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Effect of flange restraint on web crippling strength

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

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

Bhavnesh H. Bhakta

First and Second Progress Reports

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B. Bhakta
R.A. LaBoube
W.W. Yu

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

First Progress Report

EFFECT OF FLANGE RESTRAINT ON WEB CRIPPLING STRENGTH
by B. Bhakta, R. A. LaBoube and W. W. Yu
March 12, 1991

Introduction

The web crippling limit states equations given in the AISI Specification were primarily developed based on the results in which the flange was not attached to the support beams. This may not accurately represent field practice, since flanges are typically fastened by bolts or welds to their support beam. Due to these fasteners, the Specification equations may be underestimating the web crippling strength of the member. Therefore, a pilot study was proposed to study the behavior of webs, and the load carrying capacity of the webs with restrained flanges.

Test Program

The test program includes the study of the following types of sections (see Figures 1 through 5):

- Channels
- I-Sections
- Z-Sections
- Floor Decks
- Long Span Roof Decks

During the period from 12/15/90 to 3/5/91, a total of thirty-six web crippling tests have been conducted. The single web members tested were channels and unlapped Z-Sections, both were end-one-flange loading (EOF). The double web members tested includes I-Sections (back to back C's) and lapped Z-Sections, both under interior-one-flange loading (IOF). See Figure 6.

Table 1 shows an outline of the types and number of tests that will be performed. Since this is a pilot study to investigate the effect of flange restraint on web crippling strength, the number of tests are limited. Based on the results of this study, recommendations will be made regarding the effect of flange restraint and the merit of further study.

Discussion of Tests and Results

Channels:

A total of twelve channel specimens were tested. Four specimens for each h/t ratio were tested, two tests with the flanges fastened to the supports and two without fasteners. For the fastened test specimens, flanges of the test specimens were fastened to the support beam by a 1/2 inch diameter bolt. The equation used for comparison of P_{test} versus $P_{computed}$ was Equation C3.4-1 from the AISI Specification. The value from the equation was multiplied by 1.85 to take out the factor of safety. These twelve tests were all EOF loading tests. The EOF condition was achieved by adding stiffeners in the center of the test specimens to force the failure to occur at the ends. Test results are given in Table 2 and Table 5.

The first four tests were of h/t ≈ 70. The tested loads (Table 5) were within 20 percent of the computed loads (P_t/P_c). There was an average increase of nine percent in strength in the fastened flanges versus the unfastened flanges.

The next four specimens tested were of h/t ≈ 115 (Table 5). Once again the tested loads were very close to the computed loads. An increase of 14.7 percent was obtained between the fastened flanges and the unfastened.

The last four channels tested were of $h/t \approx 131$ (Table 5). The results on these four tests were unusual, because there exists a fifty-eight percent difference between the computed value and the tested value. Further study is planned in an attempt to find the cause for this unusual difference. However,there was no increase in strength with the fastened flanges and unfastened flanges tests.

I-Sections:

A total of twelve I-Sections were tested. I-Sections are fabricated from two channels connected back to back, a typical field type bolt pattern was used to connect the two channels as shown on Figure 7. Four test specimens were fabricated for each h/t ratio and two of these were with flanges fastened and the remaining two with flanges unfastened. Equation C3.4-5 of the AISI Specification was used for the computed loads. A factor of safety of 2.0 was taken out by multiplying the equation value by 2.0. These four tests were all IOF tests. The IOF load was achieved by adding stiffeners on the ends of the specimen to force the failure in the interior. Test results are given on Table 3 and Table 6.

The first four tests were of $h/t \approx 70$ (Table 6). The tested loads were within twenty percent of the computed loads. There was no increase in strength between fastened flanges and unfastened flanges.

The next four specimens tested were of $h/t \approx 115$ (Table 6). The difference between the tested loads and the computed loads was about 25-30 percent.

The last four tests were of $h/t \approx 131$ (Table 6). Poor correlation between tested loads and computed loads comparison was obtained. In these tests, there was a slight increase in strength, about seven percent, between the fastened flanges and the unfastened flanges.

The poor correlation between the tested and computed web crippling loads may be attributed to the limited number of fasteners attaching the webs together.

Z-Sections:

A total of twelve Z-Section specimens have been tested, eight of these are unlapped sections and four are the lapped sections (four lapped section tests remain to be completed). The unlapped sections will be discussed first, followed by the lapped sections. The unlapped sections were all EOF tests and the lapped sections were all IOF tests. Equation C3.4-1 from the AISI Specification was used for unlapped sections and Equation C3.4-4 was used for the lapped sections, the results of these equations were multiplied by 1.85 to take out the factor of safety. Test results are given in Table 4, Table 7, and Table 8.

<u>Unlapped Sections:</u>

The first four specimens in Table 7 were for an $h/t \approx 132$, two tests were with flanges fastened and two with flanges unfastened. The results of these tests were considerably different from what we have seen from the Channels and the I-Sections. The tested loads for the unfastened flange tests were approximately twenty-four percent higher than the computed loads, the fastened flange tests showed an even higher difference, approximately sixty-five percent higher than the computed load. There was also a 33.9 percent increase in strength between the fastened flanges and the unfastened flanges.

The remaining four specimens were of h/t ≈ 72 (Table 7). There was no difference between the tested and the computed loads for the specimens with the flanges unfastened, however with the flanges fastened the tested loads were 25-30 percent higher than the computed loads. There was an increase of 27.1 percent in strength between the fastened flanges and the unfastened flanges. Thus, there is definitely an increase in strength between the fastened flanges and the unfastened flanges in the EOF tests of Z-Sections.

Lapped Sections:

Only four specimens have been tested for the lapped Z's (Table 8), an identical set of four more test specimens will be tested in the near future. The first two tests were for h/t ≈ 132. The lapped Z-Section results are more comparable to those of the Channels and the I-Sections rather than those of the unlapped Z-sections. The tested loads were within fifteen percent of the computed loads and the there was only an increase of 8.7 percent in strength between the fastened flanges and the unfastened flanges.

For the two test specimens having h/t ≈ 72, the tested loads are within ten percent of the computed loads, and there was only an increase of 6.3 percent in strength between the fastened flanges and the unfastened flanges.

Future Work

There still remains a series of tests for the long span roof decks and the floor decks.

Preliminary Conclusions

Based on the tests conducted to date, the Channels and the I-

Sections saw little increase in strength with the flanges fastened, The Z-Sections saw an average increase of thirty percent in strength with the flanges fastened as compared to unfastened flanges for the EOF loading. The IOF tests on the Z-Sections saw little increase in strength with the flanges fastened.

Table 1
Proposed Test Program

WEB CRIPPLING TESTS

D (in.)	B (in.)	t (in.)	h/t	Number of Tests Without Connections	Number of Tests With Connections	Total
			Z-PURLINS (Figure 1)			
9.50	2.75	0.06	148	2	2	4
9.50	2.75	0.12	73	2	2	4
9.50	2.75	0.06	lapped	2	2	4
9.50	2.75	0.12	section	2	2	4
			CHANNELS (Figure 2)			
9.00	3.50	0.060	140	2	2	4
9.00	3.50	0.120	169	2	2	4
12.00	5.00	0.090	126	2	2	4
			I-SECTIONS (Figure 3)			
9.00	7.00	0.061	140	2	2	4
9.00	7.00	0.120	69	2	2	4
12.00	10.00	0.090	126	2	2	4
			LONG SPAN ROOF DECK (Figure 4)			
4.50	12.00	0.036	123	2	2	4
4.50	12.00	0.060	73	2	2	4
			FLOOR DECK (Figure 5)			
3.00	24.00	0.030	98	2	2	4
3.00	24.00	0.060	48	2	2	4
TOTAL						56

Table 2

Parameters and Test Data of Channels
Used for Web Crippling

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	Fy (ksi)	P(test) (kips)
C1-F	0.109	68.271	1.433	24.083	0.353	56.740	4.575
C2-F	0.109	69.294	1.431	24.083	0.348	56.740	4.706
C3	0.109	68.991	1.431	24.083	0.349	56.740	4.269
C4	0.109	68.775	1.431	24.083	0.350	56.740	4.244
C5-F	0.064	115.914	2.438	41.016	0.354	59.990	1.863
C6-F	0.064	115.984	2.438	41.016	0.354	59.990	1.663
C7	0.064	115.813	2.438	41.016	0.354	59.990	1.525
C8	0.064	115.781	2.438	41.016	0.354	59.990	1.550
C9-F	0.063	131.365	4.960	41.667	0.317	62.680	1.494
C10-F	0.063	131.508	4.960	41.667	0.317	62.680	1.488
C11	0.063	131.254	4.960	41.667	0.317	62.680	1.494
C12	0.063	131.492	4.960	41.667	0.317	62.680	1.513

F - Represents flanges fastened to supports.
N = 2.625 inches.

Table 3

Parameters and Test Data of I-Sections
Used for Web Crippling

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	Fy (ksi)	P(test) (kips)
I1-F	0.109	68.284	1.431	48.165	0.705	56.740	13.200
I2-F	0.109	68.202	1.431	48.165	0.706	56.740	13.600
I3	0.109	68.229	1.431	48.165	0.706	56.740	13.100
I4	0.109	68.284	1.431	48.165	0.705	56.740	13.750
I5-F	0.064	115.953	2.438	82.031	0.707	59.990	4.600
I6-F	0.064	116.375	2.438	82.031	0.705	59.990	4.800
I7	0.064	116.313	2.438	82.031	0.705	59.990	4.775
I8	0.064	116.094	2.438	82.031	0.707	59.990	4.750
I9-F	0.063	134.016	4.968	83.333	0.622	62.860	4.763
I10-F	0.063	130.921	4.968	83.333	0.637	62.860	4.838
I11	0.063	131.222	4.968	83.333	0.635	62.860	4.538
I12	0.063	131.127	4.968	83.333	0.636	62.860	4.463

F - Represents flanges fastened to supports.
N = 5.25 inches.

Table 3

Parameters and Test Data of I-Sections
Used for Web Crippling

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	Fy (ksi)	P(test) (kips)
I1-F	0.109	68.284	1.431	48.165	0.705	56.740	13.200
I2-F	0.109	68.202	1.431	48.165	0.706	56.740	13.600
I3	0.109	68.229	1.431	48.165	0.706	56.740	13.100
I4	0.109	68.284	1.431	48.165	0.705	56.740	13.750
I5-F	0.064	115.953	2.438	82.031	0.707	59.990	4.600
I6-F	0.064	116.375	2.438	82.031	0.705	59.990	4.800
I7	0.064	116.313	2.438	82.031	0.705	59.990	4.775
I8	0.064	116.094	2.438	82.031	0.707	59.990	4.750
I9-F	0.063	134.016	4.968	83.333	0.622	62.860	4.763
I10-F	0.063	130.921	4.968	83.333	0.637	62.860	4.838
I11	0.063	131.222	4.968	83.333	0.635	62.860	4.538
I12	0.063	131.127	4.968	83.333	0.636	62.860	4.463

F - Represents flanges fastened to supports.
N = 5.25 inches.

Table 4

Parameters and Test Data of Z-Sections (lapped and unlapped) Used for Web Crippling

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	Fy (ksi)	P(test) (kips)
UNLAPPED							
Z1	0.070	132.614	4.757	37.500	0.283	61.130	1.394
Z2	0.070	132.429	4.757	37.500	0.283	61.130	1.388
Z3-F	0.070	132.729	4.757	37.500	0.283	61.130	1.894
Z4-F	0.070	132.521	4.757	37.500	0.283	61.130	1.831
Z5	0.100	72.110	3.330	26.250	0.364	64.900	3.125
Z6	0.100	72.050	3.330	26.250	0.364	64.900	3.219
Z7-F	0.100	71.950	3.330	26.250	0.364	64.900	4.113
Z8-F	0.100	71.860	3.330	26.250	0.364	64.900	3.950
LAPPED							
ZL1	0.070	132.800	4.757	75.000	0.565	61.130	4.025
ZL3-F	0.070	132.886	4.757	75.000	0.564	61.130	4.375
ZL5	0.100	72.550	3.330	52.500	0.724	64.900	7.950
ZL7-F	0.100	72.020	3.330	52.500	0.729	64.900	8.450

L - Represents lapped sections.
F - Represents flanges fastened to support.
N = 2.625 inches (unlapped sections).
N = 5.25 inches (lapped sections).

Table 5

Section: Channels
End one-flange Loading (EOF) Test

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
C1-F	68.271	4.575	5.232	0.874	
C2-F	68.294	4.706	5.222	0.901	
C3	68.991	4.269	5.226	0.817	
C4	68.775	4.244	5.228	0.812	1.090
C5-F	115.914	1.863	1.566	1.190	
C6-F	115.984	1.663	1.565	1.063	
C7	115.813	1.525	1.566	0.974	
C8	115.781	1.550	1.566	0.990	1.147
C9-F	131.365	1.494	0.943	1.584	
C10-F	131.508	1.488	0.942	1.580	
C11	131.254	1.494	0.943	1.584	
C12	131.492	1.513	0.942	1.606	0.992

F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table 6

Section: I-Sections
Interior one-flange Loading (IOF) Test

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
I1-F	68.284	13.200	16.046	0.823	
I2-F	68.202	13.600	16.046	0.848	
I3	68.229	13.100	16.046	0.816	
I4	68.284	13.750	16.046	0.857	0.998
I5-F	115.953	4.600	6.449	0.713	
I6-F	116.375	4.800	6.449	0.744	
I7	116.313	4.775	6.449	0.740	
I8	116.094	4.750	6.449	0.737	0.987
I9-F	134.016	4.763	6.572	0.725	
I10-F	130.921	4.838	6.572	0.736	
I11	131.222	4.538	6.572	0.691	
I12	131.127	4.463	6.572	0.679	1.067

F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table 7

Section: Unlapped Z-Sections
End one-flange Loading (EOF) Test

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
Z1	132.614	1.394	1.122	1.242	
Z2	132.429	1.388	1.123	1.236	
Z3-F	132.729	1.894	1.122	1.688	
Z4-F	132.521	1.831	1.122	1.632	1.339
Z5	72.110	3.125	3.158	0.990	
Z6	72.050	3.219	3.159	1.019	
Z7-F	72.950	4.113	3.159	1.302	
Z8-F	71.860	3.950	3.160	1.250	1.271

F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table 8

Section: Lapped Z-Sections
Interior one-flange Loading (IOF) Test

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
ZL1	132.800	4.025	3.834	1.050	
ZL3-F	132.886	4.375	3.833	1.141	1.087
ZL5	72.550	7.950	8.828	0.901	
ZL7-F	72.020	8.450	8.835	0.956	1.063

L = Represents lapped sections.
F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load based on two webs.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

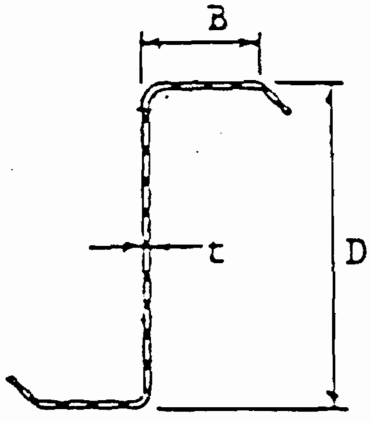

Figure 1

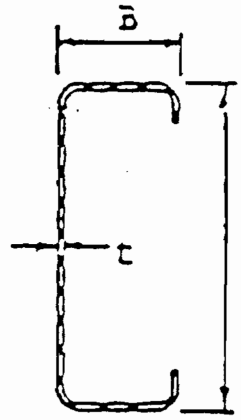

Figure 2

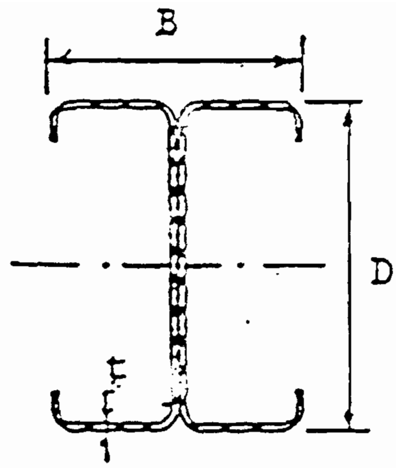

Figure 3

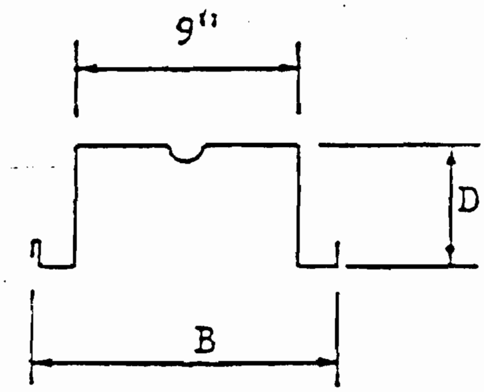

Figure 4

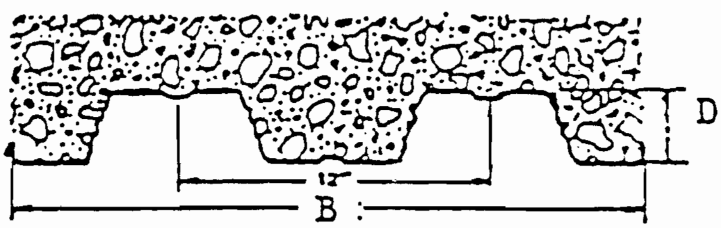

Figure 5

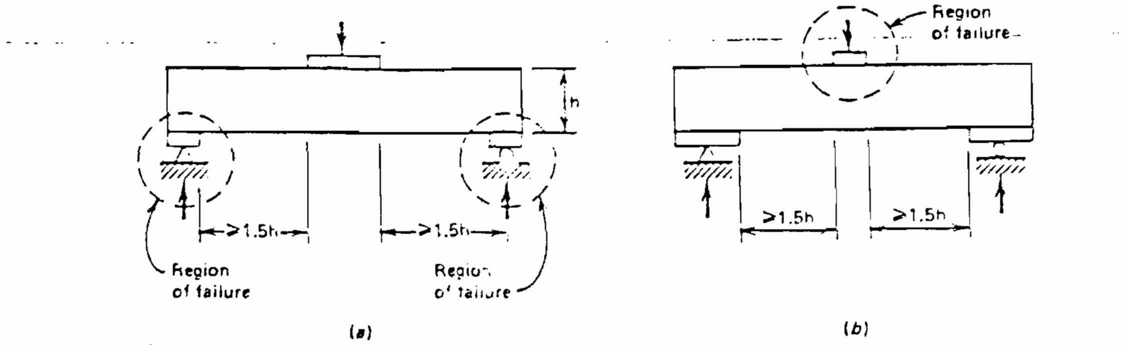

Figure 6: (a) EOF Loading (b) IOF Loading

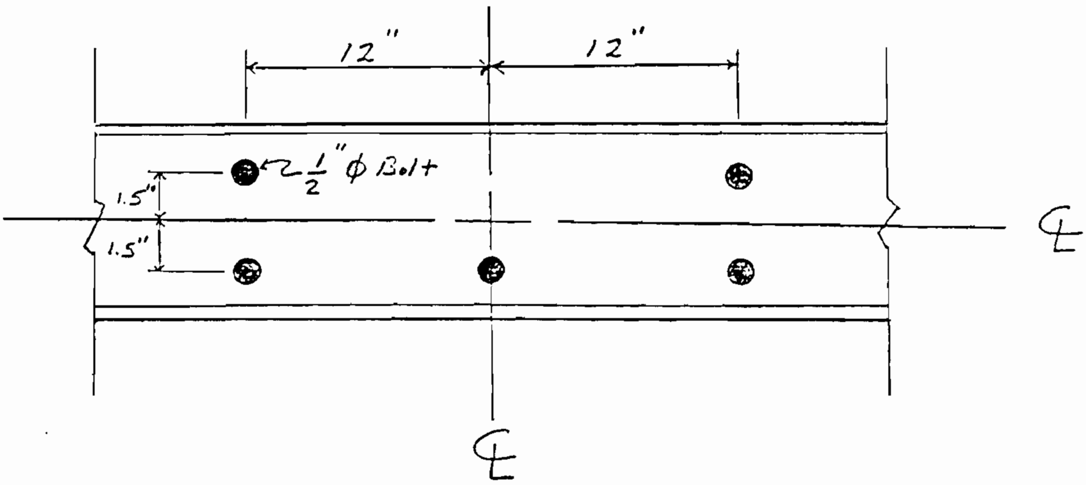

Figure 7: A typical bolt pattern for multi-web connections.

Second Progress Report

EFFECT OF FLANGE RESTRAINT ON WEB CRIPPLING STRENGTH

by B. Bhakta, R. A. LaBoube and W. W. Yu
Department of Civil Engineering
University of Missouri-Rolla
June 12, 1991

Introduction

The web crippling limit states equations given in the AISI Specification[1] were primarily developed based on test results for which the flange was not attached to the support beams. This may not accurately represent field practice for all cases because flanges are typically fastened by bolts or welds to their support beam. Due to the restraining effect of these fasteners, the Specification equations may be underestimating the web crippling strength of the member. Therefore, a pilot study was initiated in 1990 to study the load-carrying capacity of the webs with restrained and unrestrained flanges.

Test Program

The test program included the study of the following types of sections (see Figures 1 through 5):

- Channels
- I-Sections
- Z-Sections
- Long Span Roof Decks
- Floor Decks

Because this was a pilot study to investigate the effect of flange restraint on web crippling strength, the number of tests were limited. During the period from December 15, 1990 through April

30, 1991, a total of fifty-two web crippling tests have been conducted for members either with or without flange restraint. Both single web and double web beam members were tested. The single web members tested were channels and unlapped Z-Sections, subjected to end-one-flange loading (EOF). The double web members tested included I-Sections (back-to-back C's) and lapped Z-Sections, for interior-one-flange loading (IOF). Roof deck sections were tested for both EOF and IOF loading. Figure 6 provides a definition of the two loading conditions. The length of each test specimen was chosen such that the clear distance between the edges of the bearing plates would be no less than 1.5 h, where h is the flat portion of the web, as defined by the AISI Specification. For all EOF loaded specimens, the bearing length, N, was held constant at 2.625 inches. The bearing length was chosen as 5.25 inches for all IOF loaded specimens.

In addition to the beam tests, the mechanical properties of each test specimen were determined by standard coupon tests per ASTM A370 procedures.

This report summarizes the geometry and test results for the Channel and Z-sections test specimens. The failure loads have been evaluated to determine the effect of flange restraint. A comparison between tested and computed web crippling loads is also presented. The web crippling strength was evaluated by using the 1986 AISI Specification and equations developed by Santaputra[2]. The equations are summarized in Appendix A. Based on the findings of this study, conclusions are drawn regarding the effect of flange restraint on the web crippling strength of beam web elements, and the accuracy of the prediction equations to estimate the web crippling strength.

Discussion of Tests and Results

The following discussion will summarize the findings obtained from this research, as they apply to each cross-section type.

Channels:

A total of twelve channel specimens were tested for EOF loading. Four specimens for each h/t ratio were tested, two tests with the flanges fastened to the supports and two without fasteners. Table 1 summarizes the dimensions of the test specimens, and shows the typical cross section of the test specimen. The channels were interconnected by 3/4 x 3/4 x 1/8 inch angles at both the compression and tension flanges. The angles were located such that the lateral buckling of each channel was prevented. For the test specimens having restrained flanges, the flanges of the test specimens were fastened to the support beam by a 1/2 inch diameter bolt (Fig. 7). The EOF condition was achieved by adding transverse web stiffeners in the center of the test specimens to force the failure to occur at the ends.

The equations used to compute the web crippling strength, P_c, were Equation C3.4-1 from the AISI Specification and Equations 6 and 7 from Santaputra (Appendix A). The value from the AISI equation was multiplied by 1.85 to remove the factor of safety. Test parameters and results are given in Tables 5, 8, and 12.

For the four test specimens having $h/t \approx 70$ and $R/t \approx 1.4$, the tested and computed loads are listed in Tables 8 and 12. The accuracy of the prediction equations is represented by the ratio of P_t/P_c. The AISI equation (Table 8) overestimated the web crippling strength by as much as 18%, while Santaputra's equations (Table 12) overestimated the strength by as much as 24%. There was an average increase of nine percent in web crippling strength for the specimens with fastened flanges versus the specimens having unfastened flanges, as indicated by the ratio of P_f/P_{uf}.

Four specimens were also tested for $h/t \approx 115$ and $R/t \approx 2.4$ (Tables 8 and 12). The tested loads and computed loads correlated for both the AISI and Santaputra equations. An increase in the web crippling strength of 14.7 percent was obtained for the specimens having their flanges fastened to the support member.

For channels having an $h/t \approx 131$ and $R/t \approx 5$ (Table 8 and 12) there existed a 58 percent conservatism in the computed value when the AISI equation was used. Using Santaputra's equations resulted in about a 25 percent conservative estimate for the web crippling strength. There was no increase in strength resulting from flange restraint, i.e., P_f/P_{uf} equals 0.992.

I-Sections:

A total of twelve I-shaped sections were tested for IOF loading. The I-sections were fabricated from two channels connected back-to-back. See Table 2 for the specimen geometry and cross section. A typical industry type bolt pattern was used to connect the two channels, as shown by Figure 8. The member length was chosen to ensure a minimum of 1.5h between the edge of the bearing plates.

Four test specimens were fabricated for each value of h/t ratio, two with flanges fastened to the support member and the remaining two specimens with flanges unfastened. Equation C3.4-5 of the AISI Specification was used for the computed loads along with Equations 19 and 20 from Santaputra. A factor of safety of 2.0 in the AISI equation was accounted for by multiplying the AISI equation results by the value of the factor of safety. The IOF load was achieved by adding transverse web stiffeners on the ends of the specimen to force the failure in the interior. Test parameters and results are given on Tables 6, 9, and 13.

For all twelve test specimens (Tables 9 and 13), the tested loads were significantly lower than the computed loads by using both the AISI and Santaputra equations. There was no significant increase in strength between fastened and unfastened flange specimens, as indicated by the ratio of P_u/P_{uf}.

The poor correlation between the tested and computed web crippling loads may be attributed to the limited number of fasteners attaching the webs together and the location of the fasteners. Because an insufficient number of fasteners were used to attach the channel's webs, and because the fasteners were not located near the beam flange, the sections were prevented from developing the increase in web crippling strength that is typically exhibited by a built-up cross section.

Z-Sections:

A total of sixteen Z-Section specimens were tested, eight of these were unlapped sections and eight were lapped sections. The Z-sections were braced to each other by 3/4 x 3/4 x 1/8 inch angles attached to both the tension and compression flanges. The bracing interval was selected to preclude lateral movement of the individual section. Member lengths were chosen to provide a minimum 1.5h distance between the edges of bearing plates.

The unlapped Z-sections were all subjected to an EOF loading and the lapped sections were all subjected to an IOF loading. Equation C3.4-1 from the AISI Specification, and Equations 6 and 7 of Santaputra were used for the unlapped sections. Equation C3.4-4 from the AISI Specification and Equations 8 and 9 from Santaputra were used for the lapped sections. The results of the AISI equations were multiplied by 1.85 to account for the factor of safety. Test parameters and results are given in Tables 7, 10, 11, 14, and 15. Tables 3 and 4 gives the cross-section dimensions. The unlapped sections will be discussed first, followed by the lapped sections.

Unlapped Sections:

For the specimens having an $h/t \approx 132$, two tests were conducted with flanges fastened and two with flanges unfastened. The results of these tests indicated a 33.9 percent increase in strength between the fastened and the unfastened flange specimens (Tables 10 and 14). As indicated by the ratio of P_t/P_c, the tested loads for the unfastened flange test specimens (No. Z1 and Z2), were approximately 24 percent greater than the AISI predictions, while Santaputra's equations yielded good correlation with the failure load. The fastened flange test specimens showed an even greater difference between test and computed failure loads. The tested loads were approximately 65 percent higher than the AISI equation would predict (Table 10), while for the same test specimens, Santaputra's equations were about 32 percent less than the tested load (Table 14).

For the four test specimens having an h/t ≈ 72, there was an increase of 27.1 percent in strength between the fastened and the unfastened flange specimens (Tables 10 and 14). For the test specimens No. Z5 and Z6, with the flanges unfastened, there was good correlation between the tested and the computed failure loads, using both the AISI and Santaputra equations. For the specimens with the flanges attached to the support beam (No. Z7-F and Z8-F), the tested loads were 25-30 percent larger than the predicted value as given by the AISI equation (Table 10). For the same specimens, Santaputra's equations underestimated the failure load by about 45 percent (Table 14).

For the EOF loading of the Z-sections there is a significant increase in strength when the restraining effect of a fastened flange is considered. Based on this limited study, the increase in load capacity can be as much as 27 percent.

<u>Lapped Sections:</u>

Eight specimens have been tested for the lapped Z's (Tables 4 and 7). A typical industry standard lap was employed, as shown by Fig. 9. For the four test specimens having h/t ≈ 132, the tested loads compared favorably with the predictions from AISI (Table 11) and

Santaputra (Table 15). As indicated by the ratio of P_f/P_{uf}, there was only an increase of 4.5 percent in web crippling strength between the fastened flange specimens and the unfastened flange specimens.

For the four test specimens having $h/t \approx 72$, the computed loads for both the AISI and Santaputra equations were within twenty percent of the tested loads. There was only an increase of 3.0 percent in strength between the fastened and the unfastened flange specimen.

Summary and Conclusions

This pilot study had as its objectives, to investigate experimentally the influence of flange restraint on the web crippling capacity of beam web elements, and to evaluate the accuracy of the design recommendations of AISI and Santaputra to predict the web crippling strength. Based on a limited number of tests conducted in this pilot study, the following conclusions are developed:

Influence of Flange Restraint:

- Channels and I-Sections, subjected to either the EOF or IOF loading, showed little increase in strength when the flanges were fastened to the support beams. Also, the I-sections did not achieve their computed web crippling capacities because of an insufficient number of web connectors to form a built-up section.

- For the EOF loading, Z-sections experienced an average increase of 30 percent in strength with the flanges restrained by bolting to the support beam.

- For the IOF loading condition, the Z-sections exhibited only a 3 percent increase in strength when the flanges were fastened.

Test versus Computed Web Crippling Strength:

- For the test specimens with unrestrained flanges formed from C and Z shaped sections, the equations of Santaputra, on the average, yielded a better estimate of the web crippling failure load (Table 16).

- For the C and Z shaped test specimens with restrained flanges, the web crippling equations of Santaputra, on the average, provided a better prediction of the web crippling strength (Table 17).

References

1. American Iron and Steel Institute, "Specification for the Design of Cold-Formed Steel Structural Members," 1986 ed. with the 1989 Addendum, Washington, D.C.

2. Santaputra, C., Parks, M.B., and Yu, W.W., "Web-Crippling Strength of Cold-Formed Steel Beams," Journal of Structural Engineering, Vol. 115, No. 10, October 1989, pp 2511-2527.

Table 1

Measured Dimensions of Channel Sections

Specimen No.	t (in.)	B1 (in.)	B2 (in.)	D1 (in.)	D2 (in.)	D3 (in.)	R (in.)	N (in.)	L (in.)
C1-F	0.109	2.572	2.575	7.972	0.896	0.913	0.156	2.625	34.500
C2-F	0.109	2.564	2.553	8.083	0.927	0.908	0.156	2.625	34.500
C3	0.109	2.570	2.550	8.050	0.910	0.960	0.156	2.625	34.500
C4	0.109	2.549	2.553	8.027	0.927	0.929	0.156	2.625	34.500
C5-F	0.064	2.511	2.566	7.859	0.849	0.854	0.156	2.625	34.500
C6-F	0.064	2.553	2.545	7.863	0.904	0.859	0.156	2.625	34.500
C7	0.064	2.550	2.554	7.852	0.854	0.859	0.156	2.625	34.500
C8	0.064	2.548	2.547	7.850	0.853	0.841	0.156	2.625	34.500
C9-F	0.063	2.947	2.963	9.027	0.823	0.814	0.313	2.625	37.500
C10-F	0.063	3.001	2.933	9.036	0.936	0.699	0.313	2.625	37.500
C11	0.063	2.937	2.946	9.020	0.798	0.856	0.313	2.625	37.500
C12	0.063	2.980	2.934	9.035	0.940	0.730	0.313	2.625	37.500

L = Total Member Length

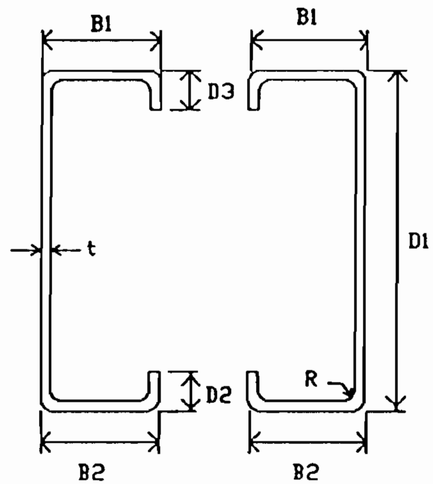

Table 2

Measured Dimensions of I-Sections

Specimen No.	t (in.)	B1 (in.)	B2 (in.)	D1 (in.)	D2 (in.)	D3 (in.)	R (in.)	N (in.)	L (in.)
I1-F	0.109	2.576	2.571	7.973	0.923	0.976	0.156	5.250	39.750
I2-F	0.109	2.573	2.586	7.964	0.904	0.965	0.156	5.250	39.750
I3	0.109	2.571	2.575	7.967	0.962	0.906	0.156	5.250	39.750
I4	0.109	2.570	2.525	7.973	0.900	0.953	0.156	5.250	39.750
I5-F	0.064	2.566	2.554	7.861	0.872	0.855	0.156	5.250	39.750
I6-F	0.064	2.575	2.576	7.888	0.864	0.873	0.156	5.250	39.750
I7	0.064	2.571	2.568	7.884	0.870	0.849	0.156	5.250	39.750
I8	0.064	2.561	2.580	7.870	0.865	0.886	0.156	5.250	39.750
I9-F	0.063	3.105	2.920	9.195	0.949	0.688	0.313	5.250	42.750
I10-F	0.063	3.005	2.947	9.000	0.959	0.721	0.313	5.250	42.750
I11	0.063	3.008	2.921	9.019	0.933	0.705	0.313	5.250	42.750
I12	0.063	3.025	2.931	9.013	0.904	0.746	0.313	5.250	42.750

L = Total Member Length

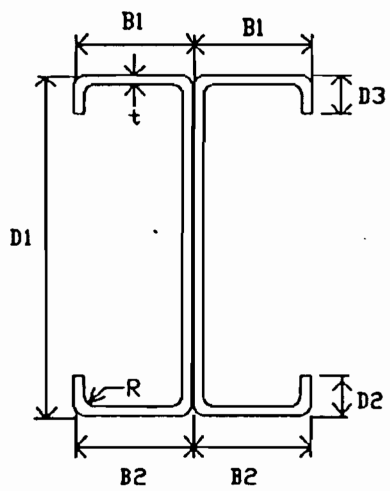

Table 3

Measured Dimensions of Unlapped Z-Sections

Specimen No.	t (in.)	B1 (in.)	B2 (in.)	D1 (in.)	D2 (in.)	D3 (in.)	R (in.)	N (in.)	L (in.)
Z1	0.070	2.454	2.506	10.089	0.639	0.615	0.333	2.625	40.500
Z2	0.070	2.505	2.501	10.076	0.672	0.623	0.333	2.625	40.500
Z3-F	0.070	2.477	2.513	10.097	0.641	0.666	0.333	2.625	40.500
Z4-F	0.070	2.482	2.519	10.083	0.649	0.622	0.333	2.625	40.500
Z5	0.100	2.561	2.558	8.077	0.688	0.679	0.333	2.625	35.250
Z6	0.100	2.548	2.577	8.071	0.653	0.674	0.333	2.625	35.250
Z7-F	0.100	2.537	2.584	8.061	0.640	0.689	0.333	2.625	35.250
Z8-F	0.100	2.536	2.552	8.052	0.635	0.702	0.333	2.625	35.250

L = Total Member Length

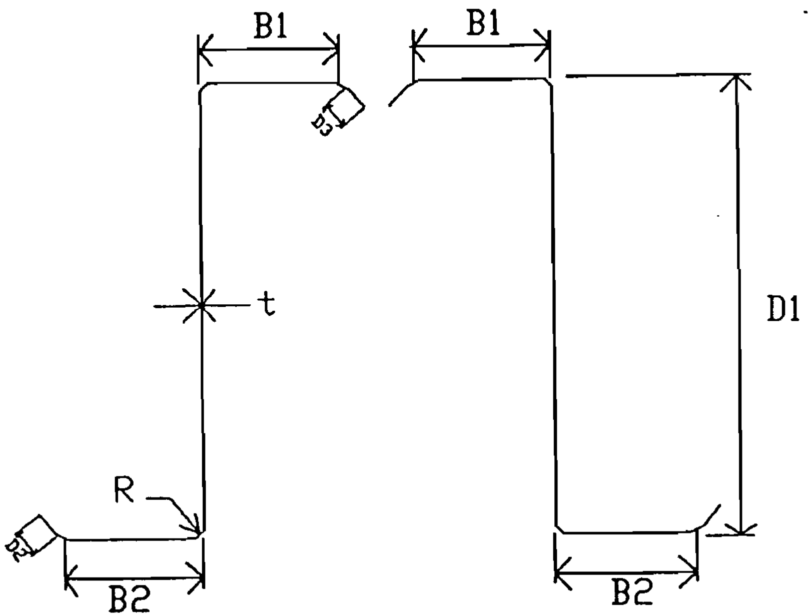

Table 4

Measured Dimensions of Lapped Z-Sections

Specimen No.	t (in.)	B1 (in.)	B2 (in.)	D1 (in.)	D2 (in.)	D3 (in.)	R (in.)	N (in.)	L (in.)
ZL1	0.070	2.500	2.490	10.102	0.648	0.636	0.333	5.250	45.250
ZL2	0.070	2.524	2.459	10.100	0.673	0.627	0.333	5.250	45.250
ZL3-F	0.070	2.520	2.454	10.108	0.630	0.690	0.333	5.250	45.250
ZL4-F	0.070	2.522	2.487	10.100	0.633	0.662	0.333	5.250	45.250
ZL5	0.100	2.517	2.585	8.121	0.641	0.689	0.333	5.250	40.500
ZL6	0.100	2.581	2.583	8.084	0.631	0.689	0.333	5.250	40.500
ZL7-F	0.100	2.592	2.509	8.068	0.697	0.649	0.333	5.250	40.500
ZL8-F	0.100	2.591	2.535	8.081	0.651	0.694	0.333	5.250	40.500

L = Total Member Length

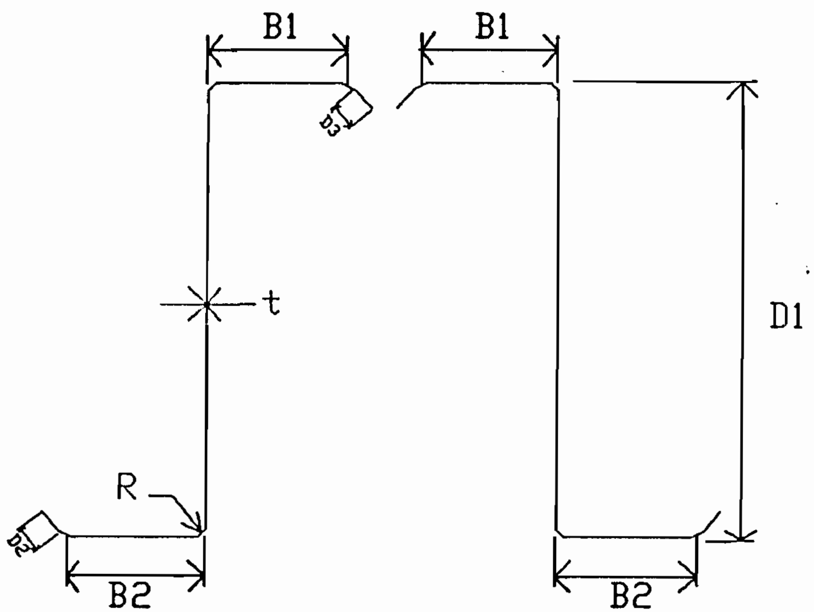

Table 5

Parameters and Test Data of Channels
Used for Web Crippling

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	Fy (ksi)	P(test) (kips)
C1-F	0.109	68.271	1.433	24.083	0.353	56.740	4.575
C2-F	0.109	69.294	1.431	24.083	0.348	56.740	4.706
C3	0.109	68.991	1.431	24.083	0.349	56.740	4.269
C4	0.109	68.775	1.431	24.083	0.350	56.740	4.244
C5-F	0.064	115.914	2.438	41.016	0.354	59.990	1.863
C6-F	0.064	115.984	2.438	41.016	0.354	59.990	1.663
C7	0.064	115.813	2.438	41.016	0.354	59.990	1.525
C8	0.064	115.781	2.438	41.016	0.354	59.990	1.550
C9-F	0.063	131.365	4.960	41.667	0.317	62.680	1.494
C10-F	0.063	131.508	4.960	41.667	0.317	62.680	1.488
C11	0.063	131.254	4.960	41.667	0.317	62.680	1.494
C12	0.063	131.492	4.960	41.667	0.317	62.680	1.513

F = Represents flanges fastened to supports.
N = 2.625 inches.

Table 6

Parameters and Test Data of I-Sections
Used for Web Crippling

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	Fy (ksi)	P(test) (kips)
I1-F	0.109	68.284	1.431	48.165	0.705	56.740	13.200
I2-F	0.109	68.202	1.431	48.165	0.706	56.740	13.600
I3	0.109	68.229	1.431	48.165	0.706	56.740	13.100
I4	0.109	68.284	1.431	48.165	0.705	56.740	13.750
I5-F	0.064	115.953	2.438	82.031	0.707	59.990	4.600
I6-F	0.064	116.375	2.438	82.031	0.705	59.990	4.800
I7	0.064	116.313	2.438	82.031	0.705	59.990	4.775
I8	0.064	116.094	2.438	82.031	0.707	59.990	4.750
I9-F	0.063	134.016	4.968	83.333	0.622	62.860	4.763
I10-F	0.063	130.921	4.968	83.333	0.637	62.860	4.838
I11	0.063	131.222	4.968	83.333	0.635	62.860	4.538
I12	0.063	131.127	4.968	83.333	0.636	62.860	4.463

F = Represents flanges fastened to supports.
N = 5.25 inches.

Table 7

Parameters and Test Data of Z-Purlins (unlapped and lapped)
Used for Web Crippling

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	Fy (ksi)	P(test) (kips)
UNLAPPED							
Z1	0.070	132.614	4.757	37.500	0.283	61.130	1.394
Z2	0.070	132.429	4.757	37.500	0.283	61.130	1.388
Z3-F	0.070	132.729	4.757	37.500	0.283	61.130	1.894
Z4-F	0.070	132.521	4.757	37.500	0.283	61.130	1.831
Z5	0.100	72.110	3.330	26.250	0.364	64.900	3.125
Z6	0.100	72.050	3.330	26.250	0.364	64.900	3.219
Z7-F	0.100	71.950	3.330	26.250	0.364	64.900	4.113
Z8-F	0.100	71.860	3.330	26.250	0.364	64.900	3.950
LAPPED							
ZL1	0.070	132.800	4.757	75.000	0.565	61.130	4.025
ZL2	0.070	132.771	4.757	75.000	0.565	61.130	3.750
ZL3-F	0.070	132.886	4.757	75.000	0.564	61.130	4.375
ZL4-F	0.070	132.771	4.757	75.000	0.565	61.130	3.750
ZL5	0.100	72.550	3.330	52.500	0.724	64.900	7.950
ZL6	0.100	72.180	3.330	52.500	0.727	64.900	7.875
ZL7-F	0.100	72.020	3.330	52.500	0.729	64.900	8.450
ZL8-F	0.100	72.150	3.330	52.500	0.728	64.900	7.850

L = Represents lapped sections.
F = Represents flanges fastened to support.
N = 2.625 inches (unlapped sections).
N = 5.25 inches (lapped sections).

Table 8

Section: Channels
End one-flange Loading (EOF) Test
Based on Equations from 1986 AISI Specification

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
C1-F	68.271	4.575	5.232	0.874	
C2-F	68.294	4.706	5.222	0.901	
C3	68.991	4.269	5.226	0.817	
C4	68.775	4.244	5.228	0.812	1.090
C5-F	115.914	1.863	1.566	1.190	
C6-F	115.984	1.663	1.565	1.063	
C7	115.813	1.525	1.566	0.974	
C8	115.781	1.550	1.566	0.990	1.147
C9-F	131.365	1.494	0.943	1.584	
C10-F	131.508	1.488	0.942	1.580	
C11	131.254	1.494	0.943	1.584	
C12	131.492	1.513	0.942	1.606	0.992

F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table 9

Section: I-Sections
Interior one-flange Loading (IOF) Test
Based on Equations from 1986 AISI Specification

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
I1-F	68.284	13.200	16.046	0.823	
I2-F	68.202	13.600	16.046	0.848	
I3	68.229	13.100	16.046	0.816	
I4	68.284	13.750	16.046	0.857	0.998
I5-F	115.953	4.600	6.449	0.713	
I6-F	116.375	4.800	6.449	0.744	
I7	116.313	4.775	6.449	0.740	
I8	116.094	4.750	6.449	0.737	0.987
I9-F	134.016	4.763	6.572	0.725	
I10-F	130.921	4.838	6.572	0.736	
I11	131.222	4.538	6.572	0.691	
I12	131.127	4.463	6.572	0.679	1.067

F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table 10

Section: Unlapped Z-Purlins
End one-flange Loading (EOF) Test
Based on Equations from 1986 AISI Specification

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
Z1	132.614	1.394	1.122	1.242	
Z2	132.429	1.388	1.123	1.236	
Z3-F	132.729	1.894	1.122	1.688	
Z4-F	132.521	1.831	1.122	1.632	1.339
Z5	72.110	3.125	3.158	0.990	
Z6	72.050	3.219	3.159	1.019	
Z7-F	72.950	4.113	3.159	1.302	
Z8-F	71.860	3.950	3.160	1.250	1.271

F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table 11

Section: Lapped Z-Purlins
Interior one-flange Loading (IOF) Test
Based on Equations from 1986 AISI Specification

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
ZL1	132.800	4.025	3.834	1.050	
ZL2	132.771	3.750	3.834	0.978	
ZL3-F	132.886	4.375	3.833	1.141	
ZL4-F	132.771	3.750	3.834	0.978	1.045
ZL5	72.550	7.950	8.828	0.901	
ZL6	72.180	7.875	8.833	0.892	
ZL7-F	72.020	8.450	8.835	0.956	
ZL8-F	72.150	7.850	8.833	0.889	1.030

L = Represents lapped sections.
F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table 12

Section: Channels
End one-flange Loading (EOF) Test
Based on Equations from Santaputra, Parks, Yu.
Journal of Structural Engineering, ASCE, Oct. 1989.

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
C1-F	68.271	4.575	5.578	0.820	
C2-F	68.294	4.706	5.583	0.843	
C3	68.991	4.269	5.583	0.765	
C4	68.775	4.244	5.583	0.760	1.090
C5-F	115.914	1.863	1.452	1.283	
C6-F	115.984	1.663	1.452	1.145	
C7	115.813	1.525	1.452	1.050	
C8	115.781	1.550	1.452	1.067	1.147
C9-F	131.365	1.494	1.189	1.257	
C10-F	131.508	1.488	1.189	1.252	
C11	131.254	1.494	1.189	1.257	
C12	131.492	1.513	1.189	1.273	0.992

F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table 13

Section: I-Sections
Interior one-flange Loading (IOF) Test
Based on Equations from Santaputra, Parks, Yu.
Journal of Structural Engineering, ASCE, Oct. 1989.

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
I1-F	68.284	13.200	16.302	0.810	
I2-F	68.202	13.600	16.302	0.834	
I3	68.229	13.100	16.302	0.804	
I4	68.284	13.750	16.302	0.843	0.998
I5-F	115.953	4.600	5.593	0.822	
I6-F	116.375	4.800	5.592	0.858	
I7	116.313	4.775	5.592	0.854	
I8	116.094	4.750	5.592	0.849	0.987
I9-F	134.016	4.763	5.371	0.887	
I10-F	130.921	4.838	5.379	0.899	
I11	131.222	4.538	5.378	0.844	
I12	131.127	4.463	5.378	0.830	1.067

F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table 14

Section: Unlapped Z-Purlins
End one-flange Loading (EOF) Test
Based on Equations from Santaputra, Parks, Yu.
Journal of Structural Engineering, ASCE, Oct. 1989.

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
Z1	132.614	1.394	1.383	1.008	
Z2	132.429	1.388	1.383	1.004	
Z3-F	132.729	1.894	1.383	1.369	
Z4-F	132.521	1.831	1.383	1.323	1.339
Z5	72.110	3.125	2.714	1.151	
Z6	72.050	3.219	2.714	1.186	
Z7-F	72.950	4.113	2.714	1.515	
Z8-F	71.860	3.950	2.714	1.455	1.271

F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table 15

Section: Lapped Z-Purlins
Interior one-flange Loading (IOF) Test
Based on Equations from Santaputra, Parks, Yu.
Journal of Structural Engineering, ASCE, Oct. 1989.

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (ave.)
ZL1	132.800	4.025	4.122	0.976	
ZL2	132.771	3.750	4.122	0.910	
ZL3-F	132.886	4.375	4.122	1.061	
ZL4-F	132.771	3.750	4.122	0.910	1.045
ZL5	72.550	7.950	9.492	0.838	
ZL6	72.180	7.875	9.492	0.830	
ZL7-F	72.020	8.450	9.492	0.890	
ZL8-F	72.150	7.850	9.492	0.827	1.030

L = Represents lapped sections.
F = Represents flanges fastened to supports.
P_t = Test load.
P_c = Computed load.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table 16

Comparison Between AISI and Santaputra Equations For Unrestrained Flange Specimens

Specimen No.	AISI P_t/P_c	Santaputra P_t/P_c
Channels, EOF Loading		
C3	0.817	0.765
C4	0.812	0.760
C7	0.974	1.050
C8	0.990	1.067
C11	1.584	1.257
C12	1.606	1.273
Mean	1.131	1.034
I-Sections, IOF Loading		
I3	0.816	0.804
I4	0.857	0.843
I7	0.740	0.854
I8	0.737	0.849
I11	0.691	0.844
I12	0.679	0.830
Mean	0.753	0.837
Unlapped Z-Section, EOF Loading		
Z1	1.242	1.008
Z2	1.236	1.004
Z5	0.990	1.151
Z6	1.019	1.186
Mean	1.121	1.087
Lapped Z-Section, IOF Loading		
ZL1	1.050	0.976
ZL2	0.978	0.910
ZL5	0.901	0.838
ZL6	0.892	0.830
Mean	0.955	0.889

Table 17

Comparison Between AISI and Santaputra Equations
For Restrained Flange Specimens

Specimen No.	AISI P_t/P_c	Santaputra P_t/P_c
Channels, EOF Loading		
C1-F	0.874	0.820
C2-F	0.901	0.843
C5-F	1.190	1.283
C6-F	1.063	1.145
C9-F	1.584	1.257
C10-F	1.580	1.252
Mean	1.199	1.100
I-Sections, IOF Loading		
I1-F	0.823	0.810
I2-F	0.848	0.834
I5-F	0.713	0.822
I6-F	0.744	0.858
I9-F	0.725	0.887
I10-F	0.736	0.899
Mean	0.765	0.852
Unlapped Z-Sections, EOF Loading		
Z3-F	1.688	1.369
Z4-F	1.632	1.323
Z7-F	1.302	1.515
Z8-F	1.250	1.455
Mean	1.468	1.416
Lapped Z-Sections, IOF Loading		
ZL3-F	1.141	1.061
ZL4-F	0.978	0.910
ZL7-F	0.956	0.890
ZL8-F	0.889	0.827
Mean	0.991	0.922

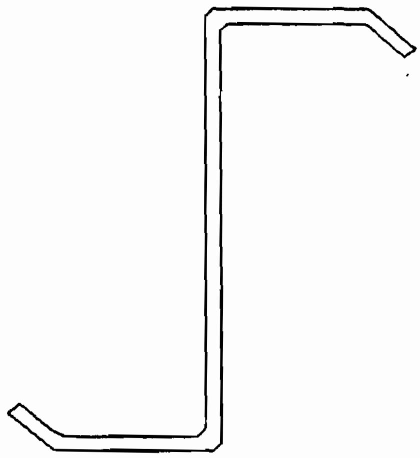

Fig. 1 Z-Section

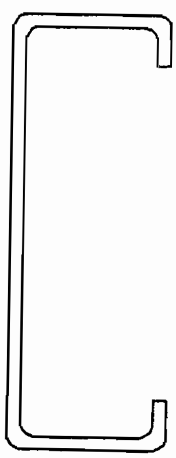

Fig. 2 Channel Section

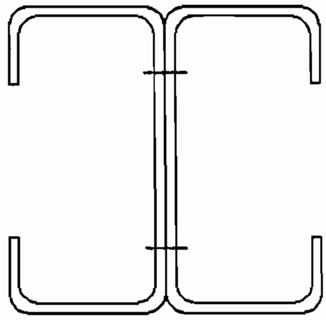

Fig. 3 I-Section

Fig. 4 Long Span Deck

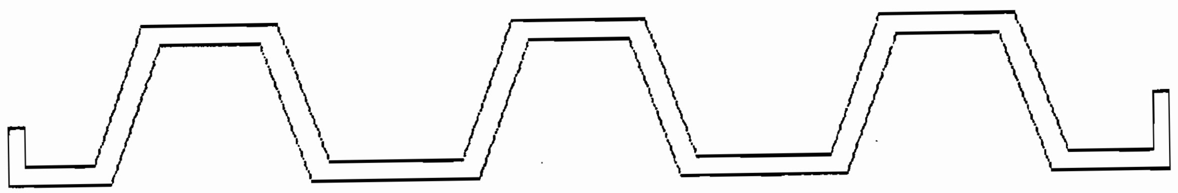

Fig. 5 Floor or Roof Deck

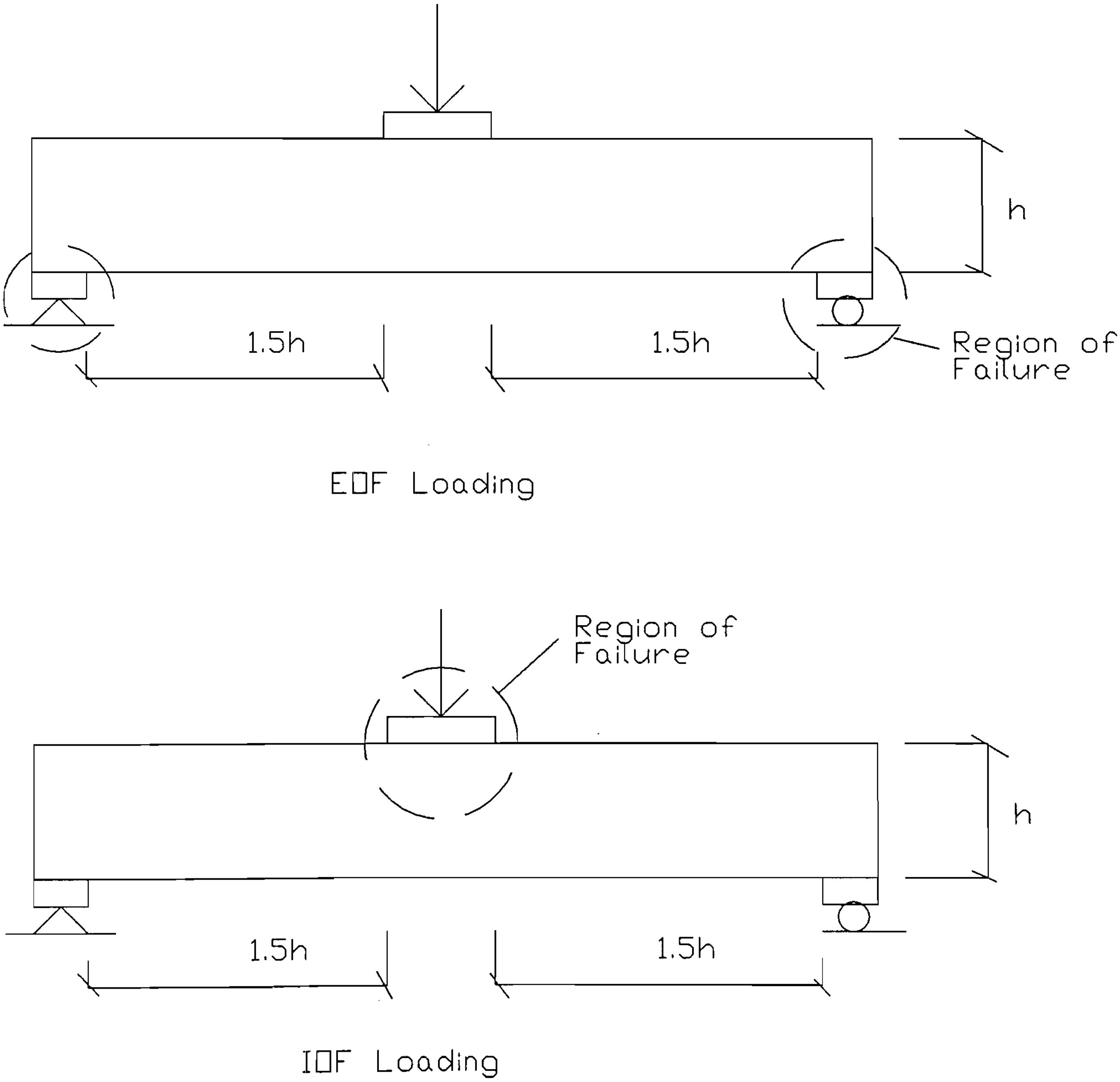

Fig. 6 Web Crippling Loading Conditions

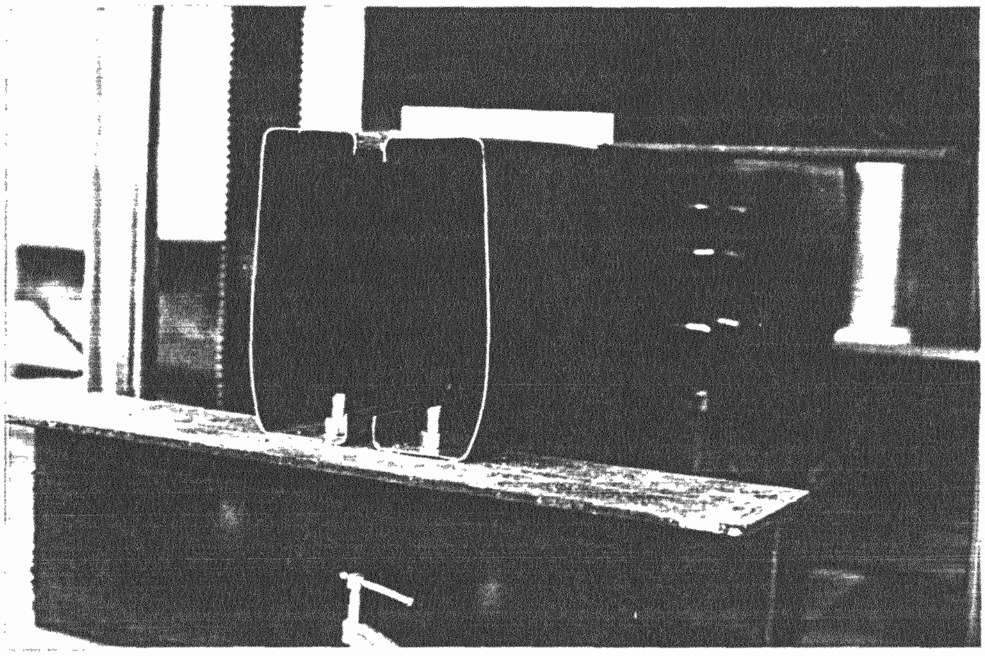

Fig. 7 Typical End Restraint for EOF Loading

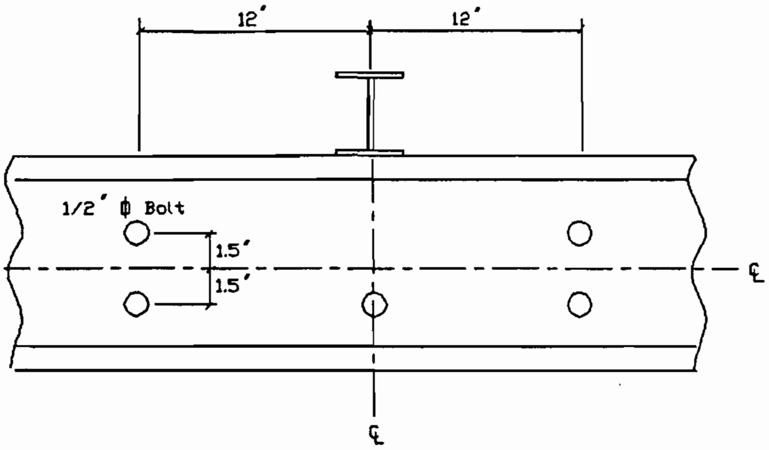

Fig. 8 Typical Bolt Pattern for I-Sections

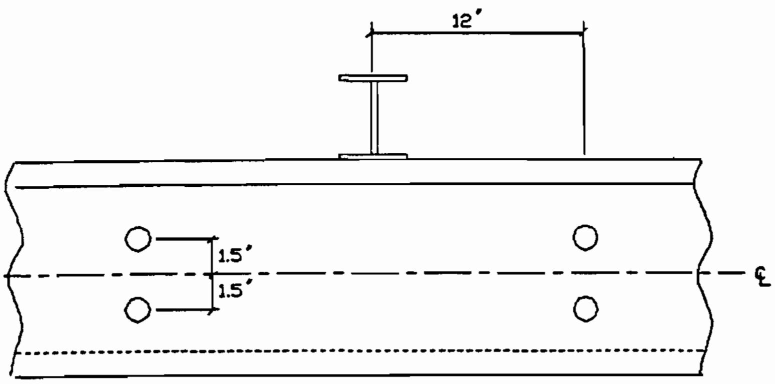

Fig. 9 Typical Bolt Pattern for Lapped Z-Sections

APPENDIX A

This appendix contains the applicable equations from Ref. 1 and 2 that were used in the evaluation of the test data.

WEB CRIPPLING EQUATIONS

Section	AISI Equations	Santaputra's Equations
Channels	C3.4-1	6 and 7
I-Sections	C3.4-5	19 and 20
Z-Sections		
Unlapped	C3.4-1	6 and 7
Lapped	C3.4-4	8 and 9

AISI Equations

$t^2kC_3C_4C_\theta[179 - 0.33(h/t)][1 + 0.01(N/t)]$ Eq. C3.4-1

$t^2kC_3C_4C_\theta[117 - 0.15(h/t)][1 + 0.01(N/t)]$ Eq. C3.4-2

$t^2kC_1C_2C_\theta[291 - 0.40(h/t)][1 + 0.007(N/t)]$ Eq. C3.4-4

$t^2F_yC_5[0.88 + 0.12m][7.50 + 1.63\sqrt{N/t}]$ Eq. C3.4-5

where,
$C_1 = (1.22 - 0.22k)$
$C_2 = (1.06 - 0.06(R/t)) \leq 1.0$
$C_3 = (1.33 - 0.33k)$
$C_4 = 0.50 < (1.15 - 0.15R/t) \leq 1.0$
$C_5 = (1.49 - 0.53k) \geq 0.6$
$C_\theta = 0.7 + 0.3(\theta/90)^2$

F_y = Design yield stress of the web, ksi
m = $t/0.075$
θ = Angle between the plane of the web and the plane of the bearing surface $\geq 45^\circ$, but not more than 90°.

Santaputra's Equations

P_c is the smaller of P_{cy} or P_{cb}.

End-One-Flange Loading for Single Unreinforced Webs:

$$P_{cy} = 9.9t^2F_yC_{11}C_{12}(\sin\theta) \qquad \text{Eq. 6}$$

$$P_{cb} = 0.047Et^2C_{41}C_{51}(\sin\theta) \qquad \text{Eq. 7}$$

Interior-One-Flange Loading for Single Unreinforced Webs:

$$P_{cy} = 7.80t^2F_yC_{12}C_{22}(\sin\theta) \qquad \text{Eq. 8}$$

$$P_{cb} = 0.028Et^2C_{32}C_{42}C_{52}(\sin\theta) \qquad \text{Eq. 9}$$

Interior-One-Flange Loading for I-Beams

$$P_{cy} = 15t^2F_yC_{12} \qquad \text{Eq. 19}$$

$$P_{cb} = 0.032Et^2C_{36}C_{46} \qquad \text{Eq. 20}$$

where,

$C_{11} = 1 + 0.0122(N/t) \leq 2.22$
$C_{12} = 1 + 0.217(N/t)^{0.5} \leq 3.17$
$C_{22} = 1 - 0.0814(R/t) \geq 0.43$
$C_{32} = 1 + 2.4(N/h) \leq 1.96$
$C_{36} = 1 + 1.318(N/h) \leq 1.53$
$C_{41} = 1 - 0.00348(h/t) \geq 0.32$
$C_{42} = 1 - 0.0017(h/t) \leq 0.81$
$C_{51} = 1 - 0.298(e/h) \geq 0.52$
$C_{52} = 1 - 0.120(e/h) \geq 0.40$

E = 29,500 ksi
e = clear distance between edges of adjacent opposite bearing plates, in.
P_c = governing ultimate web-crippling load, kips
P_{cb} = ultimate web-crippling load due to buckling, kips
P_{cy} = ultimate web-crippling load due to overstressing under bearing plate, kips