therefore they affected only the numerator of the $PSW_{A\ adj.}$ equation. The influence of b is addressed by imposing a maximum limit on b. See the section titled "Ranges of Applicability for the Reduction Factor Equation".

The $M_t/(M_n)_{comp}$ value is not included in the bivariate linear regression factor (Eq.8) which was determined from $PSW_{A\ adj.}$ vs. α and a/h. The alternative regression factor equation discussed in Appendix 1 includes $M_t/(M_n)_{comp}$, and therefore is based on a trivariate linear regression of PSW vs. α, a/h, and $M_t/(M_n)_{comp}$.

Equation 8, has the desirable characteristic of using the established practice of employing Eq.4 or Eq.6 to check bending moment interaction.

Application of Reduction Factor

The allowable web crippling load for specimens with web openings can be obtained by applying the reduction factor, which is less than or equal to unity, to Eq.10 taken from (AISI 1986, and 1989). Equation 10 corresponds to AISI Eq.C3.4-4, and provides the allowable load for single-unreinforced webs with edge-stiffened or unstiffened flanges subjected to IOF loading.

$$P_a = t^2 k C_1 C_2 C_\theta \left(291 - 0.40\frac{h}{t}\right)\left(1 + 0.007\frac{N}{t}\right), kips \qquad (Eq.\ 10)$$

Where: $k = F_y/33$
$C_1 = (1.22-0.22k)$
$C_2 = 1.06-0.06\ R/t \leq 1.00$
$C_\theta = 0.7 + 0.30\ (\theta/90)^2$
F_y = Design yield stress of the web.
h = Depth of the flat portion of the web.
t = Web thickness, inches
R = Inside bend radius of corners.
θ = Angle between the plane of the web and the plane of the bearing surface ≥ 45°, but not more than 90°. θ = 90° for all tests from the current study, therefore, $C_\theta = 1.00$.

When N/t>60, the factor [1+0.007(N/t)] may be increased to [0.75+0.011(N/t)]. Note: the $(P_n)_{comp}$ values in Table 4 use this increase for N/t>60.

For $M_t/M_a \geq 0.30$, or $M_t/(M_n)_{comp} \geq 0.35$, interaction equations Eq.4 or Eq.6 must also be checked.

The results of applying Eq.6 to the test results is shown in Table 4 under the column titled "Interaction Equation Value".

For this application, the value of $(P_n)_{comp}$ is equal to Eq.10 multiplied by Eq.8. The average of all interaction equation values is 1.373, which is approximately equal to the maximum permissible value of 1.42. This indicates that the use of Eq.8 essentially maintains the present design practice.

Ranges of Applicability for Reduction Factor Equation

The reduction factor equation (Eq.8) developed in the current study is applicable to all cross sections that meet the ranges of applicability as follows:

1. Ranges based on applicability of AISI Eq.C3.4-4 (Eq.10): Although the testing was limited to specimens with edge-stiffened flanges, the same percent reduction in strength is expected for sections with unstiffened flanges. If Eq.8 is used to reduce the allowable strength of Eq.10, the limits on h/t, R/t, N/t, and N/h ratios stated in (AISI 1986, and 1989), Section C3.4 must be met.

2. Ratio of a/h: Although the maximum a/h value tested which failed in web crippling was 0.464, Eq.8 is assumed to be valid for a/h less than or equal to 0.50. This limit corresponds to the maximum a/h employed by industry standard sections. As will be discussed, high a/h values increase the probability of a shear failure. Therefore, shear must be checked separately using results from the concurrent UMR study of shear behavior of sections with web openings.

3. End reaction length, N: Although Eq.8 is based primarily on tests at N is equal to three inches, with limited tests at N

is equal to four, five and six inches, it is applicable to all N values greater than or equal to three inches. This is the minimum limit of N for the IOF loading conditions in most situations.

As will be discussed later, every cross section will change from web crippling to shear failure at a particular N value inherent to the cross section properties. Shear capacity is not dependent on N (AISI, 1986 and 1989). Equation 8 can be used in conjunction with Eq.10 for all N values greater than three inches if shear strength is checked separately.

4. Depth of flat portion of the web, h: The tested range of specimens that exhibited web crippling failures was 2.12 to 11.54 inches. However, all h values are valid if the h/t maximum limit of 200 is not exceeded.

5. Base metal thickness (t): The tested range was 0.032 to 0.098 inches. However, all t values are valid if the h/t maximum limit of 200 is not exceeded.

6. Yield Strength (F_y): The tested range was 36 to 93 ksi. However, all F_y are valid for Eq.8. For cross sections with F_y greater than 91.5 ksi, 91.5 ksi should be used in Eq.10. This limit is imposed because these equations were developed using specimens with F_y less than 55 ksi (Hetrakul and Yu, 1978). Also, as can be seen from the product of the k and C_1 terms of the Eq.10, the maximum value of P_a is obtained when F_y is equal to 91.5 ksi.

7. Maximum opening height, a, and width, b:

a: No maximum limit is prescribed for a. However, the maximum allowable a/h ratio of 0.50 must be adhered to.

b: Although the maximum b value tested was four inches, it is recommended that the maximum limit for b be extended to the industry standard maximum of 4.5 inches. The parameter b is not included in the reduction factor equation, hence no variation in allowable load for b values between zero and 4.5 inches is recommended. Most notably, for small b values, no increase in web crippling capacity is allowed. The length of the mechanism, or path of severe web deformation, is independent of b as shown in Fig.6. Therefore, the capacity of the section is assumed to be independent of b. This phenomenon is in contrast to (Sivakumaran and Zielonka, 1989). However, the failure mechanism is much different for their tests because of the web opening being centered on the load plate, thereby justifying the incorporation of b into their reduction factor equation (Eq.1). It is recognized that the value of b might effect the capacity of the section if both b and α are very small. In this situation, the distribution of the load would intersect the region of the web shown in Fig.1 as x'.

The definitions of a and b for various shapes of web openings is given in Figure 7.

8. h/t: Although the maximum h/t ratio tested was 168, this can be extended to the maximum allowable prescribed for Eq.10 of 200. No minimum h/t is prescribed although the minimum h/t tested was 39.

9. R/t: The tested range was 1.59 to 4.88. However, all R/t values less than or equal to 6.0 are valid because this is the maximum limit imposed for Eq.10.

10. θ: Theta equalled 90° for all tests. However, it is assumed that all θ values within the allowable limits of Eq.10 of 45° to 90° are valid.

11. α: Alpha ranged from 0 to 1.5 for all tests with web openings. The recommended minimum value for α in Eq.8 is zero. It is standard industry practice to place a stiffener on all sections that have α values less than zero, i.e. when any portion of the web opening is below the member which introduces the load. Although it is presumed that in lieu of placing a stiffener, a reduction factor could be employed. Possibilities include:

i. Allowing the α value of Eq.8 to be negative. However, this is not recommended, since no upper limit for the magnitude of this negative α value, for which Eq.8 will still be valid, can rationally be determined without sufficient experimental data. Also, as the centerline of the web opening approaches the centerline of the load, the failure mode will change to those reported by Sivakumaran and Zielonka (1989)

ii. Using the Sivakumaran and Zielonka reduction factor equation (Eq.1): If used, it is recommended that no increase in allowable web crippling capacity be made for web openings not centered on the load, until further research is performed. Sivakumaran and Zielonka (1989) stated, "The web openings were directly under the load, thus the above equation establishes the influence of an opening under the worst possible scenario."

No maximum limit is placed on α. At high α values, Eq.8 will yield a value of 1.00. Furthermore, with the standard practice of using sections with openings separated by 24 inches on-center, the maximum value of α will be constrained by the α value of the web opening on the opposite side of the load.

Comparison with Previous Studies for Specimens with Solid Webs

As can be seen from Table 4, the average $(P_n)_{\text{test adj.}}/(P_n)_{\text{comp}}$ value for all solid web tests with F_y less than 70 ksi was 1.001, and therefore corresponds well with previous solid web investigations. Hetrakul and Yu (1978) in their Table 5a show an average of 0.997 for the IOF tests. All tests shown in (Hetrakul and Yu, 1978), Table 5a had a $M_t/(M_n)_{\text{comp}}$ value below 0.30, thereby justifying the use of $(P_n)_{\text{test adj.}}$ for the comparison. Cross sections IOF-SU-9 and 10 were excluded from the analysis because their yield strengths greatly exceeded those stated in Hetrakul and Yu (1978).

Hetrakul and Yu (1978) used their Eq.32 (Eq.11) to determine $(P_n)_{\text{comp}}$, which applies to the IOF condition for stiffened and unstiffened flanges:

$$(P_u)_{comp} = \frac{t^2 F_y}{10^3} C_1 C_2 (16317 - 22.52(h/t))(1 + (0.0069(N/t)), \; Kips \qquad (Eq.11)$$

where: $C_1 = (1.22-0.22k)$
$C_2 = (1.06-0.06n)$
$k = F_y/33$
$n = R/t$

When $N/t>60$, the factor $[1+0.0069(N/t)]$ may be increased to $[0.748+0.0111(N/t)]$, in accordance with Hetrakul and Yu (1978) Eq.83.

Equation 11 provides the same result as AISI Eq.C3.4-4 (Eq.10) x 1.85.

Cross sections IOF-SU-9 and 10 had $(P_n)_{test\ adj.}/(P_n)_{comp}$ values significantly greater than zero, even at the low α values tested. Examination of the parameters of cross sections IOF-SU-9 and 10 indicate that the high yield strengths resulted in the conservatism of the sections. As stated previously, AISI Eq.C3.4-4 (Eq.10), which was adopted from Eq.11, was developed from tests with F_y values less than 55 ksi. Cross sections IOF-SU-9 and 10 also had h/t ratios significantly greater than those of the other cross sections used in the current study. However, Hetrakul and Yu (1978) reported the results from numerous tests on sections with h/t values greater than or equal to 150, including values of 200 and 250. The results strongly indicate that high h/t values are not the cause of the conservative results. Therefore, it is believed that the high F_y values solely contributed to the conservative results from cross sections IOF-SU-9 and 10. It is recommended that sections with high F_y values not be exempted from the strength reduction (Eq.8) to account for web openings. The conservatism of a section should be addressed through the modification of Eq.10, and not through the modification of the reduction factor equation. It is desirable to use a reduction factor equation which possesses no parameters inherent in the solid web cross section.

The web crippling equations for solid webs developed by Santaputra, Parks, and Yu (1989) provided similar results for cross sections IOF-SU-9 and 10. Their equations are valid for F_y is less than or equal to 190 ksi. Based on the geometry of the current study, their Eqs. 8 and 9 apply, with the smaller value from the two equations providing $(P_n)_{comp}$. For both cross sections, their Eq.9 defined $(P_n)_{comp}$. For the solid web tests from cross section IOF-SU-9, the average value of $(P_n)_{comp}$ from Santaputra, Parks, and Yu (1989) divided by $(P_n)_{comp}$ from Eq.10 is 0.9970. For the solid web tests from cross section IOF-SU-10, the average value of $(P_n)_{comp}$ from Santaputra, Parks, and Yu (1989) divided by $(P_n)_{comp}$ from Eq.10 is 1.120.

Nominal Tested versus Computed Capacity

Table 3 shows the reduction values from the Sivakumaran and Zielonka study (Eq.1) and the current study (Eq.8) for each test specimen which had a web crippling failure. Table 4 shows the nominal web crippling strength from Eq.10, and the reduced strengths, based on Eq.10, multiplied by the two reduction factors. Table 4 also shows the $(P_n)_{test\ adj.}/(P_n)_{comp}$ values using the three $(P_n)_{comp}$ values for all tests that failed in web crippling.

The ϕ factor based on each of the three $(P_n)_{comp}$ values was computed using Eq.F1-2 from (AISI, 1991):

$$\Phi = 1.5(M_m F_m P_m)\exp\left(-\beta_0\sqrt{V_M^2+V_F^2+C_P V_P^2+V_Q^2}\right) \quad (Eq.\ 12)$$

Where:

In general:

M_m = Mean value of the material factor for the type of component involved.

F_m = Mean value of the fabrication factor for the type of component involved.

P_m = Mean value of the tested-to-predicted load ratios.

β_o = Target reliability index = 2.5 for structural members and 3.5 for connections.

V_M = Coefficient of variation of the material factor for the type of component involved.

V_F = Coefficient of variation of the fabrication factor for the type of component involved.

C_P = Correction factor = $(n-1)/(n-3)$

V_P = Coefficient of variation of the tested-to-predicted load ratios.

n = number of tests values.

V_Q = Coefficient of variation of the load effect = 0.21

Specific values:

M_m, V_M, F_m, and V_F are from Table F1 of (AISI, 1991). For web crippling: M_m = 1.10, V_M = 0.10, F_m = 1.00, and V_F = 0.05.

P_m and V_P: from Table 4, based on the method used to determine $(P_n)_{comp}$.

β_o = 2.5

The Allowable Stress Design, ASD, factors of safety were computed using Eq.II.7 from (Hsiao, Yu, and Galambos, 1988):

$$(F.S.)_{ASD} = (1.2D_n/L_n+1.6)/[(\Phi(D_n/L_n+1)] \quad (Eq.\ 13)$$

Where: D_n/L_n = 1/5.

Comparison of the results from Table 4 show that the use of the reduction factors from Sivakumaran and Zielonka (Eq.1) and the current study (Eq.8) provide nearly identical results in increasing the average $(P_n)_{test\ adj.}/(P_n)_{comp}$ value to account for web openings. However, this effect is the aggregate for the full range of α values tested. Because Eq.1 does not consider the effect of the web opening in relation to the load plate, it is less conservative at low α values, and more conservative for high α values, than those based on Eq.8 from the current study.

The three $(F.S.)_{ASD}$ values from Table 4 show the factors of safety required to satisfy the target reliability index, β_o, of 2.5. The $(F.S.)_{ASD}$ for the solid web tests was 2.07; this average excluded the results from the high yield strength cross sections IOF-SU-9 and 10. This average is 12 percent higher than the existing factor of safety of 1.85. The increase is due to the effect of the coefficient-of-variation for the $(P_n)_{test\ adj.}/(P_n)_{comp}$ values, which was 0.210. The value is significantly greater than the coefficient-of-variation of 0.102 from the previous web crippling tests (Hetrakul and Yu, 1978). However, their coefficient-of-variation is based on tests which had $M_t/(M_n)_{comp}$ value less than 0.30. The average $M_t/(M_n)_{comp}$ value for the 44 solid web tests from the current study, excluding cross sections IOF-SU-9 and 10, was 0.448. Therefore, the increase in the coefficient-of-variation was partially caused by the scatter associated with the bending moment - web crippling phenomenon in the current study.

Shear

Ten test specimens, performed on five pairs of identical specimens, failed in shear. The shear failures were very pronounced in the vicinity of the web opening, and formed flange hinge mechanisms described in (Narayanan and Der-Avanessian, 1985) in their Figure 1. Shear failures usually occurred with little or no web crippling deformation at the load plate.

Shear failures generally occurred for two reasons. First, higher bearing lengths, N, increased the likelihood of a shear failure because an increase in N provides an increase in the web crippling strength of the section but does not affect the shear capacity of the section.

Secondly, shear failures also occurred at high values of the ratio of web opening height, a, to web height, h. This occurred because of the removal of a considerable portion of the shear carrying portion of the cross section. Cross section IOF-SU-4 demonstrates this phenomenon for an a/h ratio of 0.73. IOF-SU-4-2 were the only tests which failed in shear at N is equal to three inches.

Since the specific web crippling - shear transition parameter values are not defined, shear must be checked separately. A concurrent UMR study is investigating the shear strength of specimens with web openings.

Many of the specimens that failed due to web crippling had a slight amount of shear deformation. The location of the shear "bulges" protruding from the diagonal compression corners of the web opening were the same as distinct shear failures, but the magnitude of the deformation was very slight. Failure modes were identified as either web crippling or shear. No attempt has been made to establish the interaction of shear and web crippling. Hetrakul and Yu (1978), state "It is expected that shear will not affect the web crippling load even for the beams having high V/V_u ratios."

Rate of loading

Hetrakul and Yu (1978) state that the specimens were loaded in 15% increments of the expected failure load, and the load maintained for five minutes at each increment. However, all tests for the current study were loaded at a constant and gradual rate. See (Langan, LaBoube, and Yu, 1992b) for diagnostic tests performed to determine the effect of the loading rate. The diagnostic tests showed that no appreciable difference in strength between the two load application techniques existed. The same trend was assumed for the IOF study.

Deformation at Failure

At failure, most specimens were severely deformed and would be considered unserviceable under most applications. Most specimens show a combination of out of plane deformation of the web, and considerable localized vertical displacement of the loaded flange. See Figures 3(c) and (d), for web crippling failures which were taken while the failure load was still applied. This is an important consideration in the selection of the design safety factor since the AISI specification does not place a serviceability limit on web crippling due to the difficulty in quantifying the deformation and implementing the results in practice. This phenomenon adds credibility to the use of the AISI web crippling design safety factor of 1.85, which is larger than for all other non-catastrophic failure modes.

Summary

A total of 148 specimens were tested for the IOF loading condition. Analysis of IOF test data provides a simple and practical reduction factor (Eq.8) for AISI Eq.C3.4-4 (Eq.10). The reduction factor equation is a function of α and a/h. A joint region of α and a/h was identified that requires no strength reduction. The reduction factor is valid for bearing lengths, N, greater than three inches, and for all sections that satisfy the ranges of applicability stated herein. Additionally, bending moment interaction using AISI Eq.3.5-1 (Eq.4) must be checked. Other failure modes, i.e. shear, flexure, and combinations thereof, must be checked separately.

Future work

The research reported herein is one phase of a comprehensive study of web elements with web openings. Future phases may address:

(1) Use of stiffeners with the web opening partially within

the bearing length (Fig.8).

(2) Type of stiffener (Fig.9).

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APPENDIX I: Alternate Reduction Factor Equation

The following reduction factor (RF) equation was derived from the ninety tests conducted on specimens with web openings that failed in web crippling. It is based on a trivariate linear regression analysis. The dependent variable is $PSW_{S\,adj.}$ The independent variables are α, a/h, and $M_t/(M_n)_{comp}$

$$PSW = 1.174-(0.264\frac{a}{h})+(0.0526\alpha)-(0.663\frac{M_t}{(M_n)_{comp}}) \leq 1.00$$

Ideally, this equation could replace interaction equations Eq.4 and Eq.6 for specimens with web openings. However, this is not suggested because of the established practice of using the current interaction equations and the existing data base of the tests that were used to define Eq.6 was not used in the development of the above equation.

Table 1: Cross Section Properties

Cross Section	D(in.)	t(in.)	R(in.) nominal	h(in.)	B(in.)	d(in.)	a(in.)	b(in.)	Fy (ksi) actual	Fy (ksi) used	h/t	a/h	R/t	(Mn)comp (K-in)
IOF-SU-1	12.05	0.098	0.156	11.54	1.65	0.64	1.50	4.00	36	36	118	0.130	1.594	179.74
IOF-SU-2	2.51	0.032	0.156	2.12	1.57	0.41	0.75	4.00	55	55	66	0.354	4.883	7.58
IOF-SU-3	2.55	0.055	0.156	2.12	1.65	0.47	0.75	4.00	55	55	39	0.354	2.841	15.53
IOF-SU-4	2.42	0.033	0.156	2.05	1.63	0.46	1.50	4.00	67	67	62	0.732	4.735	9.12
IOF-SU-5	3.62	0.033	0.156	3.23	1.62	0.44	1.50	4.00	59	59	98	0.464	4.735	14.06
IOF-SU-6	3.67	0.045	0.156	3.26	1.63	0.47	1.50	4.00	53	53	72	0.460	3.472	18.75
IOF-SU-7	3.65	0.044	0.156	3.25	1.64	0.49	NO OPENING		63	63	74	0.000	3.551	21.36
IOF-SU-8	3.69	0.067	0.156	3.22	1.63	0.49	1.50	4.00	48	48	48	0.466	2.332	28.21
IOF-SU-9	5.92	0.033	0.156	5.54	1.58	0.44	1.50	4.00	93	91.5	168	0.271	4.735	31.01
IOF-SU-10	7.94	0.045	0.156	7.54	1.59	0.47	1.50	4.00	72	72	168	0.199	3.472	58.17

Notes:

1. See Figures 1 and 2 for definitions of dimensions.
2. Cross section designations:
   IOF: Interior-One-Flange (loading)
   SU: Single Unreinforced (web)
3. AISI Eq. C3.4-4 obtains a maximum value at Fy = 91.5 Ksi, therefore, 91.5 Ksi was used to calculate the nominal computed strength for all cross sections with a Fy exceeding 91.5 Ksi.
4. Moment capacity determined for a solid web cross section. Based on AISI Section C3.1.1, Procedure I, (Initiation of Yielding) x Factor of Safety equal to 1.67.

Table 2: Ranges of Parameters and Aspect Ratios

	min.	max.
h(in.)	2.05	11.54
t(in.)	0.032	0.098
Fy(ksi)	36	93
N(in.)	3.00	6.00
Alpha	0.00	1.50
a(in.)	0.75	1.50
b(in.)	4.00	4.00
a/h	0.130	0.732
h/t	39.0	168.0
R/t	1.594	4.883
Mn(ksi)	7.58	179.74

Note: a, b, and a/h for solid web test specimens is equal to zero.

Table 3: Test Results

											REDUCTION FACTORS	
SPECIMEN NO.	L(in.)	N(in.)	ALPHA	FAILURE MODE	(Pn) test, per web (lbs.)	(PSW)app.	(Pn)test adj, per web (lbs) (Eq.2)	(PSW)A adj	Mt (K-in.)	Mt/ (Mn)comp	Sivakumaran & Zielonka (Eq.1)	Current study (Eq.8)
IOF-SU-1-1-1	44.00	3.0	SOLID	CRIPPLING	5785	97.6	5785	97.6	59.30	0.330	1.000	1.000
IOF-SU-1-1-2	44.00	3.0	SOLID	CRIPPLING	6075	102.4	6075	102.4	62.27	0.346	1.000	1.000
IOF-SU-1-2-1	44.00	3.0	0.00	CRIPPLING	6100	102.9	8100	102.9	62.53	0.348	0.985	0.929
IOF-SU-1-2-2	44.00	3.0	0.00	CRIPPLING	6000	101.2	6000	101.2	61.50	0.342	0.985	0.929
IOF-SU-2-1-1	17.00	3.0	SOLID	CRIPPLING	925	101.3	997	101.9	3.24	0.427	1.000	1.000
IOF-SU-2-1-2	17.00	3.0	SOLID	CRIPPLING	900	98.6	959	98.0	3.15	0.415	1.000	1.000
IOF-SU-2-2-1	17.00	3.0	0.00	CRIPPLING	825	90.4	849	86.9	2.89	0.381	0.872	0.868
IOF-SU-2-2-2	17.00	3.0	0.00	CRIPPLING	838	91.8	868	88.7	2.93	0.387	0.872	0.868
IOF-SU-2-3-1	28.80	3.0	0.00	CRIPPLING	588	64.4	684	69.9	3.79	0.500	0.872	0.868
IOF-SU-2-3-2	28.80	3.0	0.00	CRIPPLING	575	63.0	661	67.6	3.71	0.489	0.872	0.868
IOF-SU-2-4-1	20.00	3.0	0.50	CRIPPLING	800	87.6	881	90.1	3.40	0.448	0.872	0.899
IOF-SU-2-4-2	20.00	3.0	0.50	CRIPPLING	813	89.0	902	92.2	3.46	0.456	0.872	0.899
IOF-SU-2-5-1	22.00	3.0	1.00	CRIPPLING	813	89.0	955	97.7	3.86	0.509	0.872	0.931
IOF-SU-2-5-2	22.00	3.0	1.00	CRIPPLING	813	89.0	955	97.7	3.86	0.509	0.872	0.931
IOF-SU-2-6-1	24.00	3.0	1.50	CRIPPLING	788	86.3	964	98.6	4.14	0.546	0.872	0.962
IOF-SU-2-6-2	24.00	3.0	1.50	CRIPPLING	800	87.6	988	101.1	4.20	0.554	0.872	0.962
IOF-SU-2-7-1	17.00	4.0	SOLID	CRIPPLING	1050	99.3	1201	99.1	3.68	0.485	1.000	1.000
IOF-SU-2-7-2	17.00	4.0	SOLID	CRIPPLING	1063	100.6	1224	100.9	3.72	0.491	1.000	1.000
IOF-SU-2-8-1	18.00	4.0	0.00	SHEAR	950							
IOF-SU-2-8-2	18.00	4.0	0.00	SHEAR	950							
IOF-SU-2-9-1	18.50	6.0	SOLID	CRIPPLING	1338	101.9	1945	103.6	5.18	0.684	1.000	1.000
IOF-SU-2-9-2	18.50	6.0	SOLID	CRIPPLING	1288	98.1	1809	96.4	4.99	0.658	1.000	1.000
IOF-SU-2-10-1	20.00	6.0	0.00	SHEAR	1038							
IOF-SU-2-10-2	20.00	6.0	0.00	SHEAR	1050							
IOF-SU-3-1-1	17.00	3.0	SOLID	CRIPPLING	1975	101.3	2168	101.8	6.91	0.445	1.000	1.000
IOF-SU-3-1-2	17.00	3.0	SOLID	CRIPPLING	1925	98.7	2089	98.1	6.74	0.434	1.000	1.000
IOF-SU-3-2-1	17.00	3.0	0.00	CRIPPLING	1775	91.0	1862	87.5	6.21	0.400	0.872	0.868
IOF-SU-3-2-2	17.00	3.0	0.00	CRIPPLING	1763	90.4	1845	86.7	6.17	0.397	0.872	0.868
IOF-SU-3-3-1	28.80	3.0	0.00	CRIPPLING	1063	54.5	1162	54.8	6.86	0.441	0.872	0.868
IOF-SU-3-3-2	28.80	3.0	0.00	CRIPPLING	1050	53.6	1142	53.6	6.77	0.436	0.872	0.868
IOF-SU-3-4-1	20.00	3.0	0.50	CRIPPLING	1788	91.7	2056	96.6	7.60	0.489	0.872	0.899
IOF-SU-3-4-2	20.00	3.0	0.50	CRIPPLING	1788	91.7	2056	96.6	7.60	0.489	0.872	0.899
IOF-SU-3-5-1	22.00	3.0	1.00	CRIPPLING	1588	81.4	1819	85.4	7.54	0.486	0.872	0.931
IOF-SU-3-5-2	22.00	3.0	1.00	CRIPPLING	1575	80.8	1796	84.4	7.48	0.482	0.872	0.931
IOF-SU-3-6-1	24.00	3.0	1.50	CRIPPLING	1638	84.0	2023	95.1	8.60	0.554	0.872	0.962
IOF-SU-3-6-2	24.00	3.0	1.50	CRIPPLING	1588	81.4	1924	90.4	8.34	0.537	0.872	0.962
IOF-SU-3-7-1	17.00	4.0	SOLID	CRIPPLING	2300	100.8	2729	101.3	8.05	0.518	1.000	1.000
IOF-SU-3-7-2	17.00	4.0	SOLID	CRIPPLING	2263	99.2	2661	98.7	7.92	0.510	1.000	1.000
IOF-SU-3-8-1	18.00	4.0	0.00	CRIPPLING	2013	88.2	2306	85.6	7.55	0.486	0.907	0.868
IOF-SU-3-8-2	18.00	4.0	0.00	CRIPPLING	1975	86.5	2241	83.1	7.41	0.477	0.907	0.868
IOF-SU-3-9-1	18.50	6.0	SOLID	CRIPPLING	2763	100.0	4046	100.0	10.71	0.689	1.000	1.000
IOF-SU-3-9-2	18.50	6.0	SOLID	CRIPPLING	2763	100.0	4046	100.0	10.71	0.689	1.000	1.000
IOF-SU-3-10-1	20.00	6.0	0.00	SHEAR	2075							
IOF-SU-3-10-2	20.00	6.0	0.00	SHEAR	2063							

Table 3: Test Results

SPECIMEN NO.	L(in.)	N(in.)	ALPHA	FAILURE MODE	(Pn) test, per web (lbs.)	(PSW)app.	(Pn)test adj, per web (lbs) (Eq.2)	(PSW)A adj	Mt (K-in.)	Mt/ (Mn)comp	REDUCTION FACTORS Sivakumaran & Zielonka (Eq.1)	Current study (Eq.8)
IOF-SU-1-1-1	44.00	3.0	SOLID	CRIPPLING	5785	97.6	5785	97.6	59.30	0.330	1.000	1.000
IOF-SU-1-1-2	44.00	3.0	SOLID	CRIPPLING	6075	102.4	6075	102.4	62.27	0.346	1.000	1.000
IOF-SU-1-2-1	44.00	3.0	0.00	CRIPPLING	6100	102.9	6100	102.9	62.53	0.348	0.985	0.929
IOF-SU-1-2-2	44.00	3.0	0.00	CRIPPLING	6000	101.2	6000	101.2	61.50	0.342	0.985	0.929
IOF-SU-2-1-1	17.00	3.0	SOLID	CRIPPLING	925	101.3	997	101.9	3.24	0.427	1.000	1.000
IOF-SU-2-1-2	17.00	3.0	SOLID	CRIPPLING	900	98.6	959	98.0	3.15	0.415	1.000	1.000
IOF-SU-2-2-1	17.00	3.0	0.00	CRIPPLING	825	90.4	849	86.9	2.89	0.381	0.872	0.868
IOF-SU-2-2-2	17.00	3.0	0.00	CRIPPLING	838	91.8	868	88.7	2.93	0.367	0.872	0.868
IOF-SU-2-3-1	28.80	3.0	0.00	CRIPPLING	588	64.4	684	69.9	3.79	0.500	0.872	0.868
IOF-SU-2-3-2	28.80	3.0	0.00	CRIPPLING	575	63.0	661	67.6	3.71	0.489	0.872	0.868
IOF-SU-2-4-1	20.00	3.0	0.50	CRIPPLING	800	87.6	881	90.1	3.40	0.448	0.872	0.899
IOF-SU-2-4-2	20.00	3.0	0.50	CRIPPLING	813	89.0	902	92.2	3.46	0.456	0.872	0.899
IOF-SU-2-5-1	22.00	3.0	1.00	CRIPPLING	813	89.0	955	97.7	3.86	0.509	0.872	0.931
IOF-SU-2-5-2	22.00	3.0	1.00	CRIPPLING	813	89.0	955	97.7	3.86	0.509	0.872	0.931
IOF-SU-2-6-1	24.00	3.0	1.50	CRIPPLING	788	86.3	964	98.6	4.14	0.546	0.872	0.962
IOF-SU-2-6-2	24.00	3.0	1.50	CRIPPLING	800	87.6	988	101.1	4.20	0.554	0.872	0.962
IOF-SU-2-7-1	17.00	4.0	SOLID	CRIPPLING	1050	99.3	1201	99.1	3.68	0.485	1.000	1.000
IOF-SU-2-7-2	17.00	4.0	SOLID	CRIPPLING	1063	100.6	1224	100.9	3.72	0.491	1.000	1.000
IOF-SU-2-8-1	18.00	4.0	0.00	SHEAR	950							
IOF-SU-2-8-2	18.00	4.0	0.00	SHEAR	950							
IOF-SU-2-9-1	18.50	6.0	SOLID	CRIPPLING	1338	101.9	1945	103.6	5.18	0.684	1.000	1.000
IOF-SU-2-9-2	18.50	6.0	SOLID	CRIPPLING	1288	98.1	1809	96.4	4.99	0.658	1.000	1.000
IOF-SU-2-10-1	20.00	6.0	0.00	SHEAR	1038							
IOF-SU-2-10-2	20.00	6.0	0.00	SHEAR	1050							
IOF-SU-3-1-1	17.00	3.0	SOLID	CRIPPLING	1975	101.3	2168	101.8	6.91	0.445	1.000	1.000
IOF-SU-3-1-2	17.00	3.0	SOLID	CRIPPLING	1925	98.7	2089	98.1	6.74	0.434	1.000	1.000
IOF-SU-3-2-1	17.00	3.0	0.00	CRIPPLING	1775	91.0	1862	87.5	6.21	0.400	0.872	0.868
IOF-SU-3-2-2	17.00	3.0	0.00	CRIPPLING	1763	90.4	1845	86.7	6.17	0.397	0.872	0.868
IOF-SU-3-3-1	28.80	3.0	0.00	CRIPPLING	1063	54.5	1162	54.6	6.86	0.441	0.872	0.868
IOF-SU-3-3-2	28.80	3.0	0.00	CRIPPLING	1050	53.8	1142	53.6	6.77	0.436	0.872	0.868
IOF-SU-3-4-1	20.00	3.0	0.50	CRIPPLING	1788	91.7	2056	96.6	7.60	0.489	0.872	0.899
IOF-SU-3-4-2	20.00	3.0	0.50	CRIPPLING	1788	91.7	2056	96.6	7.60	0.489	0.872	0.899
IOF-SU-3-5-1	22.00	3.0	1.00	CRIPPLING	1588	81.4	1819	85.4	7.54	0.486	0.872	0.931
IOF-SU-3-5-2	22.00	3.0	1.00	CRIPPLING	1575	80.8	1796	84.4	7.48	0.482	0.872	0.931
IOF-SU-3-6-1	24.00	3.0	1.50	CRIPPLING	1638	84.0	2023	95.1	8.60	0.554	0.872	0.962
IOF-SU-3-6-2	24.00	3.0	1.50	CRIPPLING	1588	81.4	1924	90.4	8.34	0.537	0.872	0.962
IOF-SU-3-7-1	17.00	4.0	SOLID	CRIPPLING	2300	100.8	2729	101.3	8.05	0.518	1.000	1.000
IOF-SU-3-7-2	17.00	4.0	SOLID	CRIPPLING	2263	99.2	2661	98.7	7.92	0.510	1.000	1.000
IOF-SU-3-8-1	18.00	4.0	0.00	CRIPPLING	2013	88.2	2306	85.6	7.55	0.486	0.907	0.868
IOF-SU-3-8-2	18.00	4.0	0.00	CRIPPLING	1975	86.5	2241	83.1	7.41	0.477	0.907	0.868
IOF-SU-3-9-1	18.50	6.0	SOLID	CRIPPLING	2763	100.0	4046	100.0	10.71	0.689	1.000	1.000
IOF-SU-3-9-2	18.50	6.0	SOLID	CRIPPLING	2763	100.0	4046	100.0	10.71	0.689	1.000	1.000
IOF-SU-3-10-1	20.00	6.0	0.00	SHEAR	2075							
IOF-SU-3-10-2	20.00	6.0	0.00	SHEAR	2063							

Table 3: Test Results (cont.)

											REDUCTION FACTORS	
SPECIMEN NO.	L(in.)	N(in.)	ALPHA	FAILURE MODE	(Pn) test, per web (lbs.)	(PSW)app.	(Pn)test adj, per web (lbs) (Eq.2)	(PSW)A adj	Mt (K-in.)	Mt/ (Mn)comp	Sivakumaran & Zielonka (Eq.1)	Current study (Eq.8)
IOF-SU-4-1-1	16.00	3.0	SOLID	CRIPPLING	1150	102.2	1218	103.1	3.74	0.410	1.000	1.000
IOF-SU-4-1-2	16.00	3.0	SOLID	CRIPPLING	1100	97.8	1145	96.9	3.58	0.392	1.000	1.000
IOF-SU-4-2-1	17.00	3.0	0.00	SHEAR	750							
IOF-SU-4-2-2	17.00	3.0	0.00	SHEAR	750							
IOF-SU-4-3-1	19.00	6.0	SOLID	CRIPPLING	1550	100.8	2241	101.5	6.20	0.680	1.000	1.000
IOF-SU-4-3-2	19.00	6.0	SOLID	CRIPPLING	1525	99.2	2173	98.4	6.10	0.669	1.000	1.000
IOF-SU-4-4-1	20.00	6.0	0.00	SHEAR	850							
IOF-SU-4-4-2	20.00	6.0	0.00	SHEAR	825							
IOF-SU-5-1-1	18.69	3.0	SOLID	CRIPPLING	925	100.0	925	100.0	3.63	0.258	1.000	1.000
IOF-SU-5-1-2	18.69	3.0	SOLID	CRIPPLING	925	100.0	925	100.0	3.63	0.258	1.000	1.000
IOF-SU-5-2-1	18.69	3.0	0.00	CRIPPLING	838	90.6	836	90.6	3.29	0.234	0.871	0.838
IOF-SU-5-2-2	18.69	3.0	0.00	CRIPPLING	625	89.2	625	89.2	3.24	0.230	0.871	0.838
IOF-SU-5-3-1	28.80	3.0	0.00	CRIPPLING	675	73.0	675	73.0	4.35	0.310	0.822	0.838
IOF-SU-5-3-2	28.80	3.0	0.00	CRIPPLING	675	73.0	675	73.0	4.35	0.310	0.822	0.838
IOF-SU-5-4-1	21.00	3.0	0.50	CRIPPLING	838	90.6	838	90.6	3.77	0.268	0.871	0.869
IOF-SU-5-4-2	21.00	3.0	0.50	CRIPPLING	863	93.3	863	93.3	3.88	0.276	0.871	0.869
IOF-SU-5-5-1	22.00	3.0	0.70	CRIPPLING	838	90.6	838	90.6	3.98	0.283	0.871	0.882
IOF-SU-5-5-2	22.00	3.0	0.70	CRIPPLING	863	93.3	863	93.3	4.10	0.292	0.871	0.882
IOF-SU-5-6-1	24.00	3.0	1.00	CRIPPLING	813	87.9	813	87.9	4.27	0.304	0.871	0.901
IOF-SU-5-6-2	24.00	3.0	1.00	CRIPPLING	788	85.2	788	85.2	4.14	0.294	0.871	0.901
IOF-SU-5-7-1	27.00	3.0	1.50	CRIPPLING	688	74.4	688	74.4	4.13	0.294	0.871	0.932
IOF-SU-5-7-2	27.00	3.0	1.50	CRIPPLING	738	79.8	738	79.8	4.43	0.315	0.871	0.932
IOF-SU-5-6-1	20.00	4.0	SOLID	CRIPPLING	963	99.4	963	99.4	4.09	0.291	1.000	1.000
IOF-SU-5-8-2	20.00	4.0	SOLID	CRIPPLING	975	100.6	975	100.6	4.14	0.295	1.000	1.000
IOF-SU-5-9-1	20.00	4.0	0.00	CRIPPLING	863	89.1	863	89.1	3.67	0.261	0.898	0.838
IOF-SU-5-9-2	20.00	4.0	0.00	CRIPPLING	888	91.6	888	91.6	3.77	0.268	0.898	0.838
IOF-SU-5-10-1	25.00	4.0	0.00	CRIPPLING	850	87.7	850	87.7	4.68	0.332	0.898	0.838
IOF-SU-5-10-2	25.00	4.0	0.00	CRIPPLING	825	85.1	825	85.1	4.54	0.323	0.898	0.838
IOF-SU-5-11-1	21.69	6.0	SOLID	CRIPPLING	1125	98.9	1151	98.4	5.26	0.374	1.000	1.000
IOF-SU-5-11-2	21.69	6.0	SOLID	CRIPPLING	1150	101.1	1186	101.4	5.37	0.382	1.000	1.000
IOF-SU-5-12-1	22.00	6.0	0.00	CRIPPLING	1100	96.7	1123	96.0	5.23	0.372	0.907	0.838
IOF-SU-5-12-2	22.00	6.0	0.00	CRIPPLING	1075	94.5	1088	93.1	5.11	0.363	0.907	0.838

Table 3: Test Results (cont.)

SPECIMEN NO.	L(in.)	N(in.)	ALPHA	FAILURE MODE	(Pn) test, per web (lbs.)	(PSW)app.	(Pn)test adj, per web (lbs) (Eq.2)	(PSW)A adj	Mt (K-in.)	Mt/ (Mn)comp	REDUCTION FACTORS	
											Sivakumaran & Zielonka (Eq.1)	Current study (Eq.8)
IOF-SU-6-1-1	18.78	3.0	SOLID	CRIPPLING	1438	102.6	1438	102.6	5.67	0.302	1.000	1.000
IOF-SU-6-1-2	18.78	3.0	SOLID	CRIPPLING	1363	97.3	1363	97.3	5.38	0.287	1.000	1.000
IOF-SU-6-2-1	18.78	3.0	0.00	CRIPPLING	1188	84.8	1188	84.8	4.69	0.250	0.872	0.839
IOF-SU-6-2-2	18.78	3.0	0.00	CRIPPLING	1200	85.7	1200	85.7	4.73	0.252	0.872	0.839
IOF-SU-6-3-1	25.00	3.0	0.00	CRIPPLING	1150	82.1	1150	82.1	6.33	0.337	0.872	0.839
IOF-SU-6-3-2	25.00	3.0	0.00	CRIPPLING	1138	81.2	1138	81.2	6.26	0.334	0.872	0.839
IOF-SU-6-4-1	28.80	3.0	0.00	CRIPPLING	988	70.5	988	70.5	6.37	0.340	0.872	0.839
IOF-SU-6-4-2	28.80	3.0	0.00	CRIPPLING	988	70.5	988	70.5	6.37	0.340	0.872	0.839
IOF-SU-6-5-1	21.00	3.0	0.50	CRIPPLING	1225	87.4	1225	87.4	5.51	0.294	0.872	0.870
IOF-SU-6-5-2	21.00	3.0	0.50	CRIPPLING	1205	86.0	1205	86.0	5.42	0.289	0.872	0.870
IOF-SU-6-6-1	25.00	3.0	0.50	CRIPPLING	1188	84.8	1188	84.8	6.53	0.348	0.872	0.870
IOF-SU-6-6-2	25.00	3.0	0.50	CRIPPLING	1163	83.0	1163	83.0	6.40	0.341	0.872	0.870
IOF-SU-6-7-1	22.00	3.0	0.70	CRIPPLING	1250	89.2	1250	89.2	5.94	0.317	0.872	0.883
IOF-SU-6-7-2	22.00	3.0	0.70	CRIPPLING	1238	88.4	1238	88.4	5.88	0.314	0.872	0.883
IOF-SU-6-8-1	25.00	3.0	0.70	CRIPPLING	1188	84.8	1188	84.8	6.53	0.348	0.872	0.883
IOF-SU-6-8-2	25.00	3.0	0.70	CRIPPLING	1138	81.2	1138	81.2	6.26	0.334	0.872	0.883
IOF-SU-6-9-1	24.00	3.0	1.00	CRIPPLING	1225	87.4	1225	87.4	6.43	0.343	0.872	0.902
IOF-SU-6-9-2	24.00	3.0	1.00	CRIPPLING	1250	89.2	1250	89.2	6.56	0.350	0.872	0.902
IOF-SU-6-10-1	27.00	3.0	1.50	CRIPPLING	1213	86.6	1258	89.8	7.28	0.388	0.872	0.933
IOF-SU-6-10-2	27.00	3.0	1.50	CRIPPLING	1238	88.4	1294	92.3	7.43	0.396	0.872	0.933
IOF-SU-6-11-1	20.00	4.0	SOLID	CRIPPLING	1375	100.4	1375	100.4	5.84	0.312	1.000	1.000
IOF-SU-6-11-2	20.00	4.0	SOLID	CRIPPLING	1363	99.6	1363	99.6	5.79	0.309	1.000	1.000
IOF-SU-6-12-1	20.00	4.0	0.00	CRIPPLING	1338	97.7	1338	97.7	5.69	0.303	0.900	0.839
IOF-SU-6-12-2	20.00	4.0	0.00	CRIPPLING	1313	95.9	1313	95.9	5.58	0.298	0.900	0.839
IOF-SU-6-13-1	25.00	4.0	0.00	CRIPPLING	1238	90.4	1253	91.5	6.81	0.363	0.900	0.839
IOF-SU-6-13-2	25.00	4.0	0.00	CRIPPLING	1250	91.3	1270	92.7	6.88	0.367	0.900	0.839
IOF-SU-6-14-1	21.78	6.0	SOLID	CRIPPLING	1725	101.5	1868	102.1	8.10	0.432	1.000	1.000
IOF-SU-6-14-2	21.78	6.0	SOLID	CRIPPLING	1675	98.5	1791	97.9	7.86	0.419	1.000	1.000
IOF-SU-6-15-1	22.00	6.0	0.00	CRIPPLING	1638	96.4	1744	95.3	7.78	0.415	0.926	0.839
IOF-SU-6-15-2	22.00	6.0	0.00	CRIPPLING	1600	94.1	1687	92.2	7.60	0.405	0.926	0.839
IOF-SU-7-1-1	18.76	3.0	SOLID	CRIPPLING	1888	N/A	1888	N/A	7.44	0.348	1.000	1.000
IOF-SU-7-1-2	18.76	3.0	SOLID	CRIPPLING	1938	N/A	1952	N/A	7.64	0.357	1.000	1.000
IOF-SU-7-2-1	20.00	3.0	SOLID	CRIPPLING	1913	N/A	1969	N/A	8.13	0.381	1.000	1.000
IOF-SU-7-2-2	20.00	3.0	SOLID	CRIPPLING	1875	N/A	1916	N/A	7.97	0.373	1.000	1.000
IOF-SU-7-3-1	22.00	3.0	SOLID	CRIPPLING	1875	N/A	2000	N/A	8.91	0.417	1.000	1.000
IOF-SU-7-3-2	22.00	3.0	SOLID	CRIPPLING	1800	N/A	1889	N/A	8.55	0.400	1.000	1.000
IOF-SU-7-4-1	24.00	3.0	SOLID	CRIPPLING	2175	N/A	2628	N/A	11.42	0.535	1.000	1.000
IOF-SU-7-4-2	24.00	3.0	SOLID	CRIPPLING	2175	N/A	2628	N/A	11.42	0.535	1.000	1.000
IOF-SU-7-5-1	26.00	3.0	SOLID	CRIPPLING	2100	N/A	2629	N/A	12.08	0.565	1.000	1.000
IOF-SU-7-5-2	26.00	3.0	SOLID	CRIPPLING	2138	N/A	2709	N/A	12.29	0.576	1.000	1.000

Table 3: Test Results (cont.)

											REDUCTION FACTORS	
SPECIMEN NO.	L(in.)	N(in.)	ALPHA	FAILURE MODE	(Pn) test, per web (lbs.)	(PSW)app.	(Pn)test adj, per web (lbs) (Eq.2)	(PSW)A adj	Mt (K-in.)	Mt/ (Mn)comp	Sivakumaran & Zielonka (Eq.1)	Current study (Eq.8)
IOF-SU-8-1-1	18.66	3.0	SOLID	CRIPPLING	2950	98.7	3124	98.2	11.55	0.409	1.000	1.000
IOF-SU-8-1-2	18.66	3.0	SOLID	CRIPPLING	3025	101.2	3236	101.8	11.84	0.420	1.000	1.000
IOF-SU-8-2-1	18.66	3.0	0.00	CRIPPLING	2675	89.5	2729	85.8	10.47	0.371	0.870	0.837
IOF-SU-8-2-2	18.66	3.0	0.00	CRIPPLING	2688	90.0	2747	86.4	10.52	0.373	0.870	0.837
IOF-SU-8-3-1	28.80	3.0	0.00	CRIPPLING	1988	66.5	2203	69.3	12.82	0.455	0.870	0.837
IOF-SU-8-3-2	28.80	3.0	0.00	CRIPPLING	1950	65.3	2142	67.4	12.58	0.446	0.870	0.837
IOF-SU-8-4-1	21.00	3.0	0.50	CRIPPLING	2813	94.1	3099	97.5	12.66	0.449	0.870	0.869
IOF-SU-8-4-2	21.00	3.0	0.50	CRIPPLING	2775	92.9	3038	95.5	12.49	0.443	0.870	0.869
IOF-SU-8-5-1	22.00	3.0	0.70	CRIPPLING	2788	93.3	3139	98.7	13.24	0.470	0.870	0.881
IOF-SU-8-5-2	22.00	3.0	0.70	CRIPPLING	2738	91.6	3055	96.1	13.01	0.461	0.870	0.881
IOF-SU-8-6-1	24.00	3.0	1.00	CRIPPLING	2713	90.8	3172	99.6	14.24	0.505	0.870	0.900
IOF-SU-8-6-2	24.00	3.0	1.00	CRIPPLING	2738	91.6	3218	101.2	14.37	0.510	0.870	0.900
IOF-SU-8-7-1	27.00	3.0	1.50	CRIPPLING	2650	88.7	3311	104.1	15.90	0.564	0.870	0.932
IOF-SU-8-7-2	27.00	3.0	1.50	CRIPPLING	2600	87.0	3209	100.9	15.60	0.553	0.670	0.932
IOF-SU-8-8-1	21.66	6.0	SOLID	CRIPPLING	3613	99.3	4700	98.8	16.85	0.598	1.000	1.000
IOF-SU-8-8-2	21.66	6.0	SOLID	CRIPPLING	3663	100.7	4814	101.2	17.09	0.606	1.000	1.000
IOF-SU-8-9-1	22.00	6.0	0.00	CRIPPLING	3213	88.3	3911	82.2	15.26	0.541	0.925	0.837
IOF-SU-8-9-2	22.00	6.0	0.00	CRIPPLING	3150	86.6	3789	79.7	14.96	0.530	0.925	0.837
IOF-SU-9-1-1	25.62	3.0	SOLID	CRIPPLING	1800	101.8	1800	101.8	10.18	0.328	1.000	1.000
IOF-SU-9-1-2	25.62	3.0	SOLID	CRIPPLING	1738	98.2	1738	98.2	9.83	0.317	1.000	1.000
IOF-SU-9-2-1	25.62	3.0	0.00	CRIPPLING	1675	94.7	1675	94.7	9.47	0.305	0.945	0.890
IOF-SU-9-2-2	25.62	3.0	0.00	CRIPPLING	1638	92.6	1638	92.6	9.26	0.299	0.945	0.890
IOF-SU-9-3-1	25.62	3.0	0.50	CRIPPLING	1625	91.9	1625	91.9	9.19	0.296	0.945	0.922
IOF-SU-9-3-2	25.62	3.0	0.50	CRIPPLING	1613	91.2	1613	91.2	9.12	0.294	0.945	0.922
IOF-SU-9-4-1	28.40	3.0	1.00	CRIPPLING	1650	93.3	1650	93.3	10.48	0.338	0.945	0.953
IOF-SU-9-4-2	28.40	3.0	1.00	CRIPPLING	1613	91.2	1613	91.2	10.24	0.330	0.945	0.953
IOF-SU-10-1-1	31.62	3.0	SOLID	CRIPPLING	2263	98.9	2263	98.9	16.19	0.278	1.000	1.000
IOF-SU-10-1-2	31.62	3.0	SOLID	CRIPPLING	2313	101.1	2313	101.1	16.55	0.285	1.000	1.000
IOF-SU-10-2-1	31.62	3.0	0.00	CRIPPLING	2238	97.8	2238	97.8	16.01	0.275	0.968	0.910
IOF-SU-10-2-2	31.62	3.0	0.00	CRIPPLING	2175	95.1	2175	95.1	15.56	0.268	0.968	0.910
IOF-SU-10-3-1	31.62	3.0	0.50	CRIPPLING	2263	98.9	2263	98.9	16.19	0.278	0.968	0.941
IOF-SU-10-3-2	31.62	3.0	0.50	CRIPPLING	2163	94.5	2163	94.5	15.48	0.266	0.968	0.941

Notes:

1. The end-of-span bearing lengths for all specimens is equal to three inches.
2. Cross section designations:
   IOF: Interior-One-Flange (loading)
   SU: Single Unreinforced (web)

Table 4: Analysis of Test Results

	NOMINAL CAPACITY ((Pn)comp,per web ((lbs.)			(Pn)test adj./(Pn)comp			
		AISI Eq.C3.4-4 REDUCED			AISI Eq.C3.4-4 REDUCED		
SPECIMEN NO.	AISI Eq.C3.4-4 (Eq.10) x SF of 1.85	Sivakumaran & Zielonka (Eq.1)	Current Study (Eq.8)	AISI Eq.C3.4-4 (Eq.10) x SF of 1.85	Sivakumaran & Zielonka (Eq.1)	Current Study (Eq.8)	INTERACTION EQUATION VALUE (Eq.6)
IOF-SU-1-1-1	5425	5425	5425	1.066	1.066	1.066	1.471
IOF-SU-1-1-2	5425	5425	5425	1.120	1.120	1.120	1.545
IOF-SU-1-2-1	5425	5342	5038	1.124	1.142	1.211	1.643
IOF-SU-1-2-2	5425	5342	5038	1.106	1.123	1.191	1.617
IOF-SU-2-1-1	974	974	974	1.024	1.024	1.024	1.444
IOF-SU-2-1-2	974	974	974	0.985	0.985	0.985	1.405
IOF-SU-2-2-1	974	849	845	0.872	1.001	1.005	1.426
IOF-SU-2-2-2	974	849	845	0.891	1.023	1.027	1.448
IOF-SU-2-3-1	974	849	845	0.703	0.806	0.810	1.245
IOF-SU-2-3-2	974	849	845	0.679	0.779	0.782	1.217
IOF-SU-2-4-1	974	849	876	0.905	1.038	1.006	1.426
IOF-SU-2-4-2	974	849	876	0.927	1.063	1.030	1.449
IOF-SU-2-5-1	974	849	906	0.981	1.126	1.054	1.469
IOF-SU-2-5-2	974	849	906	0.981	1.126	1.054	1.469
IOF-SU-2-6-1	974	849	937	0.990	1.136	1.029	1.445
IOF-SU-2-6-2	974	849	937	1.015	1.165	1.055	1.467
IOF-SU-2-7-1	1162	1162	1162	1.034	1.034	1.034	1.452
IOF-SU-2-7-2	1162	1162	1162	1.054	1.054	1.054	1.470
IOF-SU-2-8-1	SHEAR FAILURE						
IOF-SU-2-8-2	SHEAR FAILURE						
IOF-SU-2-9-1	1537	1537	1537	1.265	1.265	1.265	1.615
IOF-SU-2-9-2	1537	1537	1537	1.177	1.177	1.177	1.555
IOF-SU-2-10-1	SHEAR FAILURE						
IOF-SU-2-10-2	SHEAR FAILURE						
IOF-SU-3-1-1	2696	2696	2696	0.804	0.804	0.804	1.229
IOF-SU-3-1-2	2696	2696	2696	0.775	0.775	0.775	1.198
IOF-SU-3-2-1	2696	2350	2340	0.691	0.792	0.796	1.212
IOF-SU-3-2-2	2696	2350	2340	0.684	0.785	0.788	1.204
IOF-SU-3-3-1	2696	2350	2340	0.431	0.495	0.497	0.928
IOF-SU-3-3-2	2696	2350	2340	0.424	0.486	0.488	0.916
IOF-SU-3-4-1	2696	2350	2425	0.762	0.875	0.848	1.278
IOF-SU-3-4-2	2696	2350	2425	0.762	0.875	0.848	1.278
IOF-SU-3-5-1	2696	2350	2510	0.675	0.774	0.725	1.163
IOF-SU-3-5-2	2696	2350	2510	0.666	0.764	0.716	1.153
IOF-SU-3-6-1	2696	2350	2595	0.750	0.861	0.780	1.229
IOF-SU-3-6-2	2696	2350	2595	0.714	0.819	0.741	1.192
IOF-SU-3-7-1	3024	3024	3024	0.902	0.902	0.902	1.332
IOF-SU-3-7-2	3024	3024	3024	0.880	0.880	0.880	1.311
IOF-SU-3-8-1	3024	2742	2624	0.763	0.841	0.879	1.307
IOF-SU-3-8-2	3024	2742	2624	0.741	0.817	0.854	1.282
IOF-SU-3-9-1	3805	3805	3805	1.064	1.064	1.064	1.466
IOF-SU-3-9-2	3805	3805	3805	1.064	1.064	1.064	1.466
IOF-SU-3-10-1	SHEAR FAILURE						
IOF-SU-3-10-2	SHEAR FAILURE						

Table 4: Analysis of Test Results (cont.)

	NOMINAL CAPACITY ((Pn)comp,per web ((lbs.)			(Pn)test adj./(Pn)comp			
		AISI Eq.C3.4-4 REDUCED			AISI Eq.C3.4-4 REDUCED		
SPECIMEN NO.	AISI Eq.C3.4-4 (Eq.10) x SF of 1.85	Sivakumaran & Zielonka (Eq.1)	Current Study (Eq.8)	AISI Eq.C3.4-4 (Eq.10) x SF of 1.85	Sivakumaran & Zielonka (Eq.1)	Current Study (Eq.8)	INTERACTION EQUATION VALUE (Eq.6)
IOF-SU-4-1-1	1143	1143	1143	1.066	1.066	1.066	1.486
IOF-SU-4-1-2	1143	1143	1143	1.002	1.002	1.002	1.422
IOF-SU-4-2-1	SHEAR FAILURE						
IOF-SU-4-2-2	SHEAR FAILURE						
IOF-SU-4-3-1	1796	1796	1796	1.248	1.248	1.248	1.603
IOF-SU-4-3-2	1796	1796	1796	1.210	1.210	1.210	1.577
IOF-SU-4-4-1	SHEAR FAILURE						
IOF-SU-4-4-2	SHEAR FAILURE						
IOF-SU-5-1-1	1018	1018	1018	0.908	0.908	0.908	1.230
IOF-SU-5-1-2	1018	1018	1018	0.908	0.908	0.908	1.230
IOF-SU-5-2-1	1018	886	853	0.823	0.945	0.982	1.285
IOF-SU-5-2-2	1018	886	853	0.810	0.931	0.967	1.265
IOF-SU-5-3-1	1018	837	853	0.663	0.807	0.791	1.156
IOF-SU-5-3-2	1018	837	853	0.663	0.807	0.791	1.156
IOF-SU-5-4-1	1018	886	885	0.823	0.945	0.947	1.281
IOF-SU-5-4-2	1018	886	885	0.848	0.974	0.975	1.319
IOF-SU-5-5-1	1018	886	898	0.823	0.945	0.933	1.282
IOF-SU-5-5-2	1018	886	898	0.848	0.974	0.961	1.320
IOF-SU-5-6-1	1018	886	917	0.798	0.917	0.886	1.252
IOF-SU-5-6-2	1018	886	917	0.774	0.889	0.859	1.213
IOF-SU-5-7-1	1018	886	949	0.676	0.776	0.725	1.069
IOF-SU-5-7-2	1018	886	949	0.725	0.833	0.777	1.147
IOF-SU-5-8-1	1212	1212	1212	0.794	0.794	0.794	1.141
IOF-SU-5-8-2	1212	1212	1212	0.804	0.804	0.804	1.155
IOF-SU-5-9-1	1212	1089	1015	0.712	0.793	0.850	1.170
IOF-SU-5-9-2	1212	1089	1015	0.733	0.816	0.874	1.204
IOF-SU-5-10-1	1212	1089	1015	0.701	0.781	0.837	1.228
IOF-SU-5-10-2	1212	1089	1015	0.681	0.758	0.812	1.192
IOF-SU-5-11-1	1600	1600	1600	0.719	0.719	0.719	1.126
IOF-SU-5-11-2	1600	1600	1600	0.741	0.741	0.741	1.151
IOF-SU-5-12-1	1600	1451	1340	0.702	0.774	0.838	1.250
IOF-SU-5-12-2	1600	1451	1340	0.680	0.750	0.812	1.221

Table 4: Analysis of Test Results (cont.)

	NOMINAL CAPACITY ((Pn)comp,per web ((lbs.)			(Pn)test adj./(Pn)comp			
		AISI Eq.C3.4-4 REDUCED			AISI Eq.C3.4-4 REDUCED		
SPECIMEN NO.	AISI Eq.C3.4-4 (Eq.10) x SF of 1.85	Sivakumaran & Zielonka (Eq.1)	Current Study (Eq.8)	AISI Eq.C3.4-4 (Eq.10) x SF of 1.85	Sivakumaran & Zielonka (Eq.1)	Current Study (Eq.8)	INTERACTION EQUATION VALUE (Eq.6)
IOF-SU-6-1-1	1726	1726	1726	0.833	0.833	0.833	1.194
IOF-SU-6-1-2	1726	1726	1726	0.790	0.790	0.790	1.132
IOF-SU-6-2-1	1726	1506	1448	0.688	0.789	0.820	1.128
IOF-SU-6-2-2	1726	1506	1448	0.695	0.797	0.829	1.139
IOF-SU-6-3-1	1726	1506	1448	0.666	0.764	0.794	1.187
IOF-SU-6-3-2	1726	1506	1448	0.659	0.756	0.786	1.175
IOF-SU-6-4-1	1726	1506	1448	0.572	0.656	0.682	1.070
IOF-SU-6-4-2	1726	1506	1448	0.572	0.656	0.682	1.070
IOF-SU-6-5-1	1726	1506	1502	0.710	0.814	0.815	1.166
IOF-SU-6-5-2	1726	1506	1502	0.698	0.800	0.802	1.147
IOF-SU-6-6-1	1726	1506	1502	0.688	0.789	0.791	1.195
IOF-SU-6-6-2	1726	1506	1502	0.674	0.772	0.774	1.169
IOF-SU-6-7-1	1726	1506	1524	0.724	0.830	0.820	1.194
IOF-SU-6-7-2	1726	1506	1524	0.717	0.822	0.812	1.183
IOF-SU-6-8-1	1726	1506	1524	0.688	0.789	0.779	1.182
IOF-SU-6-8-2	1726	1506	1524	0.659	0.756	0.747	1.133
IOF-SU-6-9-1	1726	1506	1557	0.710	0.814	0.787	1.185
IOF-SU-6-9-2	1726	1506	1557	0.724	0.830	0.803	1.209
IOF-SU-6-10-1	1726	1506	1611	0.729	0.835	0.781	1.194
IOF-SU-6-10-2	1726	1506	1611	0.750	0.859	0.803	1.218
IOF-SU-6-11-1	2011	2011	2011	0.684	0.684	0.684	1.043
IOF-SU-6-11-2	2011	2011	2011	0.678	0.678	0.678	1.034
IOF-SU-6-12-1	2011	1809	1687	0.666	0.740	0.793	1.152
IOF-SU-6-12-2	2011	1809	1687	0.653	0.726	0.779	1.131
IOF-SU-6-13-1	2011	1809	1687	0.623	0.693	0.743	1.149
IOF-SU-6-13-2	2011	1809	1687	0.632	0.702	0.753	1.160
IOF-SU-6-14-1	2579	2579	2579	0.724	0.724	0.724	1.147
IOF-SU-6-14-2	2579	2579	2579	0.694	0.694	0.694	1.114
IOF-SU-6-15-1	2579	2388	2164	0.676	0.730	0.806	1.225
IOF-SU-6-15-2	2579	2388	2164	0.654	0.706	0.780	1.196
IOF-SU-7-1-1	1817	1817	1817	1.039	1.039	1.039	1.460
IOF-SU-7-1-2	1817	1817	1817	1.074	1.074	1.074	1.499
IOF-SU-7-2-1	1817	1817	1817	1.084	1.084	1.084	1.507
IOF-SU-7-2-2	1817	1817	1817	1.055	1.055	1.055	1.477
IOF-SU-7-3-1	1817	1817	1817	1.101	1.101	1.101	1.521
IOF-SU-7-3-2	1817	1817	1817	1.040	1.040	1.040	1.460
IOF-SU-7-4-1	1817	1817	1817	1.447	1.447	1.447	1.815
IOF-SU-7-4-2	1817	1817	1817	1.447	1.447	1.447	1.815
IOF-SU-7-5-1	1817	1817	1817	1.447	1.447	1.447	1.802
IOF-SU-7-5-2	1817	1817	1817	1.491	1.491	1.491	1.835

Table 4: Analysis of Test Results (cont.)

SPECIMEN NO.	NOMINAL CAPACITY ((Pn)comp,per web ((lbs.)			(Pn)test adj./(Pn)comp			INTERACTION EQUATION VALUE
	AISI Eq.C3.4-4 (Eq.10) x SF of 1.85	AISI Eq.C3.4-4 REDUCED		AISI Eq.C3.4-4 (Eq.10) x SF of 1.85	AISI Eq.C3.4-4 REDUCED		
		Sivakumaran & Zielonka (Eq.1)	Current Study (Eq.8)		Sivakumaran & Zielonka (Eq.1)	Current Study (Eq.8)	(Eq.6)
IOF-SU-8-1-1	3571	3571	3571	0.875	0.875	0.875	1.293
IOF-SU-8-1-2	3571	3571	3571	0.906	0.906	0.906	1.326
IOF-SU-8-2-1	3571	3106	2990	0.764	0.879	0.913	1.329
IOF-SU-8-2-2	3571	3106	2990	0.769	0.884	0.919	1.335
IOF-SU-8-3-1	3571	3106	2990	0.617	0.709	0.737	1.166
IOF-SU-8-3-2	3571	3106	2990	0.600	0.690	0.716	1.144
IOF-SU-8-4-1	3571	3106	3102	0.868	0.998	0.999	1.419
IOF-SU-8-4-2	3571	3106	3102	0.851	0.978	0.979	1.400
IOF-SU-8-5-1	3571	3106	3147	0.879	1.010	0.997	1.417
IOF-SU-8-5-2	3571	3106	3147	0.856	0.984	0.971	1.392
IOF-SU-8-6-1	3571	3106	3215	0.889	1.021	0.987	1.408
IOF-SU-8-6-2	3571	3106	3215	0.901	1.036	1.001	1.421
IOF-SU-8-7-1	3571	3106	3328	0.927	1.066	0.995	1.416
IOF-SU-8-7-2	3571	3106	3328	0.899	1.033	0.964	1.389
IOF-SU-8-8-1	4717	4717	4717	0.997	0.997	0.997	1.417
IOF-SU-8-8-2	4717	4717	4717	1.021	1.021	1.021	1.437
IOF-SU-8-9-1	4717	4361	3949	0.829	0.897	0.990	1.412
IOF-SU-8-9-2	4717	4361	3949	0.803	0.869	0.959	1.384
IOF-SU-9-1-1	1036	1036	1036	1.738	1.738	1.738	2.188
IOF-SU-9-1-2	1036	1036	1036	1.678	1.678	1.678	2.112
IOF-SU-9-2-1	1036	979	922	1.617	1.711	1.816	2.249
IOF-SU-9-2-2	1036	979	922	1.582	1.673	1.776	2.199
IOF-SU-9-3-1	1036	979	955	1.569	1.660	1.702	2.117
IOF-SU-9-3-2	1036	979	955	1.557	1.648	1.689	2.102
IOF-SU-9-4-1	1036	979	988	1.593	1.686	1.671	2.126
IOF-SU-9-4-2	1036	979	988	1.557	1.648	1.633	2.078
IOF-SU-10-1-1	1711	1711	1711	1.322	1.322	1.322	1.693
IOF-SU-10-1-2	1711	1711	1711	1.351	1.351	1.351	1.731
IOF-SU-10-2-1	1711	1656	1557	1.308	1.352	1.437	1.813
IOF-SU-10-2-2	1711	1656	1557	1.271	1.314	1.397	1.762
IOF-SU-10-3-1	1711	1656	1611	1.322	1.367	1.405	1.781
IOF-SU-10-3-2	1711	1656	1611	1.264	1.306	1.342	1.703

Statistics: all tests			n = 138
Average	0.907	0.972	0.976
Standard Deviation	0.275	0.261	0.265
Coefficient of Variation	0.303	0.268	0.272
PHI	0.569	0.652	0.650
(F.S.)asd	2.696	2.351	2.359

AVERAGE
1.373
STANDARD DEVIATION
0.270
COEFFICIENT of VARIATION
0.197
AVERAGE/1.42
0.967

Table 4: Analysis of Test Results (cont.)

	(Pn)test adj./(Pn)comp		
		AISI Eq.C3.4-4 REDUCED	
	AISI Eq.C3.4-4 (Eq.10) x SF of 1.85	Sivakumaran & Zielonka (Eq.1)	Current Study (Eq.8)
Statistics: all tests, Fy less than 70 ksi			n = 124
Average	0.842	0.908	0.909
Standard Deviation	0.200	0.181	0.175
Coefficient of Variation	0.237	0.199	0.193
PHI	0.598	0.688	0.696
(F.S.)asd	2.564	2.228	2.204
Statistics: Solid webs, Fy less than 70 ksi			n = 44
Average	1.001	1.001	1.001
Standard Deviation	0.210	0.210	0.210
Coefficient of Variation	0.210	0.210	0.210
PHI	0.741	0.741	0.741
(F.S.)asd	2.070	2.070	2.070

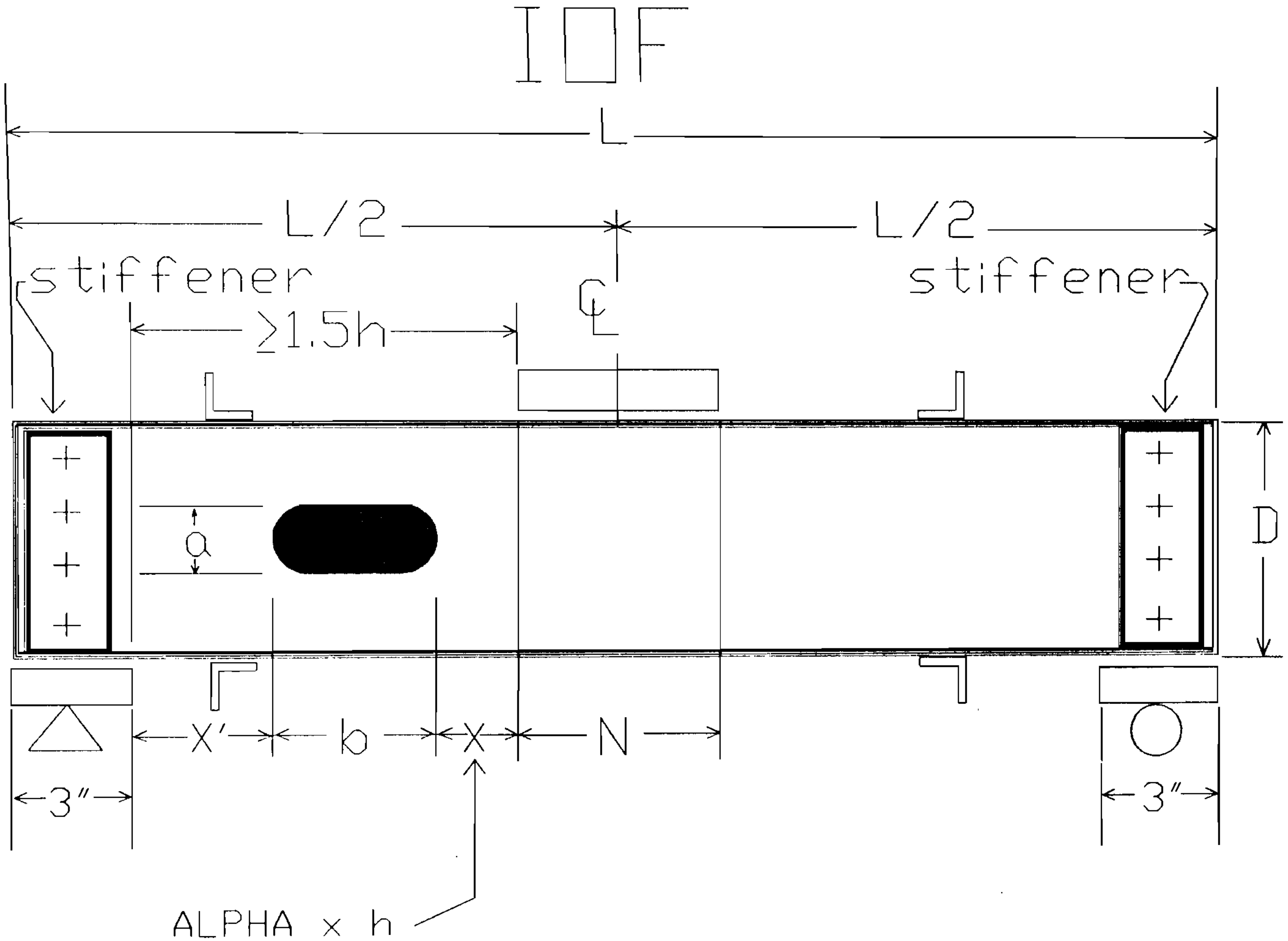


FIGURE 1: SPECIMEN PARAMETERS LONGITUDINAL VIEW

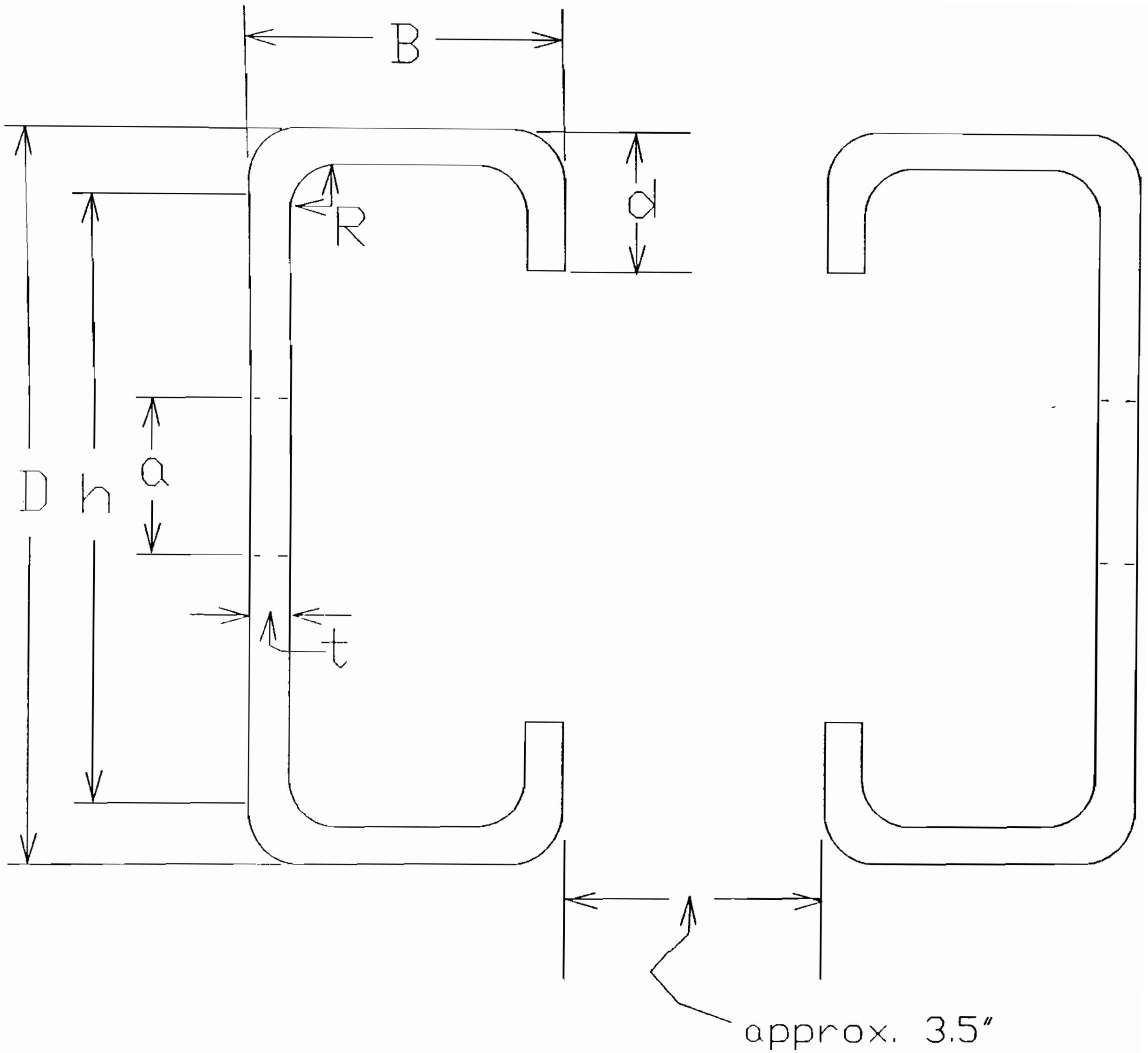


FIGURE 2: SPECIMEN PARAMETERS
END VIEW

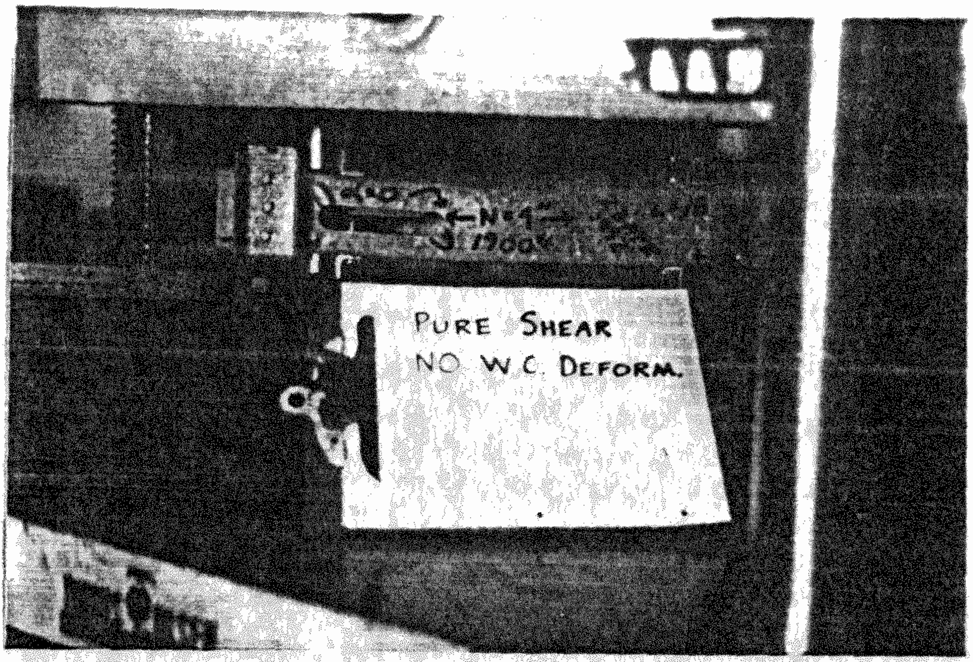


FIGURE 3a: Specimen IOF-SU-2-8-1

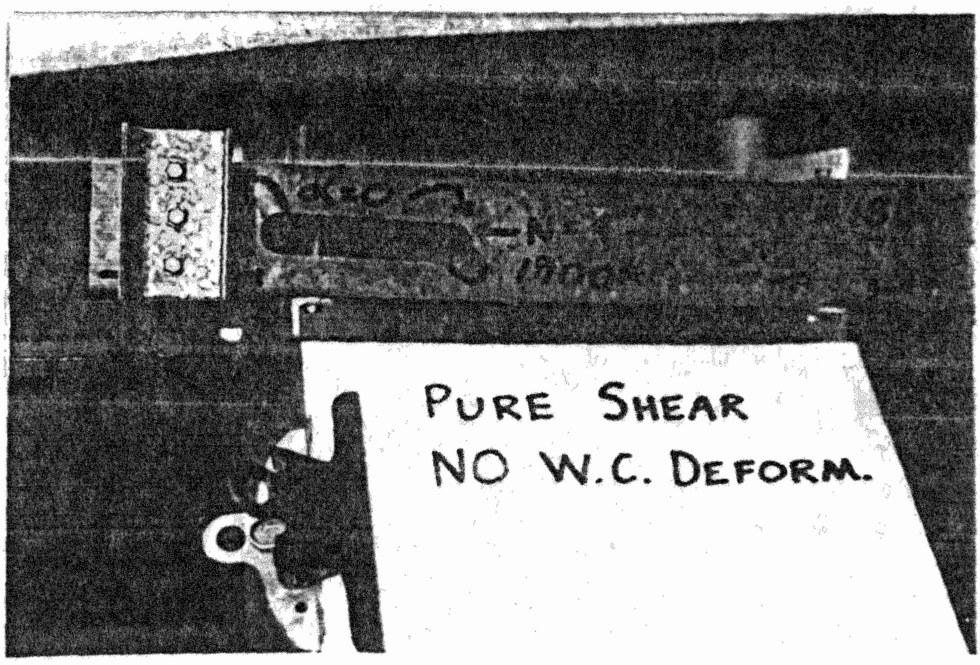


FIGURE 3b: Specimen IOF-SU-2-8-1

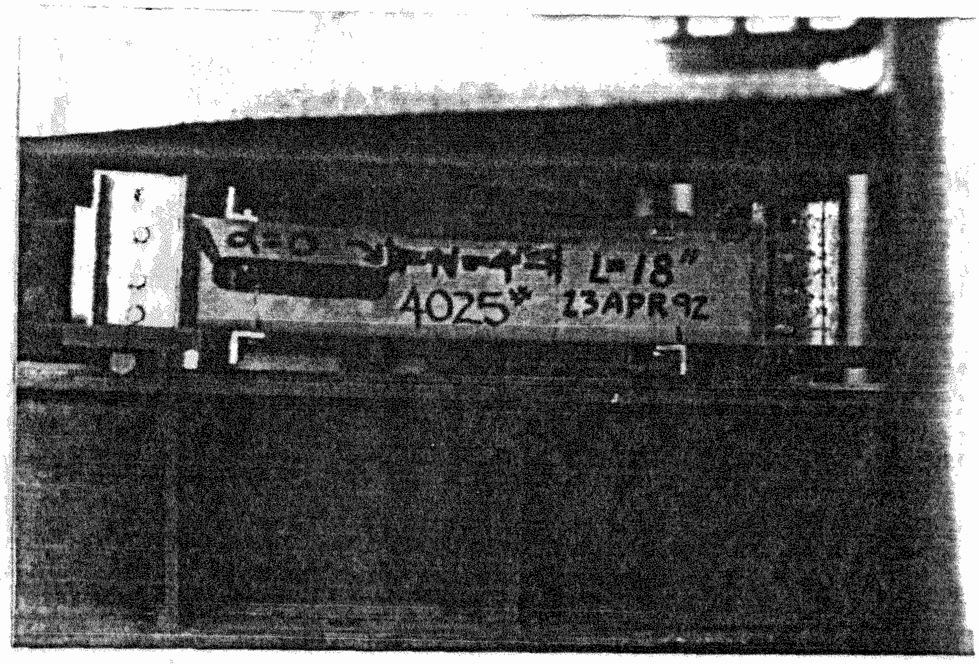


FIGURE 3c: Specimen IOF-SU-3-8-1

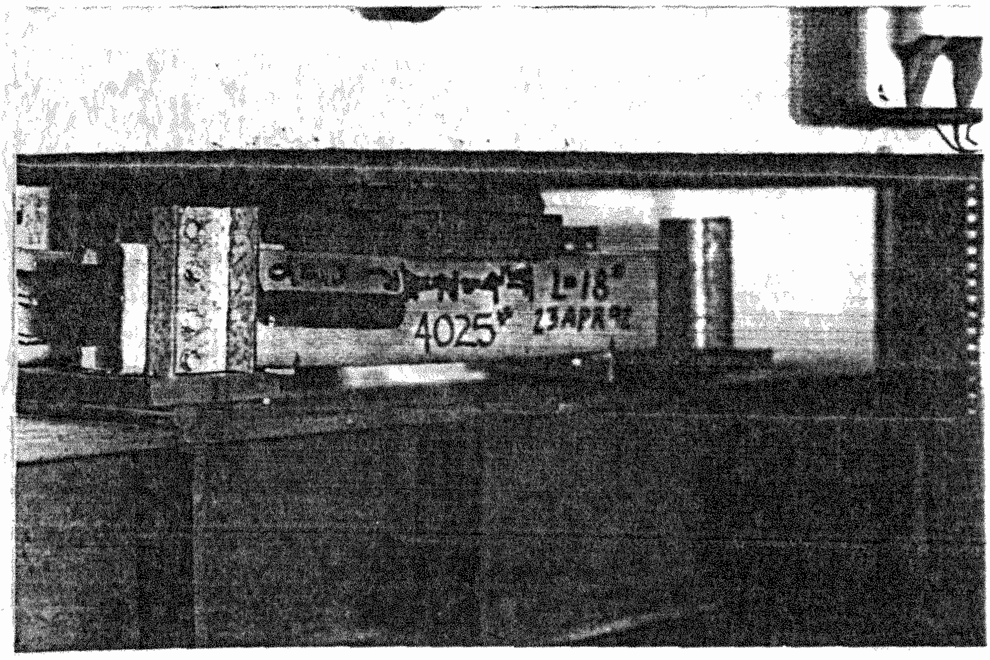


FIGURE 3d: Specimen IOF-SU-3-8-1

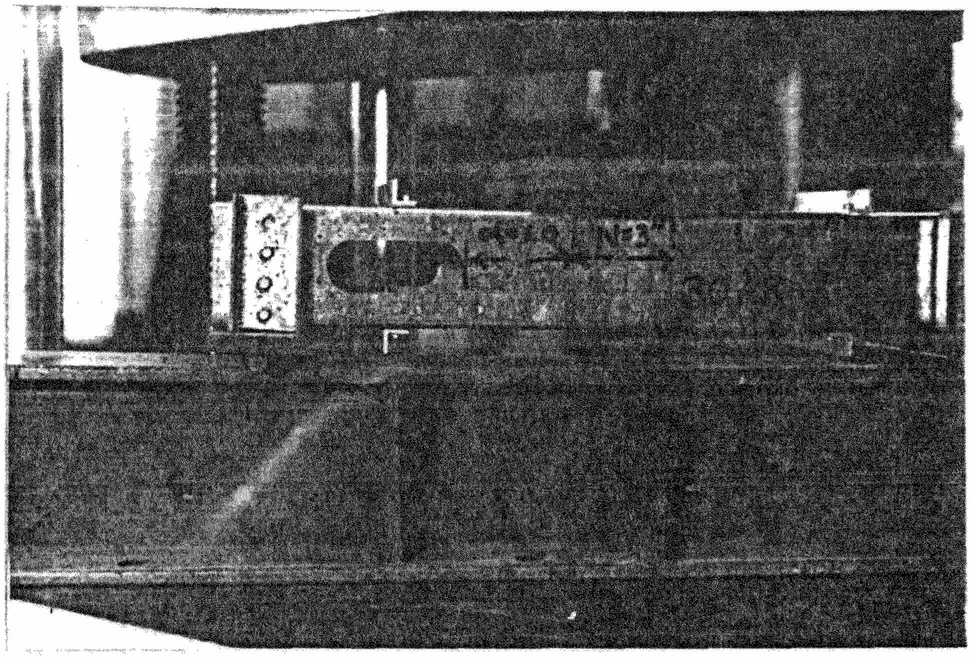


FIGURE 3e: Specimen IOF-SU-5-6-1

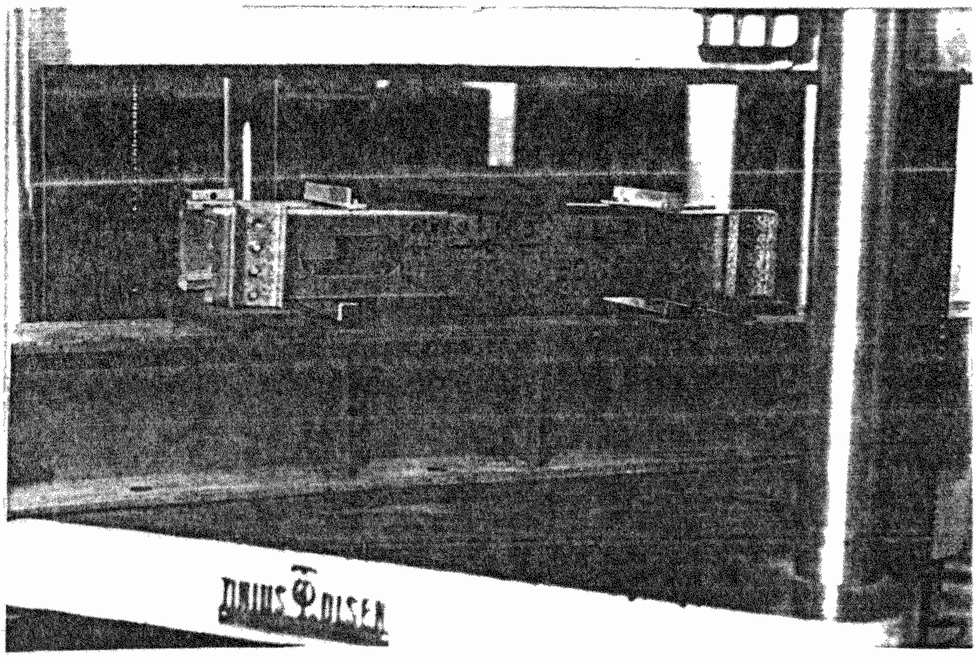


FIGURE 3f: Specimen IOF-SU-5-6-1

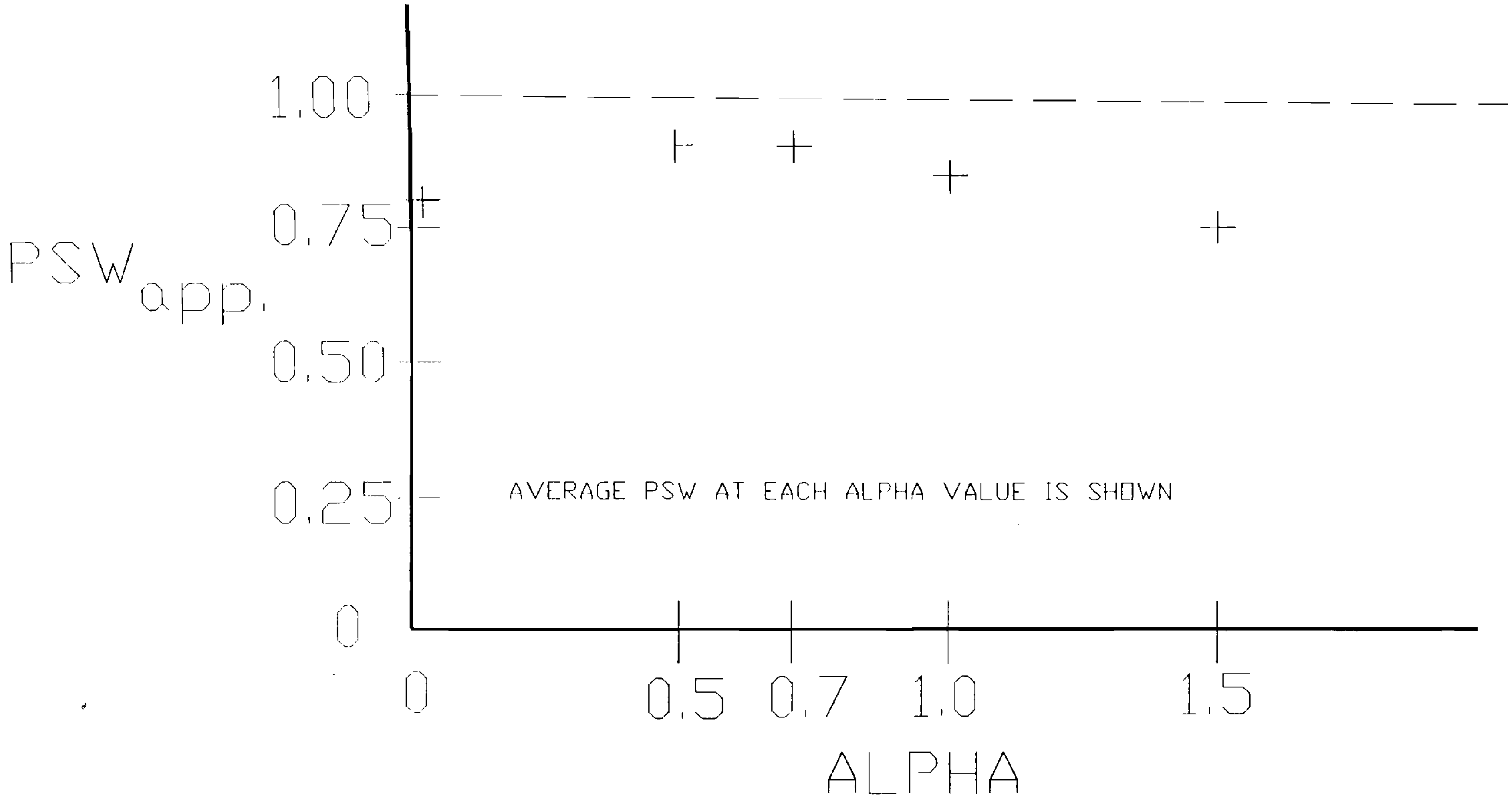


FIGURE 4: ALPHA vs. PSW(apparent) FOR CROSS SECTION
IOF-SU-5 at N = 3 inches

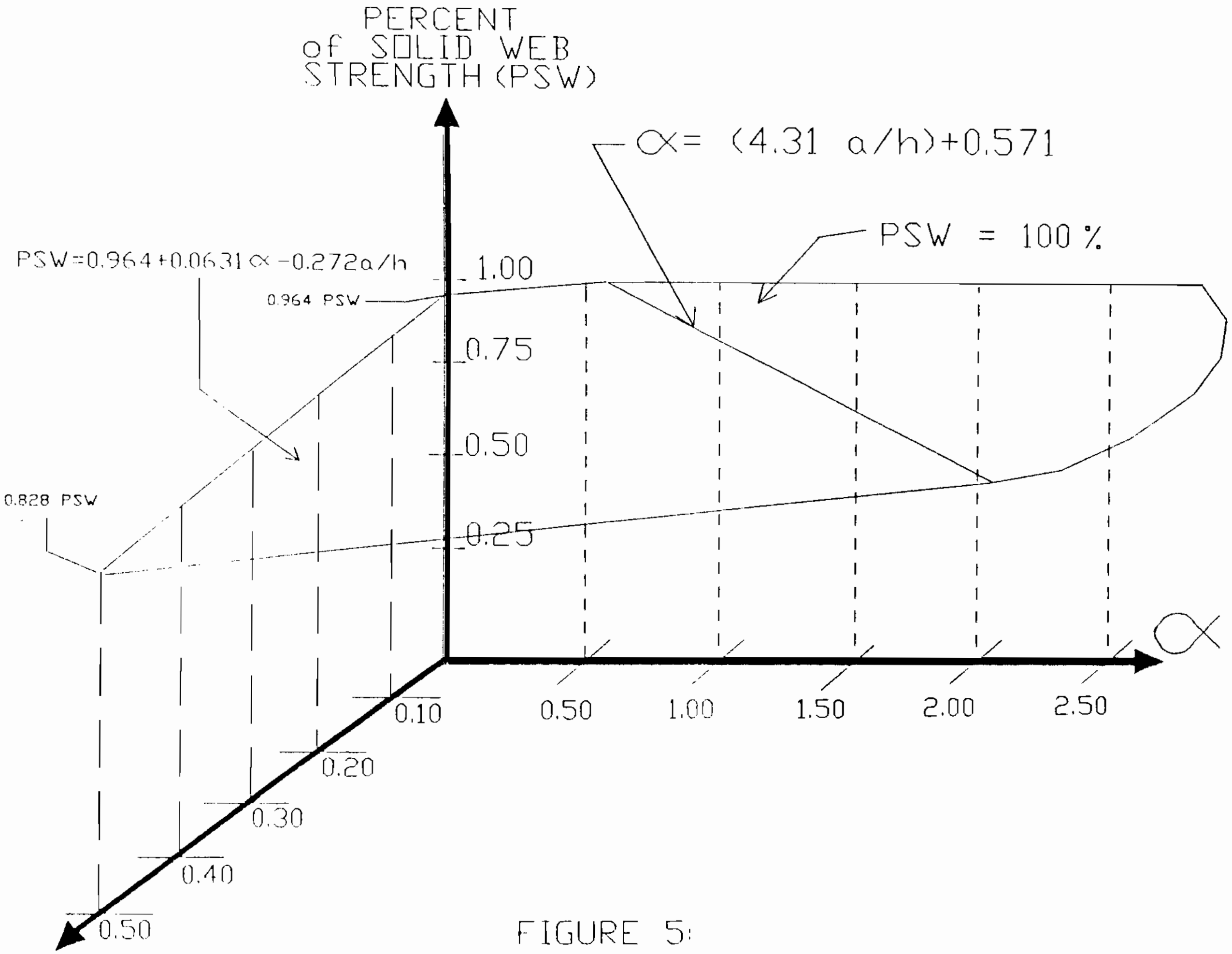
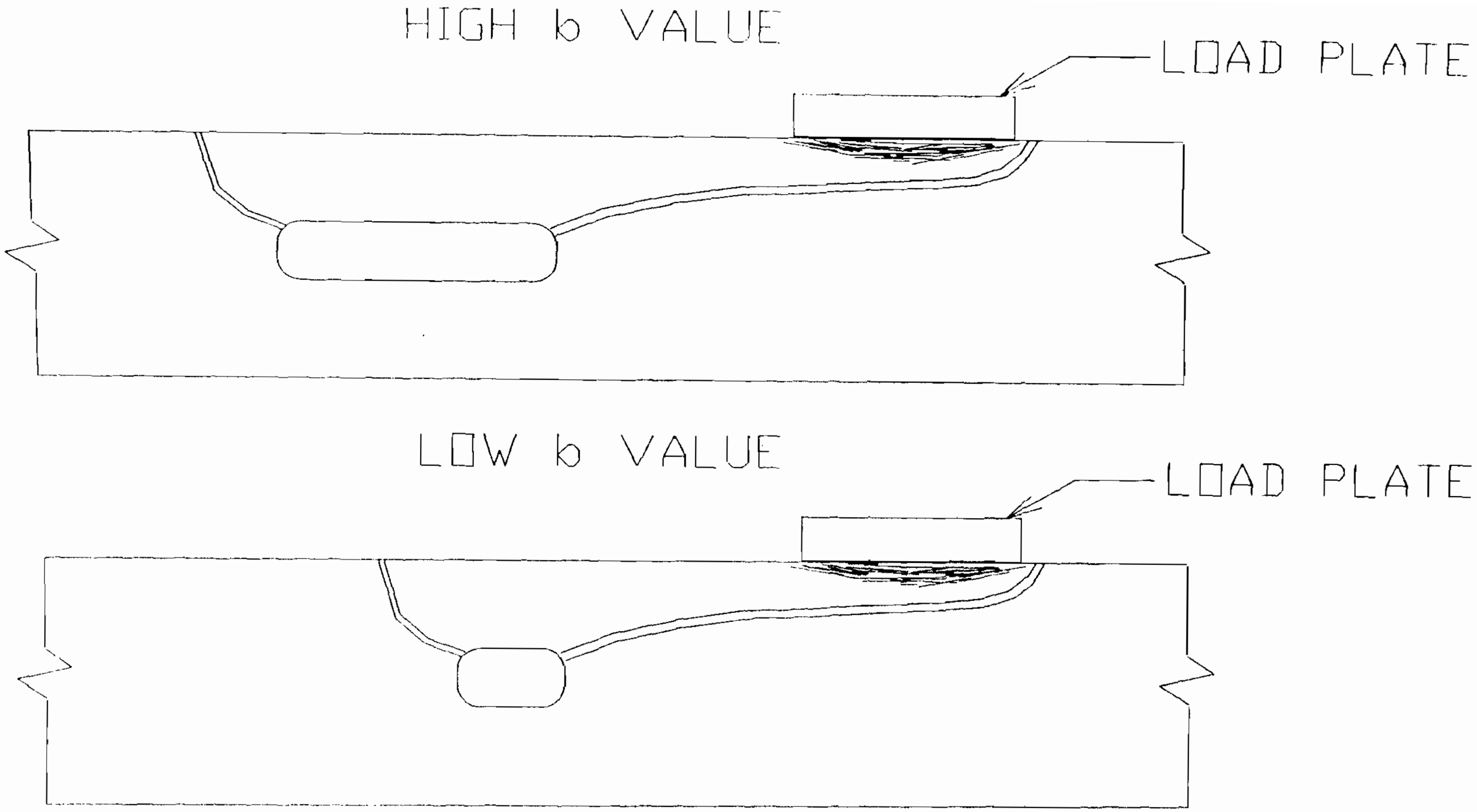


FIGURE 5:
THREE DIMENSIONAL PLOT OF
STRENGTH REDUCTION FACTOR



Key: The shaded area is the region of crushing of the flange and top region of the web.
The thin double lines are the path of severe out of plane deformation of the web.

ALL PARAMETERS EXCEPT b ARE CONSTANT

FIGURE 6: EFFECT OF b PARAMETER

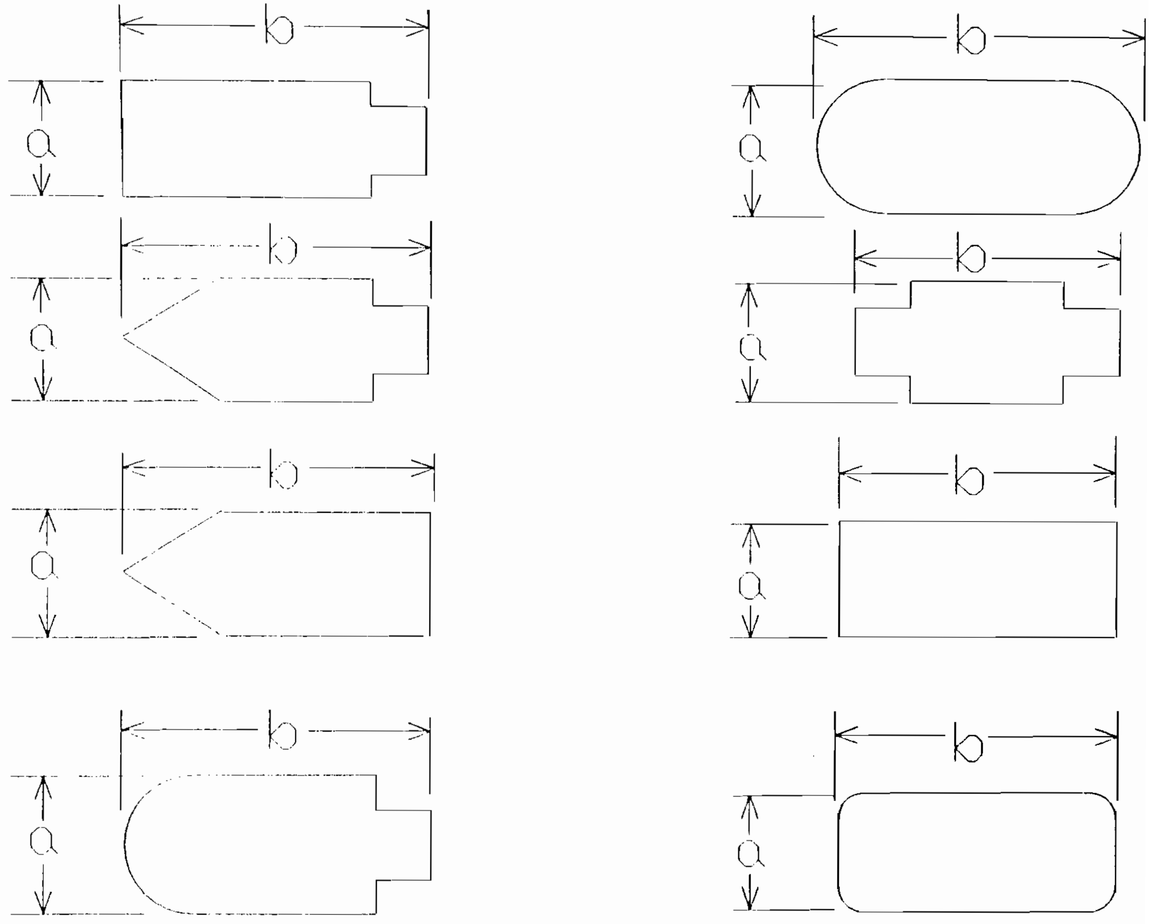


FIGURE 7: a and b DEFINITIONS
FOR INDUSTRY STANDARD WEB OPENINGS

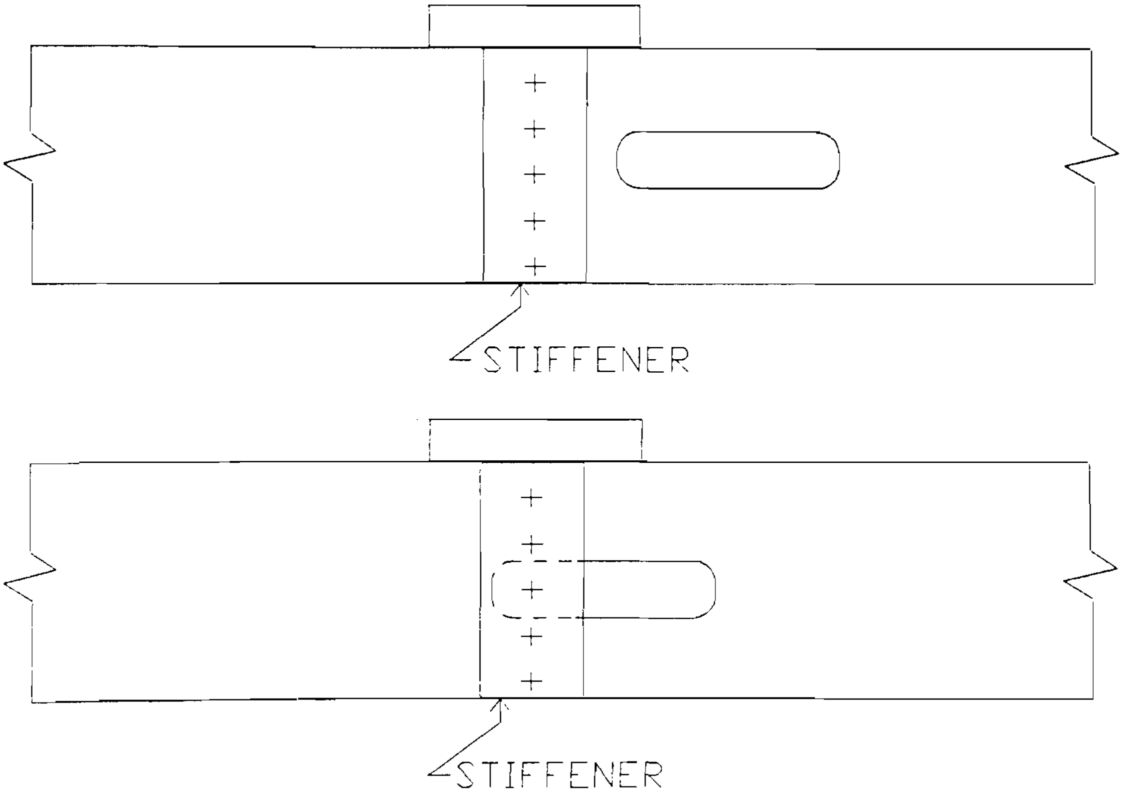


FIGURE 8: WEB OPENING AND STIFFENER LOCATIONS FOR FUTURE WORK

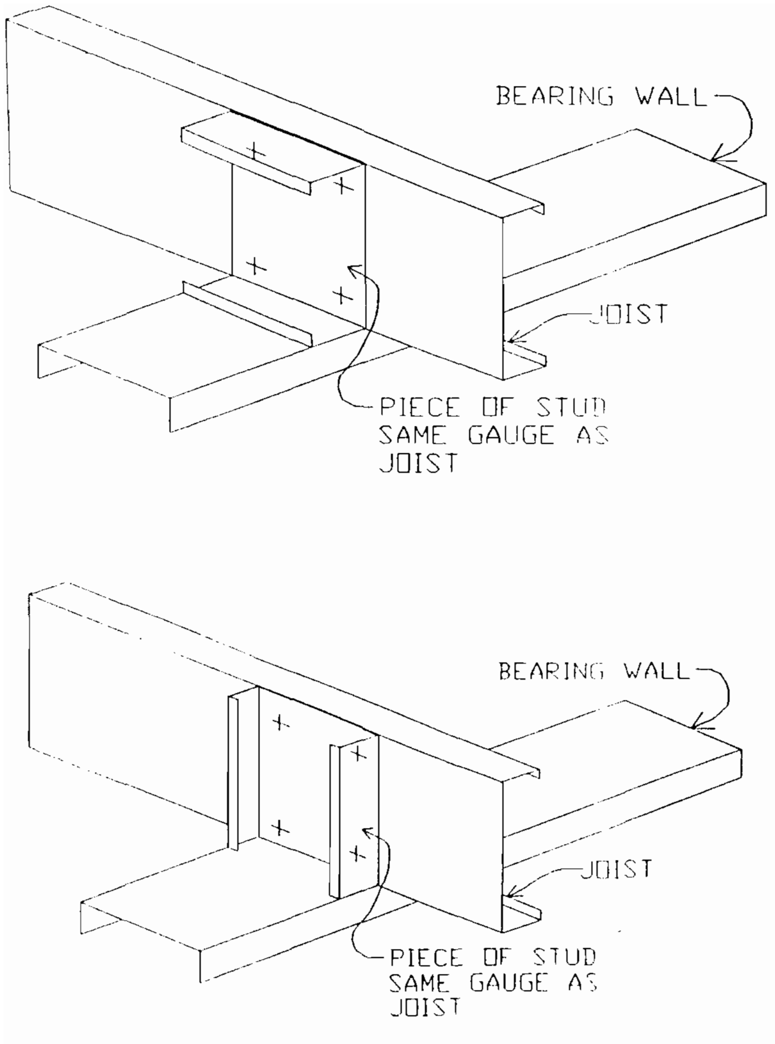


FIGURE 9: STIFFENER TYPES FOR FUTURE WORK