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FINAL REPORT

THE EFFECT OF FLANGE RESTRAINT ON WEB CRIPPLING STRENGTH

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PREFACE

When considering the web crippling strength of a cold-formed steel member, the current edition of the AISI Specification for the Design of Cold-Formed Steel Structural Members does not distinguish between the behavior of a member having its flanges attached to a support member, and a member not attached to its support. To enhance the industry and design professional's understanding of web crippling, a pilot study was initiated at the University of Missouri-Rolla to explore the influence of flange attachment. The financial assistance for this research was provided by the Metal Building Manufacturers Association (MBMA) and the American Iron and Steel Institute (AISI).

This research consisted of 52 web crippling tests on identical specimens, 26 specimens were bolted to a support beam and 26 were not attached to the support beam. This enabled direct comparison and evaluation of flange attachment. The results were compared with two design criteria, i.e., the 1986 AISI Specification and the 1986 Automotive Steel Design Manual. Because this was a pilot study, there are no new design recommendations, however, suggestions are proposed for future study.

This report is based on the thesis presented to the

Faculty of the Graduate School of the University of Missouri-Rolla (UMR) in partial fulfillment of the requirements for the degree of Masters of Science in Civil Engineering.

This investigation was sponsored by the Metal Building Manufacturer's Association (MBMA) and the American Iron and Steel Institute (AISI). The technical guidance provided by the AISI Subcommittee on Flexural Members and the AISI Staff is gratefully acknowledged. Members of the AISI Subcommittee are: J. N. Nunnery (chairman), R. E. Albrecht, R. E. Brown, D. S. Ellifritt, E. R. Estes, Jr., T. V. Galambos, M. Golovin, R B. Heagler, D. L. Johnson, K. H. Klippstein, R. A. LaBoube, J. N. Macadam, T. B. Pekoz, R. M. Schuster, T. W. Trestain, and W. W. Yu. The AISI Staff include R. B. Haws and K. L. Cole. Thanks are also extended to G. S. Harris of the Metal Building Manufacturers Association for his assistance.

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LIST OF SYMBOLS

E = modulus of elasticity of steel = 29,500 ksi (203,373 MPa);

e = clear distance between edges of adjacent opposite bearing plates, in.;

F_y = yield strength, ksi;

h = clear distance between flanges measured along plane of web, in.;

L = total length of specimen, in.;

N = actual length of bearing, in.;

P_a = the allowable design load using AISI Specification, kips;

P_c = governing ultimate web-crippling load using Santaputra's equations, kips;

P_{cb} = ultimate web-crippling load due to web buckling, kips;

P_{cy} = ultimate web-crippling load due to overstressing under bearing plate, kips;

P_f = tested web-crippling load with flanges fastened to supports, kips;

P_{uf} = tested web-crippling load with flanges unfastened to supports, kips;

R = inside bend radius, in.;

t = base steel thickness, in.;

Z = distance between edge of bearing plate to near end of beam, in.;

I. INTRODUCTION

A. GENERAL

The use of cold-formed steel members in designs of buildings, warehouses, even automotive components has been increasing quite extensively during the past fifty years. Many analytical, as well as experimental studies, have been performed in an attempt to accurately predict the strength and the behavior of these members. Researchers have developed design equations that should predict, with fairly good accuracy, the actual strength of the members under various loading conditions. These equations are not always developed using actual field practice, as is the case for the web crippling limit states for the cold-formed steel members.

The web crippling limit states equations given in the AISI Specification (1986) and the Automotive Steel Design Manual (1986) 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.

B. PURPOSE OF INVESTIGATION

The main purpose of this experimental study was not to develop new equations, but rather to determine if restraint on flanges of the members increased the web crippling strength of that member. It was intended to use the research findings as a justification for possible future research in the development of new design equations or modification of the current design equations.

C. SCOPE OF INVESTIGATION

This study consisted primarily of experimental investigations of the cold-formed steel members with flanges restrained to supports and members with flanges not restrained to supports. These members were subjected to web crippling only. Test specimens included channels, I-Sections, unlapped Z-Sections, lapped Z-Sections, long span roof decks (hat sections), and floor decks.

Since 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 were 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. 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 American Society of Testing Materials (ASTM) A370 procedures (ASTM, 1977).

This publication summarizes the geometry and test results for the different types of 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 (Santaputra, Parks, and Yu, 1989). The equations are summarized in Subsection D of Section II. 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.

As the first step of the investigation, the available research reports and technical publications relative to web crippling strength of cold-formed steel members were studied. Section II (Review of Literature) contains a summary of the literature search.

The experimental study concerning the different members subjected to web crippling is discussed in Section III (Experimental Investigation). Details of test specimens, and test procedures are also discussed in this section.

Section IV (Discussion of Results) discusses the evaluation of the results obtained by comparing the tested loads with the computed loads (based on AISI Specification and Automotive Design Manual). This section also discusses the results obtained from the study by comparing the results of the tests with beam's flanges fastened to supports to the results of the tests with beam's flanges unfastened to supports. Each type of section tested is discussed thoroughly.

Finally, Sections V (Proposed Recommendations) and VI (Conclusion) list some proposed recommendations for future research and summarize the results of this particular study, respectively.

II. REVIEW OF LITERATURE

A. GENERAL

In this phase of the investigation, several publications and research reports have been carefully studied. They are related to previous analytical and experimental studies of the strength of web plates subjected to web crippling and a combination of web crippling and bending moment, the latter is not discussed since this particular study concentrated on plates subjected to web crippling only. A brief review of the history of analytical and experimental studies is discussed in the next section as well as present available design criteria for determining web crippling strength are discussed in detail.

B. ANALYTICAL STUDIES

To discuss the theoretical background for the problem of web crippling, a brief overview of the elastic-plastic theory is presented. In the elastic-plastic theory, even though the web and the flange of the section are interactive, it is useful to consider the behavior of idealized separate rectangular flat plates subjected to locally distributed in-plane edge forces. The elastic buckling capacity of a plate is related to the dimensions of the plate, the elastic properties of the plate (Young's Modulus), the nature of stress distribution and the boundary conditions at the perimeter of the plate. Solving Bryan's differential equation can lead to determining the critical buckling stress of a rectangular plate (Yu, 1991). Solving this equation based on the small deflection theory (i.e., the significant deflection at buckling is of the order of the thickness of the plates or less) as follows:

$$\frac{\partial^4 \omega}{\partial X^4}+2\frac{\partial^4 \omega}{\partial X^2 \partial Y^2}+\frac{\partial^4 \omega}{\partial Y^4}+\frac{f_x t}{D}\frac{\partial^2 \omega}{\partial X^2}=0 \qquad \text{(Eq. 1)}$$

where,

$$D=\frac{Et^3}{12(1-\mu^2)} \qquad \text{(Eq. 2)}$$

E = Modulus of Elasticity (29,500 ksi for steel)
t = thickness of the plate
μ = Poisson's ratio (0.3 for steel in elastic range)
ω = deflection of the plate perpendicular to surface
f_x = compression stress in the x-direction

The steps involved in solving this equation are explained in detail by W. W. Yu (Yu, 1991).

The members under study must be considered to be composed of a series of flat plates. As discussed above, each plate's buckling capacity is a function of the plate's boundary conditions and the nature of loading on the member. The boundary conditions for a plate element within a cross section will depend on the shape of the cross section and the location of the plate within the cross section.

Two basic types of flat plates may exist, a flat plate can be a "stiffened compressive element" or an "unstiffened compressive element"; each may fail either in yielding or local buckling (Yu, 1991). A stiffened element is a flat plate or an element of a cross section which is supported on both edges parallel to the direction of the compressive stress. The supports can be any element of a cross section that have sufficient stiffness perpendicular to edge of a plate. These supports are generally assumed as simple supports. An example of a stiffened element within a cross section would be a web of a channel, I-Section, Z-Section, or a hat section, a web is also considered a stiffened element with stress gradient. An unstiffened compressive element is a flat plate or an element of a cross section which is supported on only one edge parallel to the direction of the compressive stress. An example of this can be the flange of an I-Section (Yu, 1991).

Several researchers have studied the problem of plate buckling and have developed equations to predict the elastic critical buckling load. The history of this research is discussed in detail in a report by Santaputra and Yu (Santaputra and Yu, 1986).

Recent analytical study outside of the United States have been conducted regarding cold-formed steel members. Research by Bakker, Pekoz, and Stark at Eindhoven University of Technology in the Netherlands presents a mechanism approach for analyzing the web crippling behavior of thin-walled members subjected to the combined action of a concentrated load and a bending moment (Bakker, Pekoz, and Stark, 1990). The approach was based on yield line analysis of failure mechanism and it was found that the corner radius largely influenced the type of mechanism that takes place.

C. EXPERIMENTAL STUDIES

The current design equations used in the United States for web crippling are all based on empirical studies. This is due to the mathematical difficulties encountered in deriving a solution for web crippling load.

The AISI design equations used in the early editions of the specification were primarily based on research by Winter, Pian, and Zetlin at Cornell University during the 1940's and 1950's (Winter, Pian, and Zetlin). The first phase of their study was an investigation of the I-Section (I-beams). These I-beams, which provide a high degree of restraint against rotation, were tested under various loading conditions. The results indicated that the ultimate web crippling loads of I-beams depend primarily on the ratio of N/t and F_y. See List of Abbreviations.

The second phase studied the cold-formed steel sections having single unreinforced webs, such as channels, Z-Sections, hat sections and rectangular tubes. The parameters primarily controlling the ultimate web crippling load for these sections were found to be ratios N/t, R/t, h/t and F_y. See List of

Abbreviations. Empirical expressions were derived on the basis of the Cornell research findings for predicting the ultimate web crippling load for each type of section. These formulas were used as a basis for the design criteria in the AISI Specifications (AISI, 1968).

Research performed by Hetrakul and Yu (Hetrakul and Yu, 1978) at University of Missouri-Rolla (UMR) during the 1970's was used to modify the design equations in the 1968 AISI Specification. Additional research at UMR in the 1980's by Santaputra and Yu (Santaputra and Yu, 1986) resulted in the development of an entirely new set of equations for web crippling capacities. These new empirical equations distinguishes web crippling failure caused by overstressing (bearing failure) and web buckling. These equations have been incorporated in the 1986 Automotive Steel Design Manual as an alternate method to the same procedure used in the 1986 AISI Specification for determining the web crippling capacities and the combination of web crippling and bending moment. These equations are presented later in this report.They introduced two additional parameters in the modification, Z (distance between the edge of the bearing plate of reaction or a concentrated load and the free end of the beam), and e (distance between the adjacent opposite bearing plates of concentrated loads or reactions).

Research performed by Rolfes at University of Wisconsin-Milwaukee (Rolfes, 1990) evaluated the web crippling and combined bending and web crippling capacities of the lapped Z-

Sections over a support. This research incorporated the effects of lapping and bolting of the Z-Sections over the interior supports (as is typically done with continuous purlin systems), and the bolting of the bearing flange of the Z-shape to the flange of the supporting rafter (also typically done with purlin systems). Based on the results of the tests, the web crippling strength of lapped Z-Sections may be accurately predicted by adding the web crippling strengths of the individual Z-Sections multiplied by an adjustment factor. This adjustment factor (AF) is a function of the web depth to thickness ratio (h/t) as shown below:

$$AF=[0.48+0.0046(\frac{2h}{\Sigma thicknesses})]\leq 1.0 \qquad \text{(Eq. 3)}$$

where,

h = the flat width to thickness ratio for the web of the Z-Sections
Σthicknesses = sum of thicknesses of each lapped Z-Sections.

Studies outside of the United States have been performed primarily targeting the multi-web deck sections. Research by Wing and Schuster at University of Waterloo, Ontario, Canada performed some web crippling tests on deck sections (Wing and Schuster, 1982). The test data was compared with the 1980 AISI Specification web crippling expressions and the comparison resulted in a scatter much larger than twenty percent, and in many cases the AISI expressions underestimated the load carrying capacity by an average of seventy-five percent (Wing and Schuster, 1982). This comparison resulted in new equations developed by Wing and Schuster and these new equation predicted the web crippling loads for their study within the commonly accepted scatter range of twenty percent.

Research by Studnicka at Czech Technical University in Prague, Czechoslovakia investigated the load resistance of multi-web deck sections subjected to end and interior reaction loading (Studnicka, 1990). The results of the tests were compared to both 1986 AISI Specification and the Canadian - 1986 Standard (Studnicka, 1990). Based on the results of the tests, the following conclusions were made. For the interior support condition, both the AISI and the Canadian Specification predicted the web crippling capacities within twenty percent. For the end support condition, a new modified equation was developed to better predict the web crippling capacity. Another finding was that the distance from the edge of the bearing plate to the end of multi-web deck can bring substantial increases for the web crippling capacity (Studnicka, 1990).

D. CURRENT DESIGN CRITERIA

A total of five types of cold-formed steel members were tested in this investigation. Therefore, careful attention had to be placed on choosing the appropriate equation(s) to be used in the computation of the predicted failure loads. Two different design specification were used to compute the web crippling strength of the different test specimens, the 1986 AISI Specification and the 1986 Automotive Steel Design Manual. (Note: From here on, the set of equations used from the 1986 Automotive Steel Design Manual will be referred to as Santaputra's equations (Santaputra, Parks, and Yu, 1989)). First, the equations from the 1986 AISI Specification will be discussed followed by the Santaputra's equations.

1. <u>1986 AISI Specification:</u>

a. <u>Beams Having Single Unreinforced Webs:</u> These specimens include channels, unlapped Z-Sections, floor decks, and long span roof decks, all under the EOF loading condition; and lapped Z-Sections under the IOF loading condition. The following sets of equations are taken from Section C3 of the AISI Specification (AISI, 1986).

<u>Stiffened Flanges (EOF):</u>

$$P_a = t^2 k C_3 C_4 C_\theta [179 - 0.33(h/t)][1 + 0.01(N/t)] \quad \text{(Eq. 4)}$$

<u>Unstiffened Flanges (EOF):</u>

$$P_a = t^2 k C_3 C_4 C_\theta [117 - 0.15(h/t)][1 + 0.01(N/t)] \quad \text{(Eq. 5)}$$

when N/t > 60, the factor [1+0.01(N/t)] may be increased to [0.71+0.015(N/t)].

Stiffened Flanges (IOF):

$$P_a=t^2kC_1C_2C_\theta[291-0.40(h/t)][1+0.007(N/t)] \quad \text{(Eq. 6)}$$

when N/t > 60, the factor [1+0.007(N/t)] may be increased to [0.75+0.011(N/t)].

where,

P_a = the allowable design load per web, kips (with a factor of safety of 1.85)

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_θ = $0.7 + 0.3(\theta/90)^2$

F_y = Design yield stress of the web, ksi

k = $F_y/33$

θ = Angle between the plane of the web and the plane of the bearing surface $\geq$ 45°, but not more than 90°.

b. I-Sections (IOF):

$$P_a=t^2F_yC_5[0.88+0.12m][7.50+1.63\sqrt{N/t}] \quad \text{(Eq. 7)}$$

where,

P_a = the allowable design load per web, kips (with a factor of safety of 2.00)

C_5 = (1.49 - 0.53k) $\geq$ 0.6

m = t/0.075

2. Santaputra's Equations (1986 Automotive Steel Design Manual):

a. Beams Having Single Unreinforced Webs:

End-One-Flange Loading:

$$P_{cy}=9.9\,t^2F_yC_{11}C_{12}(\sin\theta) \qquad \text{(Eq. 8)}$$

$$P_{cb}=0.047\,t^2Et^2C_{41}C_{51}(\sin\theta) \qquad \text{(Eq. 9)}$$

Interior-One-Flange Loading:

$$P_{cy}=7.80\,t^2F_yC_{12}C_{22}(\sin\theta) \qquad \text{(Eq. 10)}$$

$$P_{cb}=0.028Et^2C_{32}C_{42}C_{52}(\sin\theta) \qquad \text{(Eq. 11)}$$

b. I-Sections (IOF):

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

$$P_{cb}=0.032Et^2C_{36}C_{46} \qquad \text{(Eq. 13)}$$

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

P_c = governing ultimate web-crippling load per web (lower of P_{cy} or P_{cb}), kips

P_{cb} = ultimate web-crippling load due to buckling, kips

P_{cy} = ultimate web-crippling load due to overstressing under bearing plate, kips

III. EXPERIMENTAL INVESTIGATION

A. GENERAL

As stated in the Introduction, the current available design criteria for determining web crippling strength of cold-formed steel members were developed with the flanges unfastened to the supporting beams. Usual field practice is to bolt the flanges of the cold-formed steel members to their supporting beams. In order to determine if a change occurs in the web crippling strength due to the flange restraint, this pilot study was proposed to the American Iron and Steel Institute (AISI) and the Metal Building Manufactures Association in 1989.

The objective of this experimental investigation was to determine if for cold-formed steel members subjected to web crippling, is there an increase in web crippling strength with the flanges restrained? The test program included the study of the following types sections (see Figures 1 to 6):

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

As summarized in Table I, a total of 52 tests were performed. The test specimens were subjected to the following two types of loading cases (see Figure 7):

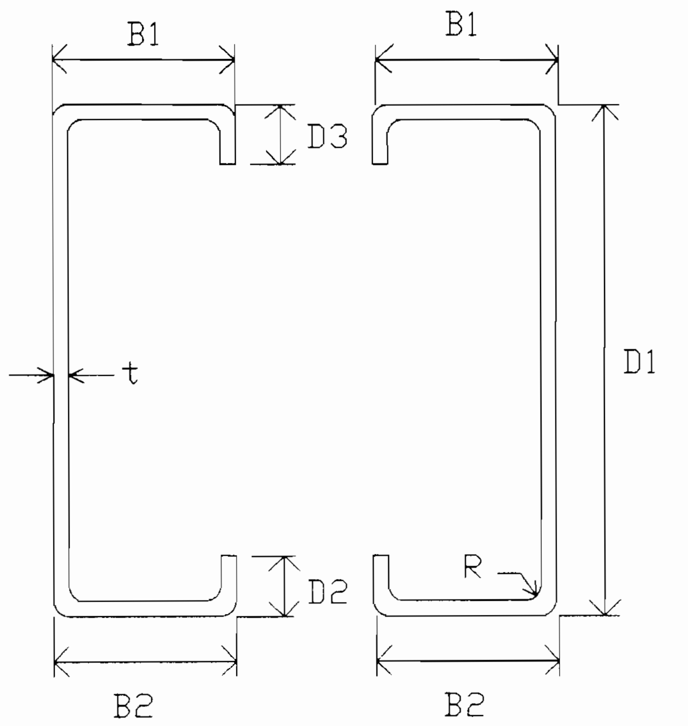


Figure 1. Cross Section View of a Channel Section Specimen.

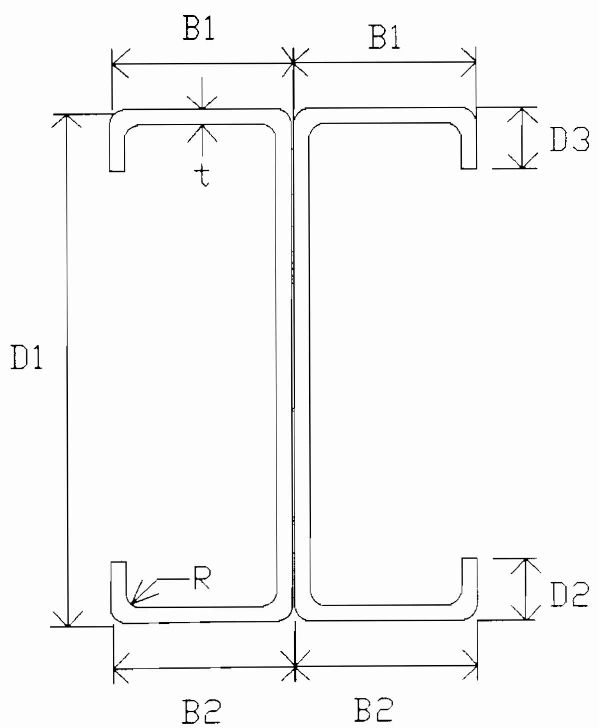


Figure 2. Cross Section View of an I-Section Specimen.

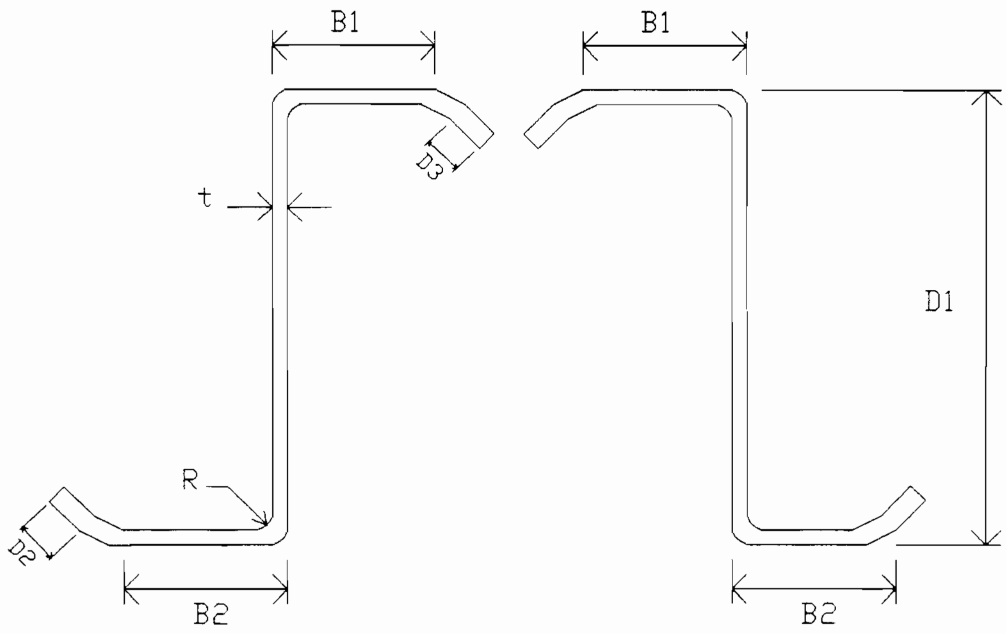


Figure 3. Cross Section View of an Unlapped Z-Section Specimen.

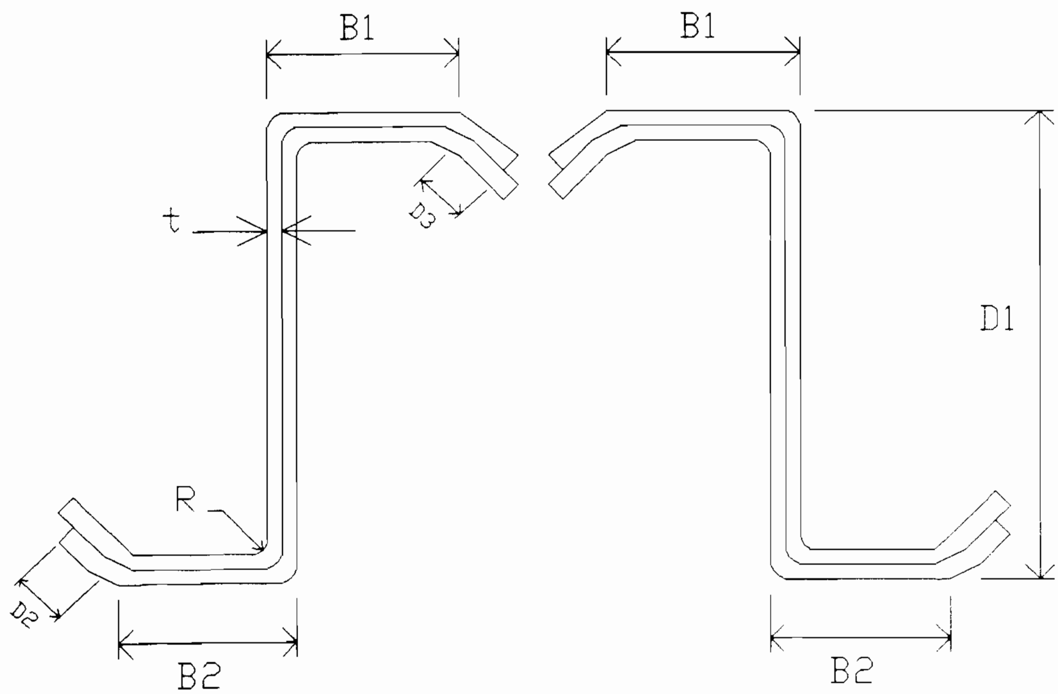


Figure 4. Cross Section View of a Lapped Z-Section Specimen.

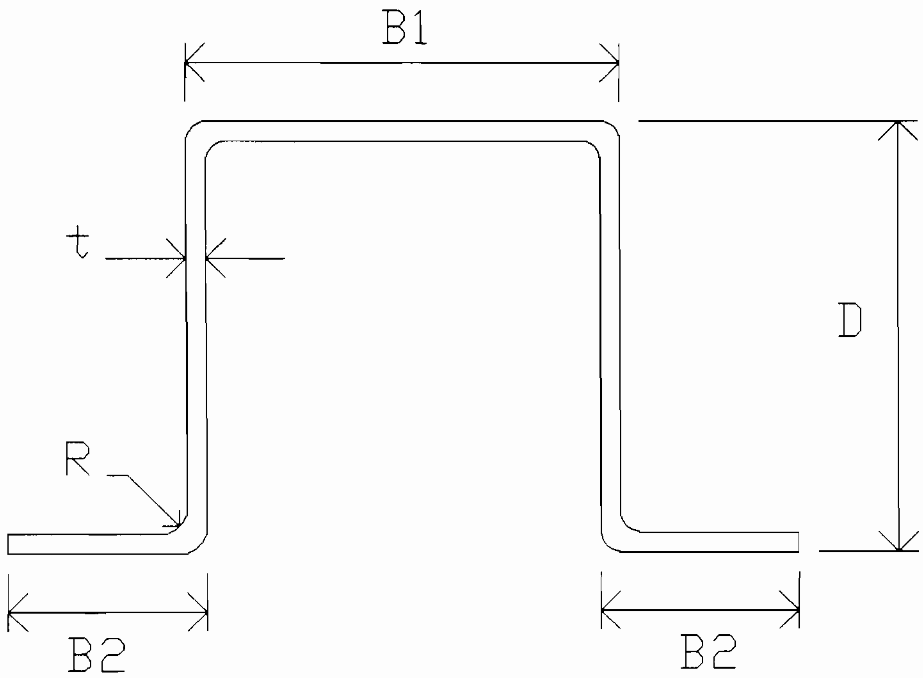


Figure 5. Cross Section View of a Long Span Roof Deck Specimen.

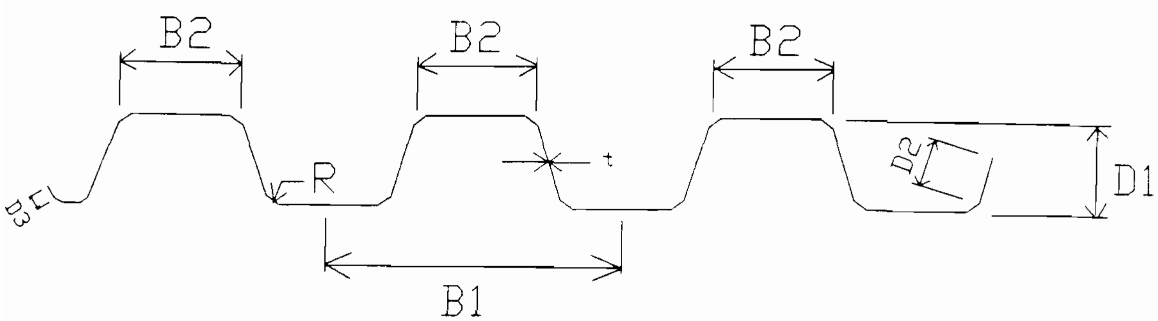


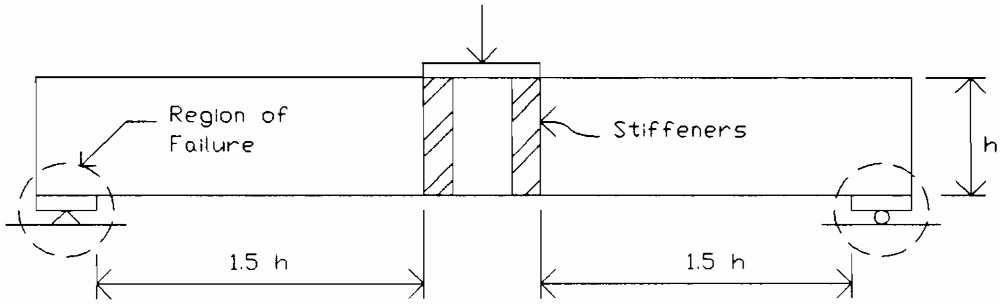
Figure 6. Cross Section View of a Floor Deck Specimen.

Table I TEST PROGRAM

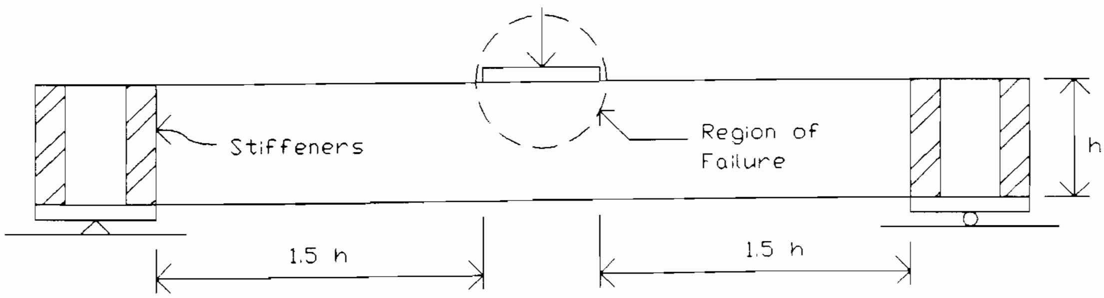
Specimen Type	h/t	Number of Tests Without Connections	With Connections	Total
Channels	70	2	2	4
	116	2	2	4
	132	2	2	4
I-Sections	70	2	2	4
	116	2	2	4
	132	2	2	4
Z-Sections				
Unlapped	72	2	2	4
	132	2	2	4
Lapped	72	2	2	4
	132	2	2	4
LSRD	145	2	2	4
Floor Decks	102	4	4	8
TOTAL				52

1. End one-flange loading (EOF)
2. Interior one-flange loading (IOF)

The EOF loading condition was used in testing twelve channel sections, eight unlapped Z-Sections, four long span roof decks (hat sections) and four floor decks. The IOF loading condition was used for testing twelve I-Sections, eight lapped Z-Sections, and four floor decks. See Figures 8 and 9 for definitions of the variables e and Z used in Santaputra's



EOF Loading



IOF Loading

Figure 7. Web Crippling Loading Conditions.

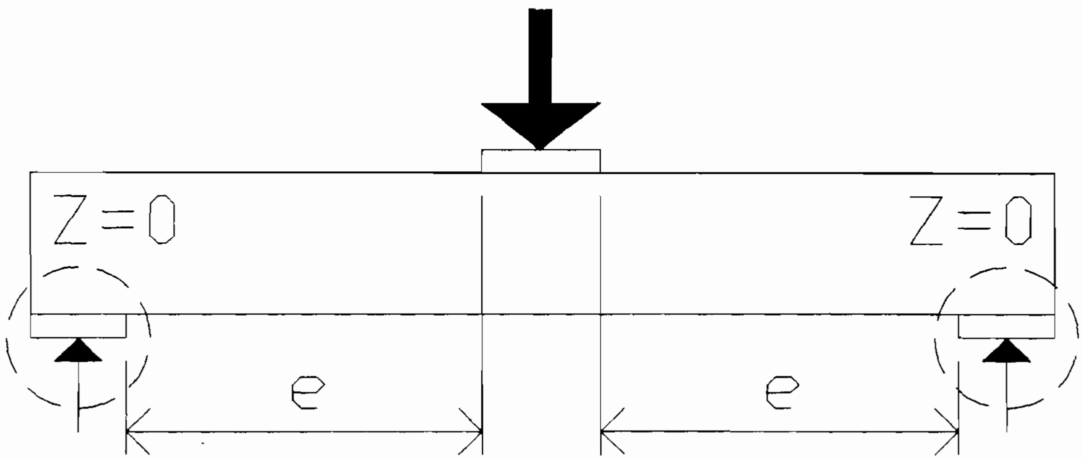


Figure 8. Definitions of the Parameters e and Z Used in Santaputra's Equations for EOF Loading.

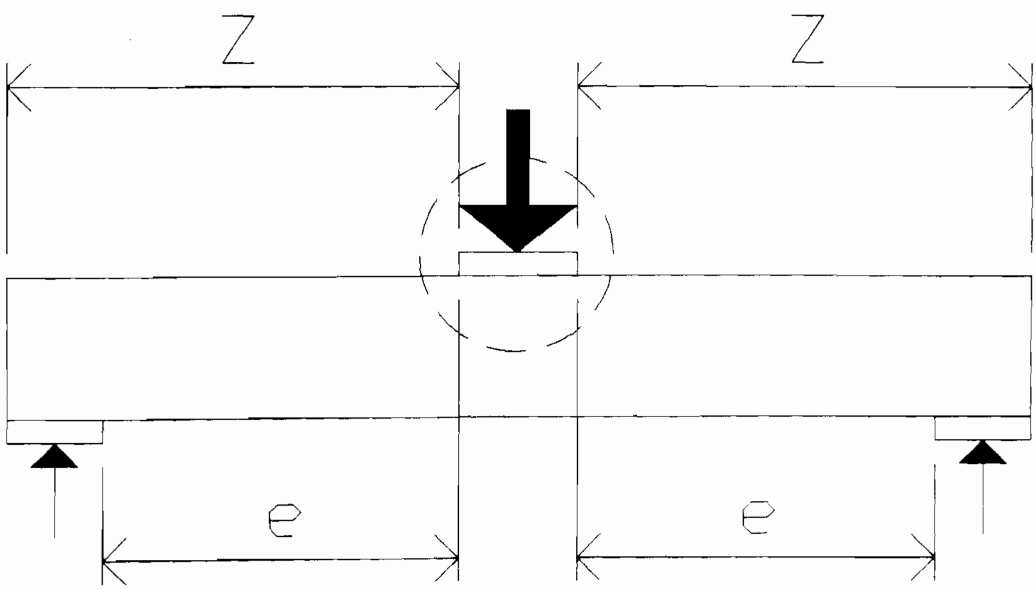


Figure 9. Definitions of the Parameters e and Z Used in Santaputra's Equations for IOF Loading.

Equations as they apply to both the EOF and IOF loading conditions, respectively.

All tests were performed on the 120,000 pound Tinius Olsen universal testing machine (Figure 10) located in the Engineering Research Laboratory of the University of Missouri-Rolla. All test specimens were cold-formed steel specimens, the supporting beams were hot-rolled I-beams.

During the initial phase of this study, pertinent mechanical properties were determined. Table II shows the mechanical properties and thicknesses of the test specimens used in this investigation. The mechanical properties were determined by Standard Coupon tests per ASTM A370 procedures (ASTM, 1977).

B. TEST SPECIMENS

The nominal dimensions of the cross sections are shown in Tables III through VIII, in which all dimensions are defined in Figures 1 through 6, respectively. Test specimens were cut to length from 20 to 25 feet long sections by using a chop saw. During the process of cutting short sections from longer sections, residual stresses were released in the test specimens. This caused some minor twisting initially between the flanges and the webs of the specimens. This initial twisting sometimes resulted in slight rotation of the test specimen under loading, but braces were placed in appropriate

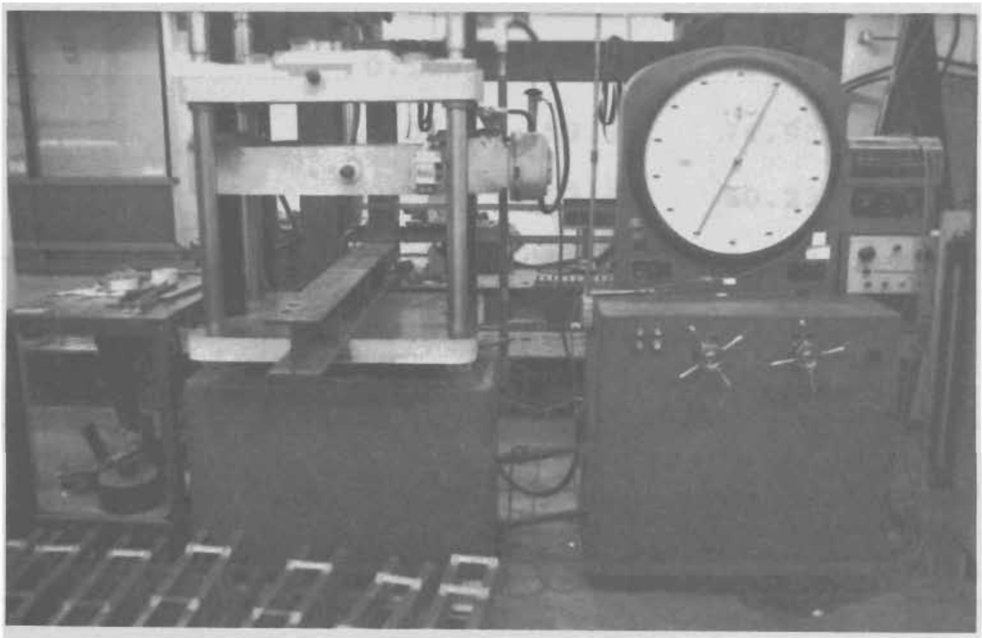


Figure 10. Photograph of the Tinius Olsen Testing Machine.

locations to keep the twisting at a minimum. These braces did not effect the outcome of the tests.

The length of the beam specimen was selected so that only the effect of web crippling rather than the combined bending and web crippling effect was realized. The equations used to determine the length, L, of the specimens were as follows:

Table II MATERIAL PROPERTIES AND THICKNESSES OF SECTIONS USED IN THE EXPERIMENTAL STUDIES

Section	t (in.)	F_y (ksi)	F_u (ksi)	Elongation (%)*
Channels	0.109	56.74	75.86	16.4
	0.064	59.99	74.93	24.2
	0.063	62.68	80.23	30.0
Z-Sections	0.070	61.13	78.90	32.2
	0.100	64.90	89.14	31.1
Long Span Roof Decks	0.049	43.82	55.73	29.0
Floor Decks	0.026	57.49	61.33	27.9

* Elongation was measured over a 2-in. gage length.

EOF Loading Condition:

$$L=2(1.5h)+2N+5\frac{1}{4}'' \qquad \text{(Eq. 14)}$$

IOF Loading Condition:

$$L=2(1.5h)+N+2(5\frac{1}{4}'') \qquad \text{(Eq. 15)}$$

where, h = length of the web, inches

N = bearing length, inches

Table III 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

NOTE: Refer to Figure 1 for definitions.

Table IV 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

NOTE: Refer to Figure 2 for definitions.

Table V 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

NOTE: Refer to Figure 3 for definitions.

Table VI 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

NOTE: Refer to Figure 4 for definitions.

Table VII MEASURED DIMENSIONS OF LONG SPAN ROOF DECKS

Specimen No.	t (in.)	B1 (in.)	B2 (in.)	D (in.)	R (in.)	N (in.)	L (in.)
RD1	0.049	7.627	3.067	7.630	0.203	2.625	33.000
RD2	0.049	7.631	3.060	7.624	0.203	2.625	33.000
RD3-F	0.049	7.625	3.058	7.627	0.203	2.625	33.000
RD4-F	0.049	7.629	3.063	7.631	0.203	2.625	33.000

NOTE: Refer to Figure 5 for definitions.

Table VIII MEASURED DIMENSIONS OF FLOOR DECKS

Specimen No.	t (in.)	B1 (in.)	B2 (in.)	D1 (in.)	D2 (in.)	D3 (in.)	R (in.)	N (in.)	L (in.)
EOF Tests									
FD1	0.026	8.110	1.901	3.022	1.187	0.196	0.172	2.625	19.500
FD2	0.026	8.110	1.907	3.017	1.182	0.201	0.172	2.625	19.500
FD3-F	0.026	8.110	1.896	3.025	1.185	0.196	0.172	2.625	19.500
FD4-F	0.026	8.110	1.900	3.021	1.179	0.199	0.172	2.625	19.500
IOF Tests									
FD5	0.026	8.110	1.897	3.015	1.182	0.201	0.172	5.250	24.750
FD6	0.026	8.110	1.910	3.022	1.189	0.198	0.172	5.250	24.750
FD7-F	0.026	8.110	1.888	3.020	1.185	0.209	0.172	5.250	24.750
FD8-F	0.026	8.110	1.897	3.025	1.190	0.195	0.172	5.250	24.750

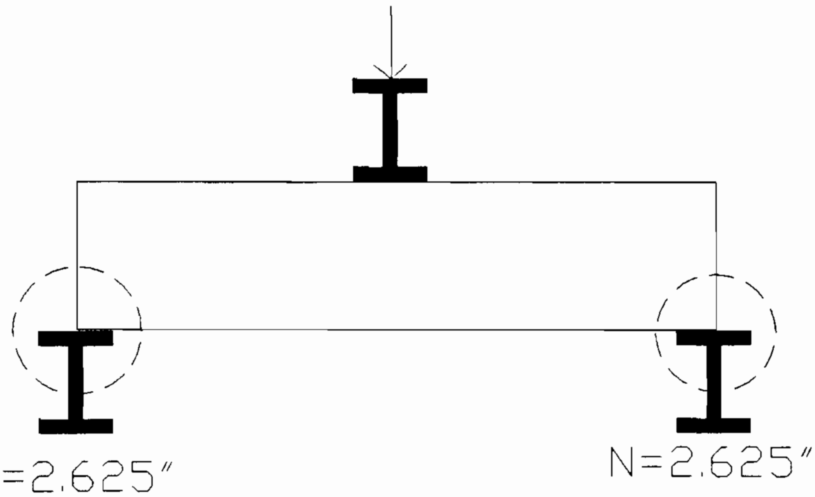
NOTE: Please refer to Figure 6 for definitions.

Figure 11 shows typical bearing conditions of the EOF loading condition and the IOF loading condition. The clear span distance between the bearing was kept slightly greater than 1.5h to maintain one-flange loading.

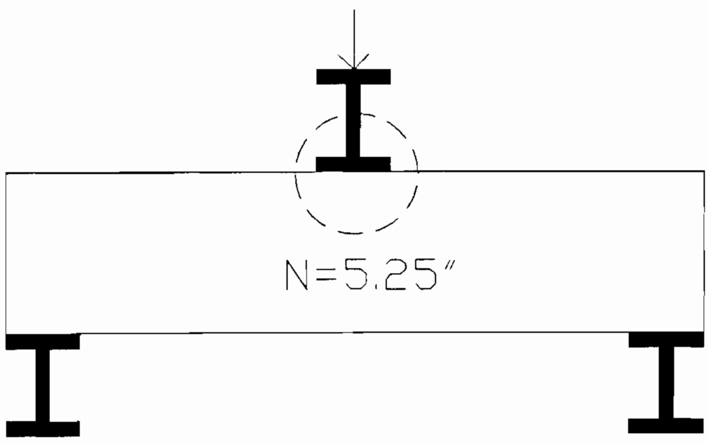
All I-beam specimens were fabricated by adjoining the webs of two identical channels sections. The two channels were connected by bolts as shown in Figure 12. The lapped Z-Sections were also connected using a bolted connection, as shown in Figure 13. Test specimens of channels, unlapped Z-Sections, and lapped Z-Sections required bracing to maintain a constant cross section. A complete explanation of the test specimen geometry is given under Test Procedure.

In order to cause a particular type of failure to occur at particular locations, stiffeners were added on the specimens. For example, for the case of EOF loading, the portion of the web directly under the concentrated load was stiffened to force the failure on the ends. The opposite was done for the case of IOF loading, for which the portions of the web directly above the end supports were stiffened to force the failure to occur under the interior support.

As stated earlier, a total of fifty-two tests were performed under these two types of loading conditions. One-half of the fifty-two tests were with the flanges fastened to the supports and the other half without flanges fastened. The fasteners used for restraining the flanges were 1/2 inch diameter A307 bolts. They were fastened to the support beams on center. For the EOF loading case the fasteners were placed



a) EOF Loading Condition



b) IOF Loading Condition

Figure 11. Typical Bearing Conditions for a) EOF Loading Condition and b) IOF Loading Condition.

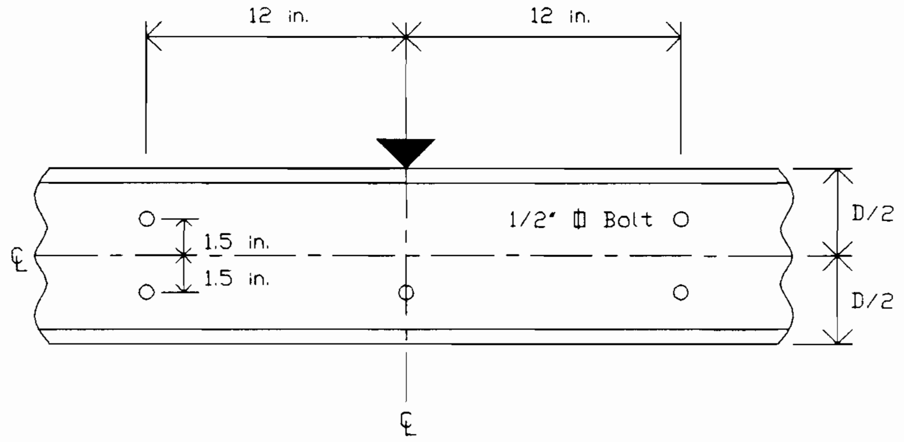


Figure 12. Typical Bolt Pattern for I-Sections.

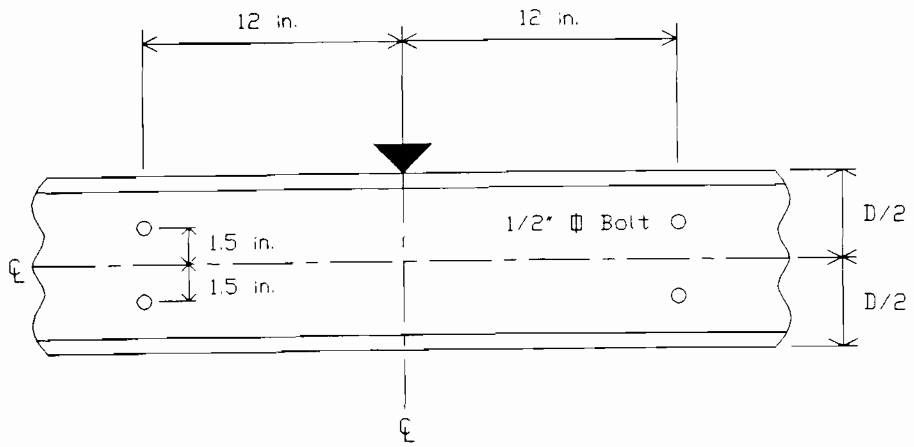


Figure 13. Typical Bolt Pattern for Lapped Z-Sections.

on the end supports and for the IOF loading case the fasteners were placed under the applied concentrated load.

The measured dimensions of the test specimens and the important parameters used in calculations are presented in Tables III through XIII. The cross section dimensions of the tested specimens were measured from photocopies of the cross section.

Table IX PARAMETERS AND TEST DATA OF CHANNELS

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	F_y (ksi)	P_t (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 X PARAMETERS AND TEST DATA OF I-SECTIONS

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	F_y (ksi)	P_t (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	62.680	4.763
I10-F	0.063	130.921	4.968	83.333	0.637	62.680	4.838
I11	0.063	131.222	4.968	83.333	0.635	62.680	4.538
I12	0.063	131.127	4.968	83.333	0.636	62.680	4.463

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

C. TEST PROCEDURE

All specimens tested were loaded to failure. Details of the test arrangement under each loading condition are summarized as follows:

1. Channels: A total of twelve channel sections were tested as simply supported members subjected primarily to web crippling by a concentrated load applied at midspan. All of the channel sections were tested under the EOF loading condition. The test arrangement and the test set-up are shown in Figures 14 and 15. All of the specimens were loaded at

Table XI PARAMETERS AND TEST DATA OF Z-SECTIONS

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	F_y (ksi)	P_t (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 XII PARAMETERS AND TEST DATA OF LONG SPAN ROOF DECKS

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	F_y (ksi)	P_t (kips)
RD1	0.049	145.429	4.143	53.571	0.368	43.820	0.688
RD2	0.049	145.306	4.143	53.571	0.369	43.820	0.681
RD3-F	0.049	145.367	4.143	53.571	0.369	43.820	0.931
RD4-F	0.049	145.449	4.143	53.571	0.368	43.820	0.950

F = Represents flanges fastened to supports.
N = 2.625 inches (EOF Tests).

Table XIII PARAMETERS AND TEST DATA OF FLOOR DECKS

Specimen No.	t (in.)	h/t	R/t	N/t	N/h	F_y (ksi)	P_t (kips)
EOF TESTS							
FD1	0.026	102.731	6.615	100.962	0.983	57.494	0.340
FD2	0.026	102.885	6.615	100.962	0.981	57.494	0.333
FD3-F	0.026	102.885	6.615	100.962	0.981	57.494	0.402
FD4-F	0.026	102.808	6.615	100.962	0.982	57.494	0.415
IOF TESTS							
FD5	0.026	103.000	6.615	201.923	1.960	57.494	0.738
FD6	0.026	102.769	6.615	201.923	1.965	57.494	0.758
FD7-F	0.026	102.769	6.615	201.923	1.965	57.494	0.788
FD8-F	0.026	102.846	6.615	201.923	1.963	57.494	0.779

F = Represents flanges fastened to supports.
N = 2.625 inches (EOF Tests).
N = 5.25 inches (IOF Tests).

mid-span with the clear distance between the opposite bearing plates being 1.5h. Three different types of channel sections were tested. They varied in their h/t ratio as follows: h/t ≈ 69, h/t ≈ 116, and h/t ≈ 132. Four test specimens for each h/t ratio were tested, two tests with flanges fastened to supports and two with flanges unfastened to supports.

For all tests, a 2-5/8" bearing length was used at the ends and a 5-1/4" bearing length was used under the applied concentrated load. All specimens were braced by 3/4 X 3/4 X 1/8 in. aluminum angles at every 1/3 points on both the compression and the tension side of the beam to maintain a constant cross section during the test. Smaller cold-formed steel channel sections were used as stiffeners by means of self-tapping screws directly under the applied concentrated load to force the failure to occur on the ends.

During the test, the geometry of the sections caused some rotation in the specimen as the applied load increased. To minimize this problem a strip of metal (12 X 3/4 X 0.05 in.) was added by connecting one of the flanges of the test specimen to the flanges of the end support (I-beam). The ultimate test loads were very similar with or without this adaptation.

2. I-Sections: A total of twelve I-Sections were subjected to web crippling loads. The application of the concentrated load was the same as the channel sections except that the I-Sections were tested under the IOF loading condition. The I-Sections were fabricated from two channels

connected back-to-back. See Figures 4, 16 and 17. A typical industry type bolt pattern was used to connect the two channels, as shown by Figure 12. As explained earlier, 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 h/t ratio (same as the channels sections), two with flanges fastened to the support member and two with flanges unfastened. Two fasteners, 1/2-inch A307 bolts, were attached to the flanges of the specimen and the I-beam used as the concentrated load in the interior as shown on Figure 18.

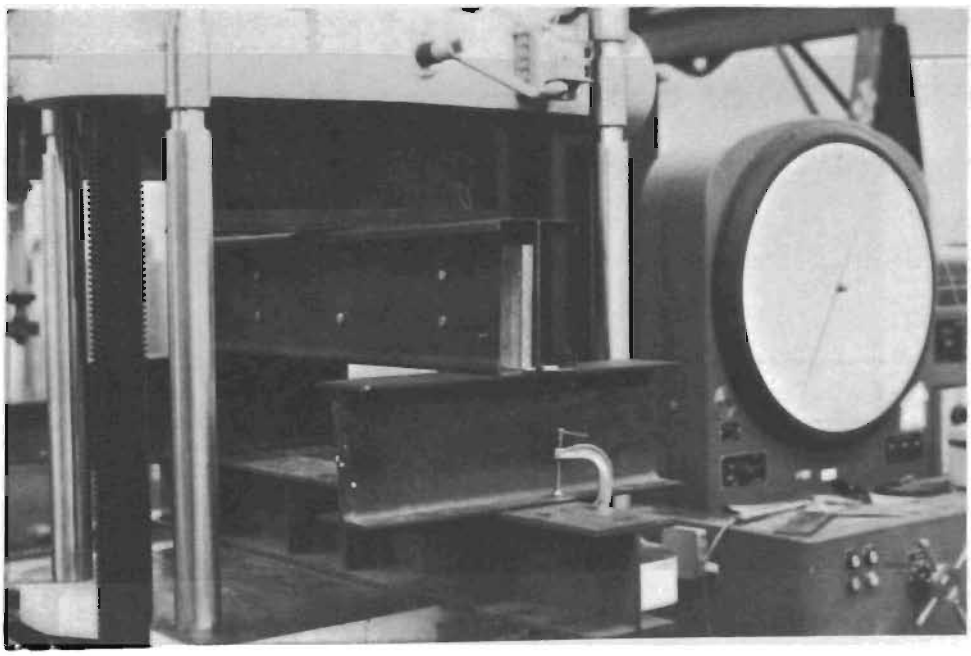


Figure 16. Photograph of a Typical I-Section Specimen Subjected to IOF Loading with Unrestrained Flanges.

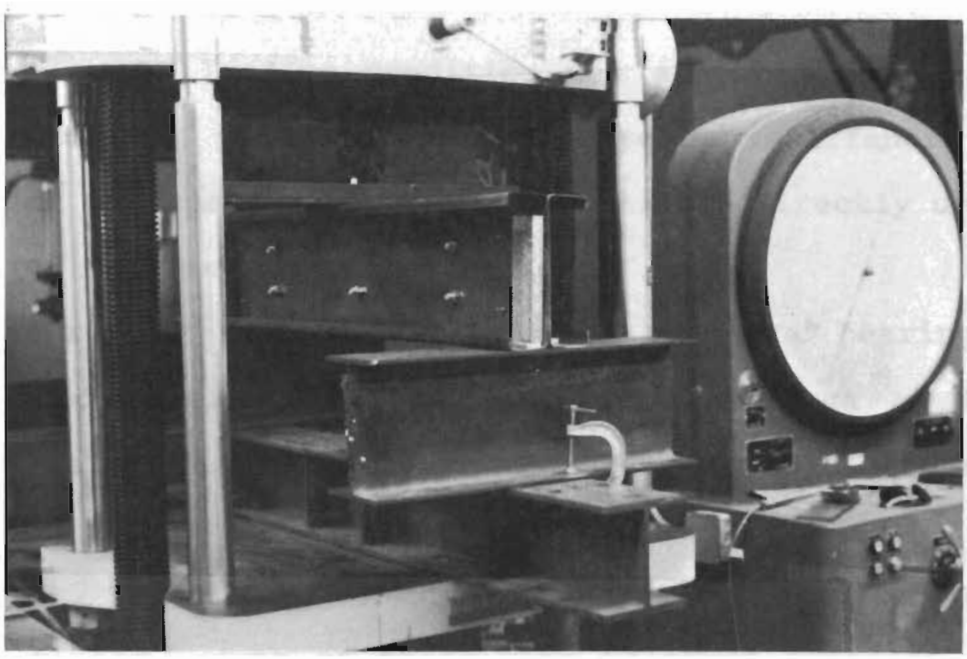


Figure 17. Photograph of a Typical I-Section Specimen Subjected to IOF Loading with Restrained Flanges.

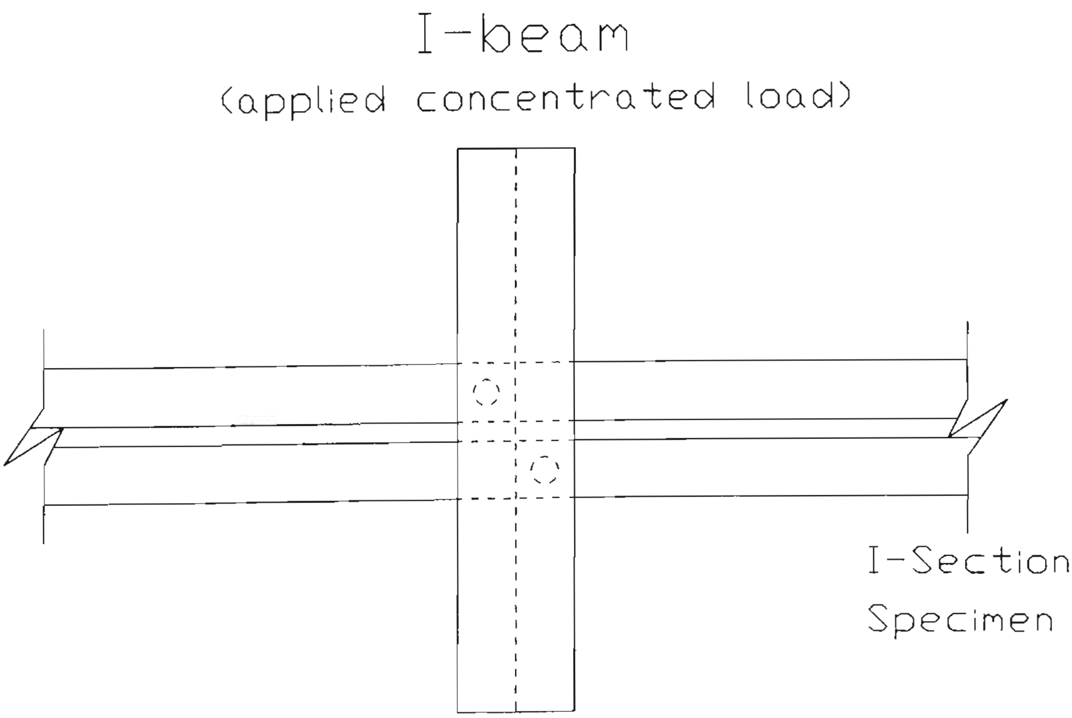


Figure 18. Top View of a Typical Connection of an I-Section With Flanges Restrained.

The IOF loading condition was achieved by adding the small channel sections as transverse web stiffeners on the ends of the specimen to force the failure directly under the applied interior concentrated load.

For all I-Section test specimens, a 5-1/4" bearing length was used under the interior load as well as at the end supports. Test parameters and results are discussed in Section IV.

3. Z-Sections: A total of sixteen Z-Section specimens were tested, eight of these were unlapped sections and the remaining were lapped sections. The test arrangement for each case is discussed as follows:

a. Unlapped Z-Sections: The eight unlapped Z-Sections tested were all under the EOF loading condition. 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 the compression flanges. The bracing interval was selected to preclude lateral movement of the individual section. Once again, the member length was chosen to provide a minimum of 1.5h distance between the edges of bearing plates. From the eight sections tested, four were with flanges fastened to supports and four with flanges unfastened. The fasteners, 1/2-inch diameter A307 bolts were attached to the flanges on the ends of the specimen and the end supports. See Figures 19 and 20 for test set-up of the unlapped Z-Sections subjected to the EOF loading condition.

Figure 19. Photograph of a Typical Failure of an Unlapped Z-Section Subjected to EOF Loading with Unrestrained Flanges.

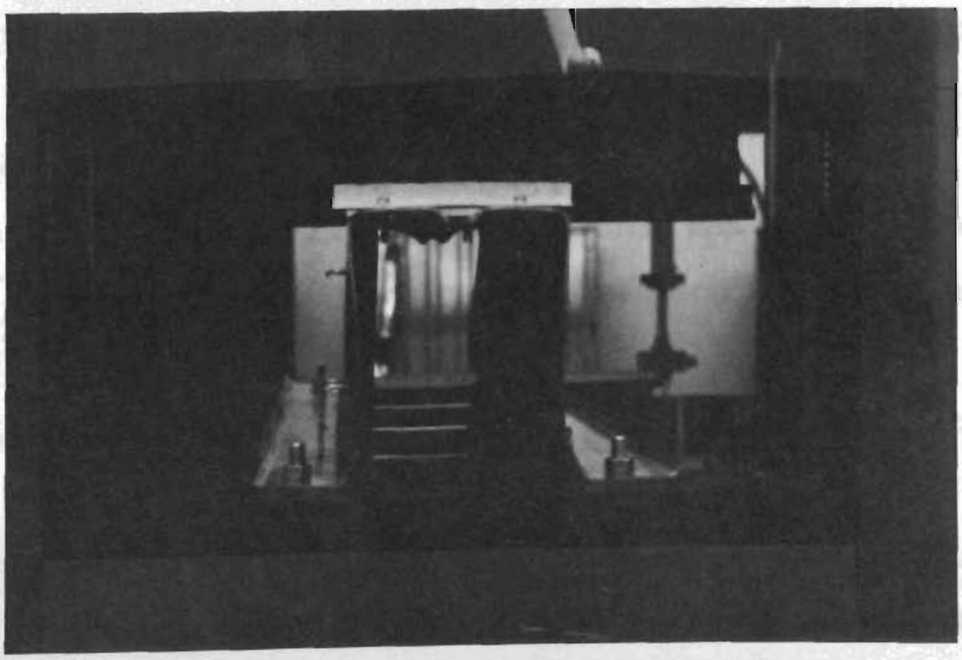


Figure 20. Photograph of a Typical Failure of an Unlapped Z-Section Subjected EOF Loading with Restrained Flanges.

For all tests, a 2-5/8" bearing length was used for the end supports and a 5-1/4" bearing length under the interior applied concentrated load. Test parameters and results are discussed in Section IV.

b. Lapped Z-Sections: The eight lapped Z-Sections tested were all under the IOF loading condition. The bracing and the member length used were based on the same guidelines as used for the unlapped sections. Four out of the eight tests were with flanges fastened to the support (applied concentrated load) and the remaining four were without fasteners. Because this was an IOF loading condition, the fasteners were placed to attach the flanges of the test specimen and the concentrated load beam. The two lapped Z-Sections were connected by 1/2-inch diameter A307 bolts. A typical industry standard lap was employed as shown by Figure 13. See Figures 21 and 22 for test set-up of lapped Z-Sections subjected to IOF loading.

For all tests, a 5-1/4" bearing length was used for all support attachments. Test parameters and results are discussed in Section IV.

4. Long Span Roof Decks (LSRD): A total of four long span roof deck (hat sections) sections were tested, all under the EOF loading condition. Two specimens were with flanges fastened to the end supports and two without any fasteners. The test set-up remained the same as used in previous tests. See Figures 23 and 24. The member length was chosen to ensure a minimum of 1.5h between the edges of the bearing plates.

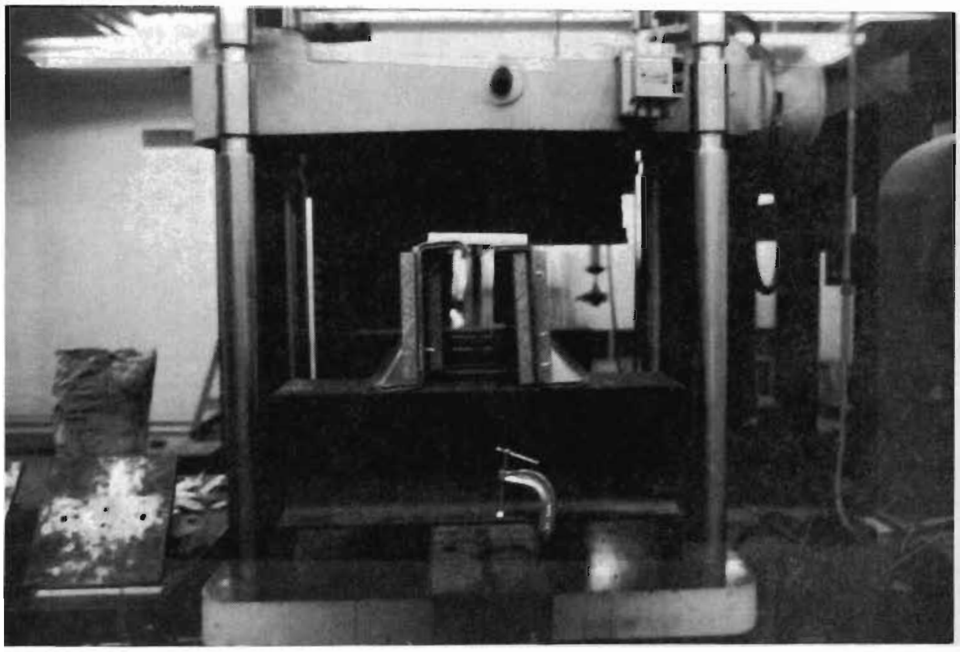


Figure 21. Photograph of a Typical Lapped Z-Section Subjected to IOF Loading with Unrestrained Flanges.

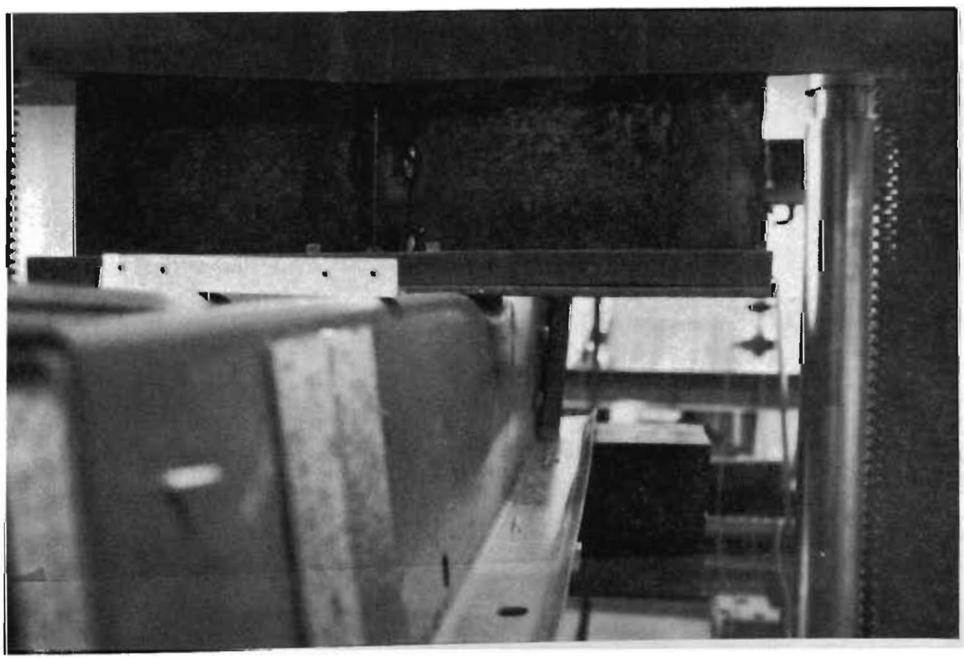


Figure 22. Photograph of a Typical Failure of a Lapped Z-Section Subjected IOF Loading with Restrained Flanges.

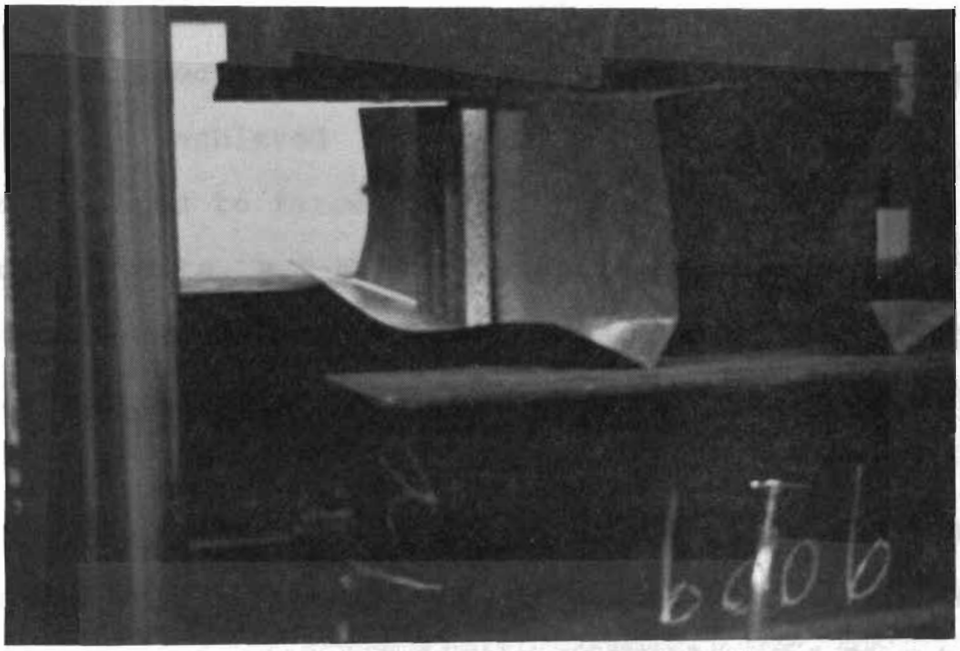


Figure 23. Photograph of a Typical Failure of a LSRD Specimen Subjected to EOF Loading with Unrestrained Flanges.

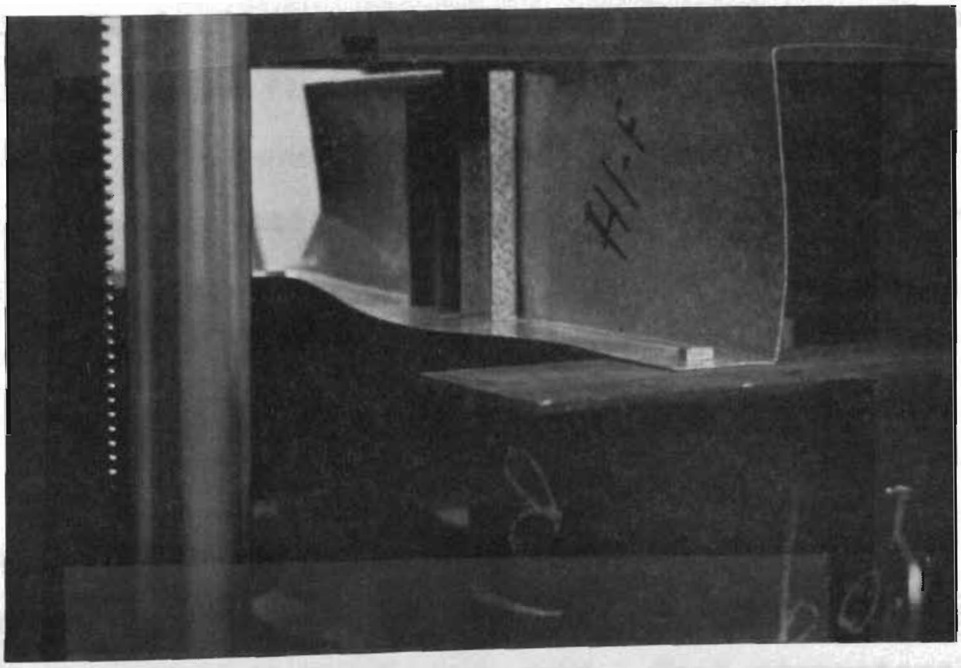


Figure 24. Photograph of a Typical Failure of a LSRD Specimen Subjected to EOF Loading with Restrained Flanges.

All four test specimens were for h/t ≈ 145. The EOF loading condition was achieved by adding stiffeners under the concentrated load to force the failure on the ends.

For all tests, a 2-5/8" bearing length was used on the end supports and a 5-1/4" bearing length at the interior support. Test parameters and results are discussed in Section IV.

5. <u>Floor Decks:</u> A total of eight floor decks were tested under two different loading conditions. Four tests were performed under the EOF loading condition and four tests were performed under the IOF loading condition. The test arrangement for each case is discussed as follows:

a. <u>EOF Loading Condition:</u> A minimum of 1.5h distance between the edges of the bearing plate was again provided. The four test specimens were all of h/t ≈ 103, with two specimens having flanges fastened to end supports and two with flanges unfastened. The EOF loading condition was achieved by adding stiffeners under the concentrated load. The stiffeners used for floor decks were 5-1/4" wide sections of the same floor deck simply placed over the test specimen and connected with self-tapping screws. See Figures 25 for a typical test set-up.

For all four tests, the bearing length on the end supports was 2-5/8" and under the applied concentrated load beam a 5-1/4" bearing length was used. Test parameters and results are discussed in Section IV.

b. IOF Loading Condition: The four test specimens prepared were of h/t ≈ 103. The member length guidelines were the same as for the EOF loading condition. The IOF loading condition was achieved by placing the floor deck stiffener at the ends of the test specimen. For all four tests, the bearing length was 5-1/4" at the end supports as well as under the applied concentrated load beam. See Figure 26. Test parameters and results are discussed in Section IV.

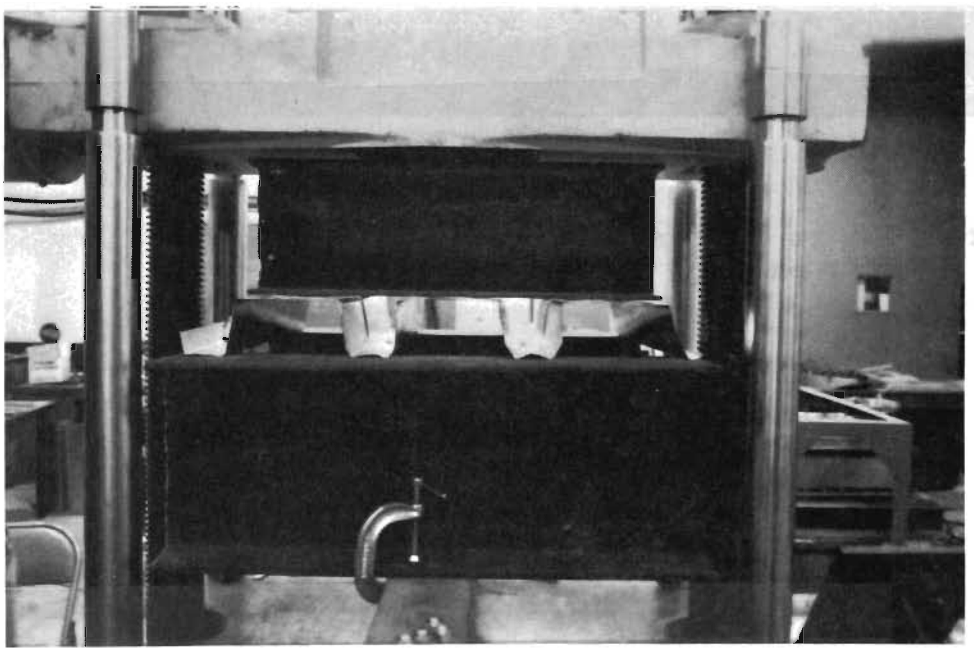


Figure 25. Photograph of a Typical Failure of a Floor Deck Specimen Subjected to EOF Loading with Unrestrained Flanges.

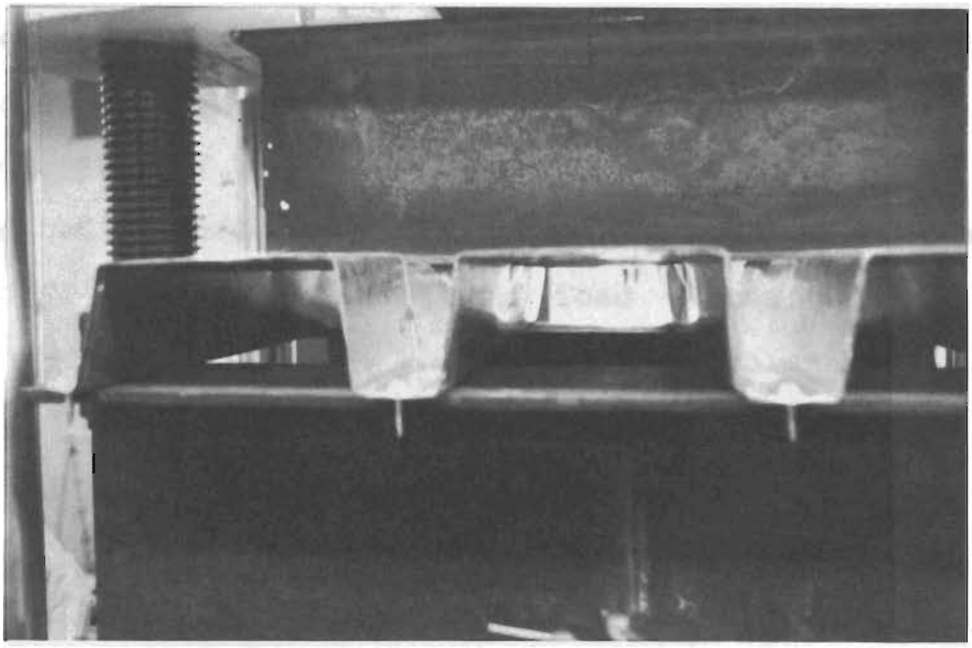


Figure 26. Photograph of a Typical Failure of a Floor Deck Specimen Subjected to IOF Loading with Unrestrained Flanges.

IV. DISCUSSION OF RESULTS

All test specimens were loaded to failure. The tested failure load values and the nature of the failure modes were recorded and appear to be very consistent for identical specimens. For each type of section tested, the total failure load was divided by the number of webs responsible for carrying the applied load. The tested load values per web are denoted by P_t, and the computed load values per web are denoted by P_c. The results are recorded in Tables XIV through XXXI.

The following discussion will summarize the findings obtained from this research as they apply to each of the cross section types. A comparison of the computed load value, from both the AISI Specification and Santaputra's equations, versus the tested load value is presented along with the comparison of the tested load values of specimens with flanges restrained versus specimens with flanges unrestrained. Also, the behavior of the test specimens under either the EOF or the IOF loading conditions is presented.

A. <u>CHANNELS</u>

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 III summarizes the dimensions of the test specimens, and Figure 1 shows the typical cross section of the test specimen. The equations used to compute the web crippling strength, P_c, were Equation 4 (AISI) and Equations 8 and 9 (Santaputra). The value computed from the AISI equation was multiplied by 1.85 to consider the factor of safety. Test parameters and results are given in Tables IX, XIV, and XV.

Table XIV CHANNELS (EOF): COMPARISON OF RESULTS BASED ON AISI SPECIFICATION

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
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 per web.
P_c = Computed load per web.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table XV CHANNELS (EOF): COMPARISON OF RESULTS BASED ON SANTAPUTRA'S EQUATIONS

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
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	1.192	1.253	
C10-F	131.508	1.488	1.192	1.248	
C11	131.254	1.494	1.192	1.253	
C12	131.492	1.513	1.192	1.269	0.992

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

For the four test specimens having h/t ≈ 70 and R/t ≈ 1.4, the tested and computed loads are listed in Tables XIV and XXI. The accuracy of the prediction equations is represented by the ratio of P_t/P_c. The AISI equation (Table XIV) overestimated the web crippling strength by as much as 18%, while Santaputra's equations (Table XV) overestimated the strength by as much as 24% for specimens C3 and C4. 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} (Tables XIV and XV).

Four specimens were also tested for $h/t \approx 115$ and $R/t \approx 2.4$ (Tables XIV and XV). The tested loads and computed loads correlated well for both the AISI and Santaputra's equations for specimens C7 and C8. 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 XIV and XV) there existed a 58 percent conservatism in the computed value when the AISI equation was used. This is considerably more conservative than the other channels section tested, but it is still well within the scatter of data points of previous research (Figure 24 of Hetrakul and Yu, 1978). 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.

All web crippling failures for the channel specimens occurred directly above the end supports. The specimens with the flanges unfastened to the supports showed a relatively large vertical deflection of the bottom flanges at the end supports combined with lateral deformation in the webs. The test specimens with the flanges fastened to the end supports behaved differently. The fasteners prevented the bottom flanges from deflecting under loading, therefore there was slightly more lateral deformation in the webs as shown in Figure 15.

There was some concern with some test specimens encountering twisting in the specimens. To minimize this problem, a metal strip was attached to the specimen and the end support. There was initial concern that this may lead to invalid comparisons with tested load values with and without this adaptation. However, two identical channel sections were tested in which one specimen had some twisting problems and the other did not, and the ultimate tested loads were very similar, as evidenced by the results of test specimens C3 and C4 (Table IX) which yielded results of 4.269 kips per web and 4.244 kips per web, respectively.

B. <u>I-SECTIONS</u>

Sections used to fabricate the channel specimens were also used to fabricate the I-Sections. Four test specimens were fabricated for each h/t value, two with flanges fastened to the support member and the remaining two specimens with flanges unfastened. Equation 7 (AISI) was used for the computed loads along with Equations 12 and 13 (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. Test parameters and results are given in Tables X, XVI, and XVII.

For all twelve test specimens, as indicated by Tables XVI and XVII, 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.

The failure modes of all twelve test specimens, under the IOF loading condition, were observed to be a local bearing type failure directly under the applied concentrated load. See Figures 17 and 18. There did not appear to be a great difference in the failure pattern in the I-Section with the flanges fastened versus flanges unfastened to supports, and as a result no significant increase in the load carrying capacity of the latter type specimen as discussed above.

Table XVI I-SECTIONS (IOF): COMPARISON OF RESULTS BASED ON AISI SPECIFICATION

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
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 per web.
P_c = Computed load per web.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

C. Z-SECTIONS

A total of sixteen Z-Section specimens were tested, eight of these were unlapped sections and eight were lapped sections. The unlapped Z-sections were all subjected to an EOF loading and the lapped sections were all subjected to an

Table XVII I-SECTIONS (IOF): COMPARISON OF RESULTS BASED ON SANTAPUTRA'S EQUATIONS

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
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 per web.
P_c = Computed load per web.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

IOF loading. Equation 4 (AISI), and Equations 8 and 9 (Santaputra) were used for the unlapped sections. Equation 6 (AISI) and Equations 10 and 11 (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 XI, XVIII, XIX, XX, and XXI. Tables IV and V give the cross section dimensions. The unlapped sections will be discussed first, followed by the lapped sections. Two sets of Z-Sections were tested with varying h/t ratios, h/t ≈ 133 and h/t ≈ 72.

1. Unlapped Sections: For the specimens having an h/t ≈ 132, two tests were conducted with flanges fastened to the support 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 XVIII and XIX). 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 XVIII), while for the same test specimens, Santaputra's equations were about 32 percent less than the tested load (Table XIX).

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 XVIII and XIX). 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 to 30 percent larger than the predicted value as given by the

AISI equation (Table XVIII). For the same specimens, Santaputra's equations underestimated the failure load by about 45 percent (Table XIX).

For the EOF loading of the Z-sections there was 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.

The failure modes of these unlapped Z-Sections were very similar to those of the channel specimens discussed earlier. A combination of vertical deflection of the bottom flanges and lateral deformation in the webs (reverse curvature of the web) was observed directly above the end supports for specimens with the flanges unrestrained. The test specimens with the flanges restrained were limited to only lateral deformation in the webs. See Figures 19 and 20. Once again, there was some twisting problem encountered in some of the test specimens and this was resolved by using the same solution as discussed for the channel specimens.

2. Lapped Sections: Eight specimens have been tested for the lapped Z's (Tables XI, XX and XXI). A typical industry lap was employed, as shown by Figure 13. All eight lapped Z-Section specimens were subjected to the IOF loading condition.

For the four test specimens having $h/t \approx 132$, the tested loads compared favorably with the predictions from AISI (Table

XX) and Santaputra (Table XXI). 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 ≈ 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.

Table XVIII UNLAPPED Z-SECTIONS (EOF): COMPARISON OF RESULTS BASED ON AISI SPECIFICATION

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
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 per web.
P_c = Computed load per web.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

Table XIX UNLAPPED Z-SECTIONS (EOF): COMPARISON OF RESULTS BASED ON SANTAPUTRA'S EQUATIONS

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
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	1.324	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 per web.
P_c = Computed load per web.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

These eight specimens experienced very little deflection in the flanges under the applied concentrated load. The primary deformation occurred was a combination of some flange curling and lateral deformation of the webs. There was no noticeable difference in the failure modes between specimens with flanges restrained and specimens with flanges unrestrained. Figures 21 and 22 shows a typical set-up and failure mode of a lapped Z-Sections under the IOF loading condition.

Table XX LAPPED Z-SECTIONS (IOF): COMPARISON OF RESULTS BASED ON AISI SPECIFICATION

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
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 per web.
P_c = Computed load per web.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

D. LONG SPAN ROOF DECKS

A total of four specimens were tested under the EOF loading condition, all with a h/t ratio of h/t ≈ 145. Two specimens were with the flanges fastened to the supports and two without fasteners. Equation 5 (AISI) and Equations 8 and 9 (Santaputra) were used to compute the web crippling strength. The value from the AISI Equation was multiplied by 1.85 to account for the factor of safety. Test parameters and results are given in Tables XII, XXII and XXIII.

Table XXI LAPPED Z-SECTIONS (IOF): COMPARISON OF RESULTS BASED ON SANTAPUTRA'S EQUATIONS

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
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 per web.
P_c = Computed load per web.
P_f = Test load with flanges fastened to supports.
P_{uf} = Test load with flanges unfastened to supports.

The tested and the computed loads are listed in Tables XXII and XXIII. For this very limited study, the AISI Equation underestimates the web crippling strength by almost 70%, while Santaputra's equations underestimated by as much as 25%. There was a significant increase in the web crippling strength with flanges restrained. An average increase of 37.4% in web crippling strength was sighted with the flanges fastened to supports versus flanges unfastened to supports, as indicated by the P_f/P_{uf} ratio in Table XXII.

The failure mode was similar to that of the unlapped Z-Sections. Figures 23 and 24 shows typical failure modes of a LSRD under the EOF loading condition.

Table XXII LONG SPAN ROOF DECKS (EOF): COMPARISON OF RESULTS BASED ON AISI SPECIFICATION

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
RD1	145.429	0.688	0.406	1.695	
RD2	145.306	0.681	0.406	1.677	
RD3-F	145.367	0.931	0.406	2.293	
RD4-F	145.449	0.950	0.406	2.340	1.374

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

E. <u>FLOOR DECKS</u>

The two cases of loading conditions used in floor decks were the EOF loading condition and the IOF loading condition. Each is explained in the following discussion.

1. <u>EOF Loading:</u> Four specimens tested under this loading case were for h/t ≈ 103 with two specimen's flanges

Table XXIII LONG SPAN ROOF DECKS (EOF): COMPARISON OF RESULTS BASED ON SANTAPUTRA'S EQUATIONS

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
RD1	145.429	0.688	0.551	1.249	
RD2	145.306	0.682	0.551	1.238	
RD3-F	145.367	0.932	0.551	1.691	
RD4-F	145.449	0.950	0.551	1.724	1.374

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

fastened to supports and two specimens with flanges unfastened to supports. Equation 4 (AISI) and Equations 8 and 9 (Santaputra) were used to compute the theoretical value. The AISI equation underestimated the tested value by almost 50% and Santaputra's equations underestimated the tested value by 25%. This is also very consistent with results of previous research. There was an increase of 21.3% in web crippling strength with flanges fastened to supports as opposed to flanges without fasteners. See Tables XIII, XXIV, and XXV.

All four test specimens experienced a buckling failure in the webs of the specimens. For the four test specimens, the flanges on the ends had very little deflection, while the interior flanges had some flange curling. However, lateral

Table XXIV FLOOR DECKS (EOF): COMPARISON OF RESULTS BASED ON AISI SPECIFICATION

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
FD1	102.731	0.340	0.228	1.491	
FD2	102.885	0.333	0.228	1.461	
FD3-F	102.885	0.402	0.228	1.763	
FD4-F	102.808	0.415	0.228	1.820	1.213

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

Table XXV FLOOR DECKS (EOF): COMPARISON OF RESULTS BASED ON SANTAPUTRA'S EQUATIONS

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
FD1	102.731	0.340	0.271	1.255	
FD2	102.885	0.333	0.271	1.229	
FD3-F	102.885	0.402	0.271	1.483	
FD4-F	102.808	0.415	0.271	1.531	1.213

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

deformation of the webs directly above the end supports was the controlling failure mode for all specimens. Refer to Figure 25 for a typical failure of a floor deck under the EOF loading condition.

2. <u>IOF Loading:</u> The four test specimens tested under the IOF loading condition were for h/t ≈ 103. Equation 6 (AISI) and Equations 10 and 11 (Santaputra) were used to determine the computed load values of web crippling strength. The AISI Specification underestimated the tested value by 53% and Santaputra's equations underestimated the tested values by about 70%. There was no significant increase in the web crippling strength with fastened flanges and unfastened flanges. See Tables XIII, XXVI and XXVII.

The four test specimens experienced a combination of flange curling and lateral deformation of the webs directly under the applied concentrated load. Figure 26 shows an example of this failure mode.

To summarize the results of the comparison of the P_{tested} values versus the $P_{computed}$ values for all tests performed, Figures 27 through 32 and Tables 28 through 31 have been created. Figures 27 through 32 summarizes the results in a graphical format. A plot of P_{tested} versus $P_{computed}$ is shown for all tests under the EOF and IOF loading conditions. Two sets of graphs are created, one with $P_{computed}$ based on the AISI Specification equations and the other with $P_{computed}$ based on Santaputra's equations.

Table XXVI FLOOR DECKS (IOF): COMPARISON OF RESULTS BASED ON AISI SPECIFICATION

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
FD5	103.000	0.738	0.489	1.509	
FD6	102.769	0.758	0.489	1.550	
FD7-F	102.769	0.788	0.489	1.611	
FD8-F	102.846	0.779	0.489	1.593	1.047

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

Table XXVII FLOOR DECKS (IOF): COMPARISON OF RESULTS BASED ON SANTAPUTRA'S EQUATIONS

Specimen No.	h/t	P_t (kips)	P_c (kips)	P_t/P_c	P_f/P_{uf} (avg.)
FD5	103.000	0.738	0.439	1.681	
FD6	102.769	0.758	0.439	1.727	
FD7-F	102.769	0.788	0.439	1.795	
FD8-F	102.846	0.779	0.439	1.774	1.047

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

Tables 28 through 31 shows a summary of the P_t/P_c ratios for all tests performed. The tables are separated into categories of tests with unrestrained flanges and tests with restrained flanges for both AISI and Santaputra comparison.

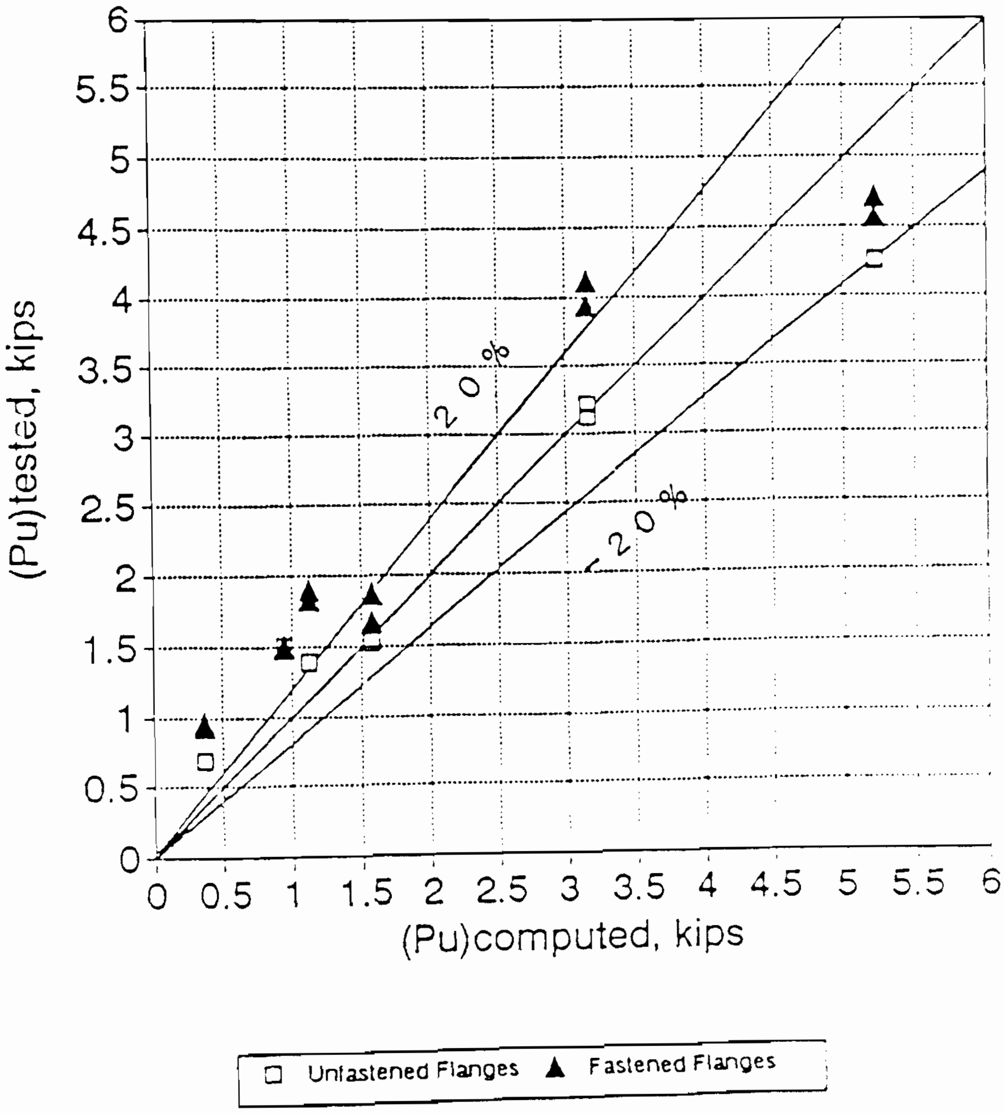


Figure 27. Plot of P_t vs. P_c of all EOF Tests with P_c Based on AISI Specification.

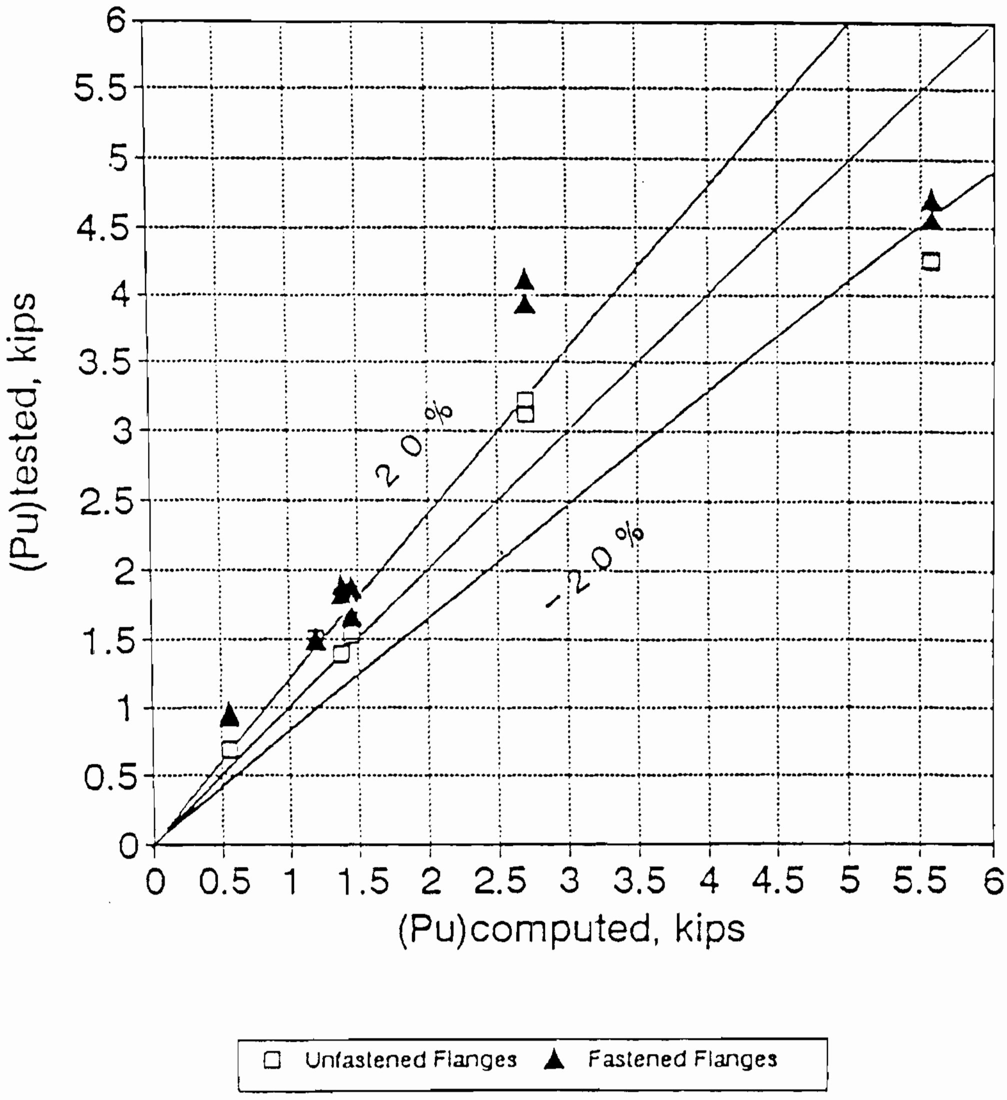


Figure 28. Plot of P_t vs. P_c of all EOF Tests with P_c Based on Santaputra's Equations.

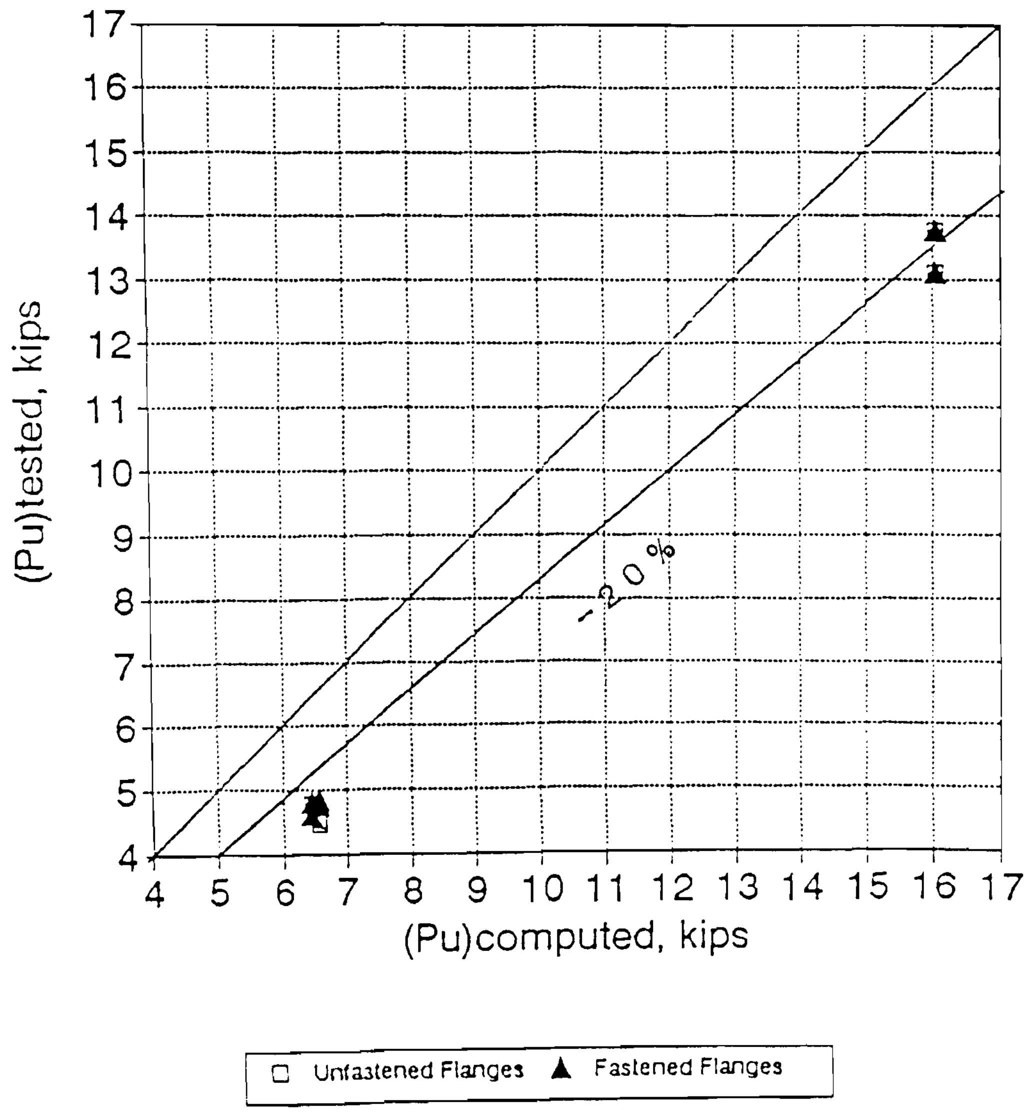


Figure 29. Plot of P_t vs. P_c of I-Sections with P_c Based on AISI Specification.

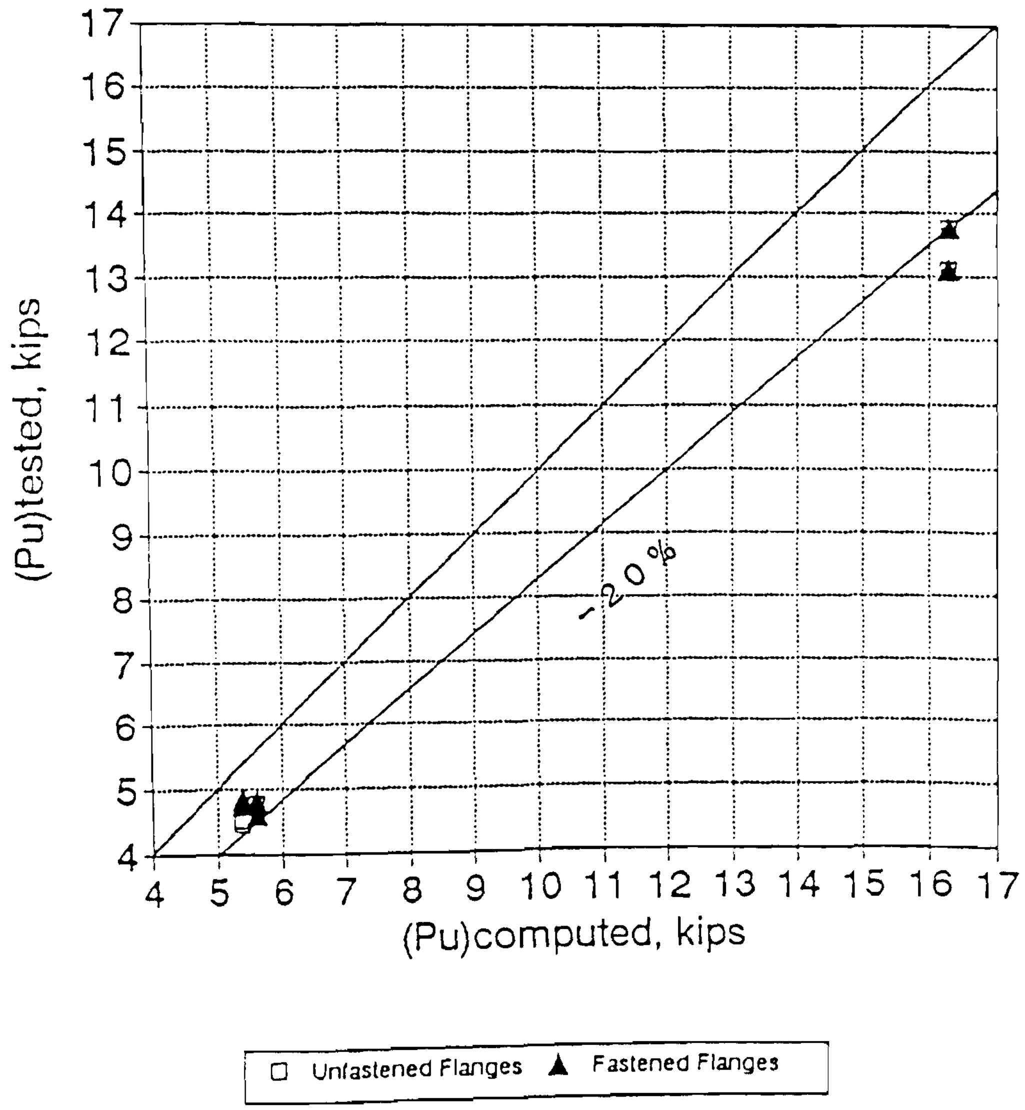


Figure 30. Plot of P_t vs. P_c of I-Sections with P_c Based on Santaputra's Equations.

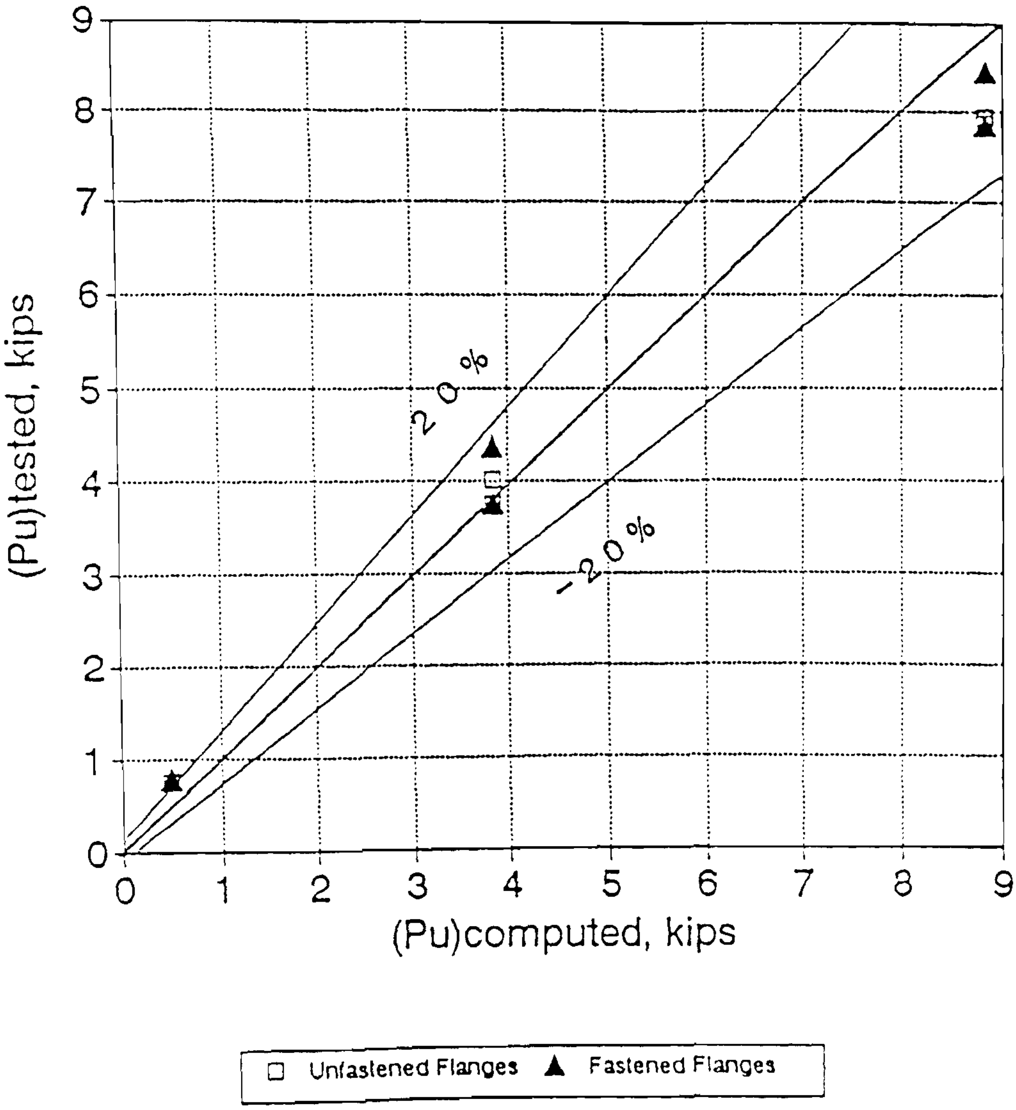


Figure 31. Plot of P_t vs. P_c of all IOF Tests (excluding I-Sections) with P_c Based on AISI Specification.

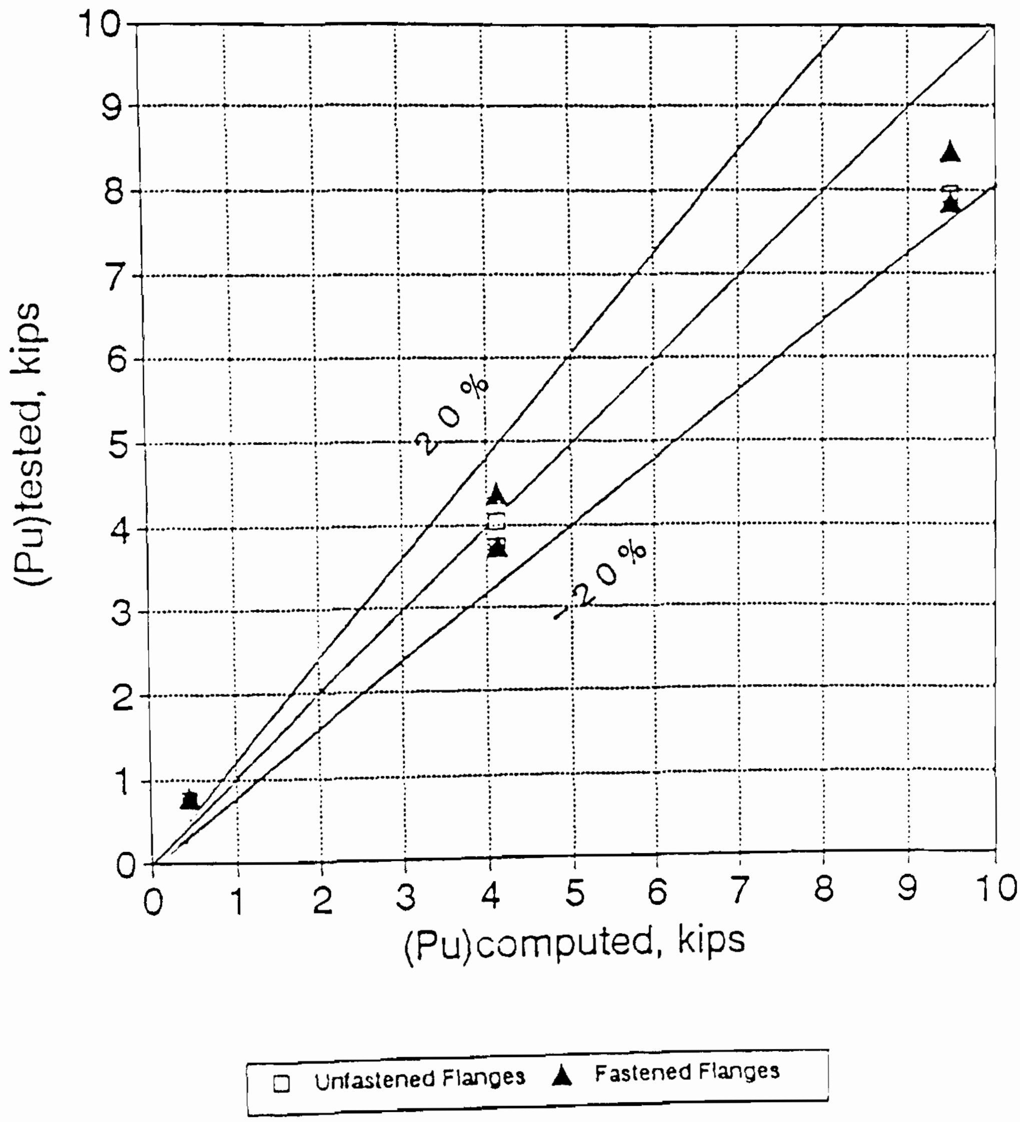


Figure 32. Plot of P_t vs. P_c of all IOF Tests (excluding I-Sections) with P_c Based on Santaputra's Equations.

Table XXVIII 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	1.253
C12	1.606	1.269
Mean	1.131	1.027
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

Table XXIX COMPARISON BETWEEN AISI AND SANTAPUTRA EQUATIONS FOR UNRESTRAINED FLANGE SPECIMENS

Specimen No.	AISI P_t/P_c	Santaputra P_t/P_c
Unlapped Z-Sections, EOF Loading		
Z1	1.242	1.008
Z2	1.236	1.004
Z5	0.990	1.151
Z6	1.019	1.186
Mean	1.122	1.087
Lapped Z-Sections, 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
Long Span Roof Decks, EOF Loading		
RD1	1.695	1.249
RD2	1.677	1.238
Mean	1.686	1.244
Floor Decks, EOF Loading		
FD1	1.491	1.255
FD2	1.461	1.229
Mean	1.476	1.242
Floor Decks, IOF Loading		
FD5	1.509	1.681
FD6	1.550	1.727
Mean	1.530	1.704

Table XXX 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	1.253
C10-F	1.580	1.248
Mean	1.199	1.099
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

Table XXXI COMPARISON BETWEEN AISI AND SANTAPUTRA EQUATIONS FOR RESTRAINED FLANGE SPECIMENS

Specimen No.	AISI P_t/P_c	Santaputra P_t/P_c
Unlapped Z-Sections, EOF Loading		
Z3-F	1.688	1.369
Z4-F	1.632	1.324
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
Long Span Roof Decks, EOF Loading		
RD3-F	2.293	1.691
ED4-F	2.340	1.724
Mean	2.317	1.708
Floor Decks, EOF Loading		
FD3-F	1.763	1.483
FD4-F	1.820	1.531
Mean	1.792	1.507
Floor Decks, IOF Loading		
FD7-F	1.611	1.795
FD8-F	1.593	1.774
Mean	1.602	1.785

V. PROPOSED RECOMMENDATIONS

Based on the results of this study, the following recommendations are made for future research:

- An in depth study of web crippling capacities of I-Sections, subjected to IOF loading, to better define a built-up section.
- Additional study to better quantify the capacities of Z-Sections, long span roof decks, and floor decks subjected to EOF loading condition when flanges are fastened to supports.
- Further study of the web crippling capacities of long span roof decks and floor decks subjected any type of loading condition to improve the prediction equations as necessary.
- Future studies should address the broad range of parameters that influence the web crippling strength, i.e., N/t, R/t, h/t, Fy.

VI. 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 and the location 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.
- For the long span roof decks (EOF), an average increase of over 37 percent in strength was

experienced with flanges restrained by bolting to the support beam.

- For the floor decks under the EOF loading experienced an average increase of over 20 percent in strength with flanges restrained by bolting to the support beam. No significant increase was observed for the floor decks under IOF loading.

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. See Tables XXVIII through XXXI.
- 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. See Tables XXVIII through XXXI.
- For the two types of deck sections tested, the equations of Santaputra, on the average, provided a better prediction of the web crippling strength. See Tables XXIX and XXXI.

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