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Web Crippling of Cold Formed Steel Members

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WEB CRIPPLING OF COLD FORMED STEEL MEMBERS

K. Prabakaran[1] and R.M. Schuster[2]

ABSTRACT

A new design expression for web crippling of cold formed steel members has been developed. An extensive statistical analysis was performed using published test data from Canada, the United States, Sweden and France to develop new expressions for the web crippling strength of cold formed steel members under four different loading cases, i.e. (1) end one-flange loading (EOF), (2) interior one-flange loading (IOF), (3) end two-flange loading (ETF) and (4) interior two-flange loading (ITF). I-sections made of two channels connected back-to-back, Z-sections, channels and multiple web sections (decks) were considered. Comparisons were made with the web crippling expressions presented in the Canadian Standard for the design of cold formed steel structural members, CAN/CSA-S136-M89 (from here on referred to as S136) and with the 1991 LRFD edition of the American Iron and Steel Institute Specification (from here on referred to as AISI).

The web crippling strength depends primarily on the web thickness (t), the yield strength (F_y), the inside bend radius (r), the bearing length of the load (n), the flat dimension of the web measured in the plane of the web (h) and the angle between the plane of web and the plane of the bearing surface (θ). The definition of web depth, h, in both current design standards in Canada (S136) and the United States (AISI) was incorporated in the development of the new expressions. The new developed expression is nondimensional, therefore any consistent units of measurement can be used such as imperial or SI. Certain unnecessary complexities which now exist in both design standards have been removed to simplify the web crippling expressions. Eight simplified new expressions have been developed and one particular expression is recommended for design, which has already been adopted by the 1994 edition of S136.

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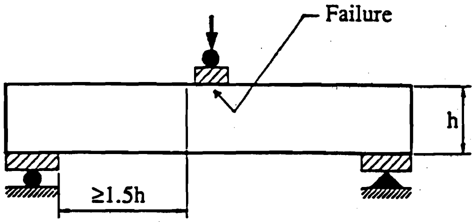
INTRODUCTION

The use of cold formed steel members in building construction started in the United States and the United Kingdom at about the same time around 1850, however, their actual real use began in 1940 and the United States led the way in terms of research, application and design. The reason being that cold formed steel members can be produced in many different shapes in a most cost efficient manner.

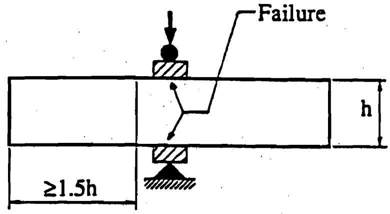
When a cold formed steel member is subjected to load, a concentrated load is normally induced into the web at the point of load application between supports or by way of the reaction at a support. Hence, these loads can cause localized crushing or crippling in the web if the web is relatively thin. Exterior (end) one-flange loading (EOF) or interior one-flange loading (IOF) can be caused by a concentrated load acting on a member at the end (exterior) or somewhere in the middle (interior) of the span. Two-flange loading is experienced if the load is located at the end, exterior two-flange loading (ETF) or in the middle of the span, interior two-flange loading (ITF). See Fig. 1 for schematic illustration of these four load cases.

In addition to these four load cases, the web crippling strength also depends on the web thickness (t), the tensile yield strength (F_y), the inside bend radius (r), the bearing length of the load (n), the flat dimension of the web measured in the plane of the web (h) and the angle between the plane of web and the plane of the bearing surface (θ). Therefore, it is clear that a purely theoretical analysis of web crippling under concentrated loading is extremely complex and it is necessary to use experimental test data in the development of any web crippling strength expression.

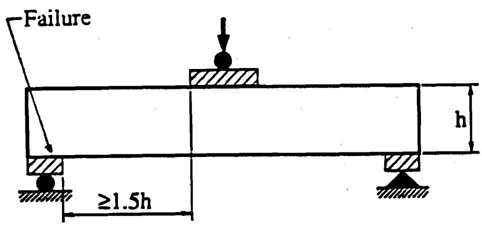
Winter and Pian [9] first investigated the problem of web crippling of cold formed steel members in 1946 at Cornell University. They carried out over 100 tests on I-sections to develop expressions for computing the web crippling strength, considering four different load cases, as shown in Fig. 1. Since then, numerous experimental tests have been carried out relating to web crippling of cold formed steel sections. Used in this study are the test results contained in References [2], [4] to [9]. The current cold formed steel design standards in both the United States (AISI[1]) and Canada (S136[3]) use similar expressions to calculate the web crippling strengths of cold formed steel members. These expressions have been modified over the years, such as in case of the introduction of k {= F_y(ksi)/33 (F_y(N/mm^2)/228)} to take into account different yield strengths of steel. Also, the steel thickness term ,t, was introduced in some of the web crippling expressions, resulting in a dimensional dependency. As well, the web dimension, h, has been changed from the clear distance between flanges ,h', to the flat dimension of the web, an item that has not been incorporated in the current web crippling expressions (see Fig. 2).



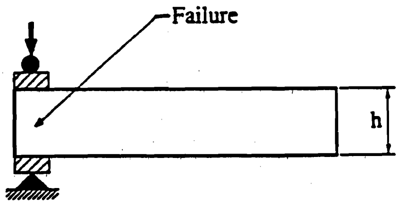
(a) Interior One-Flange Loading (IOF)



(c) Interior Two-Flange Loading (ITF)

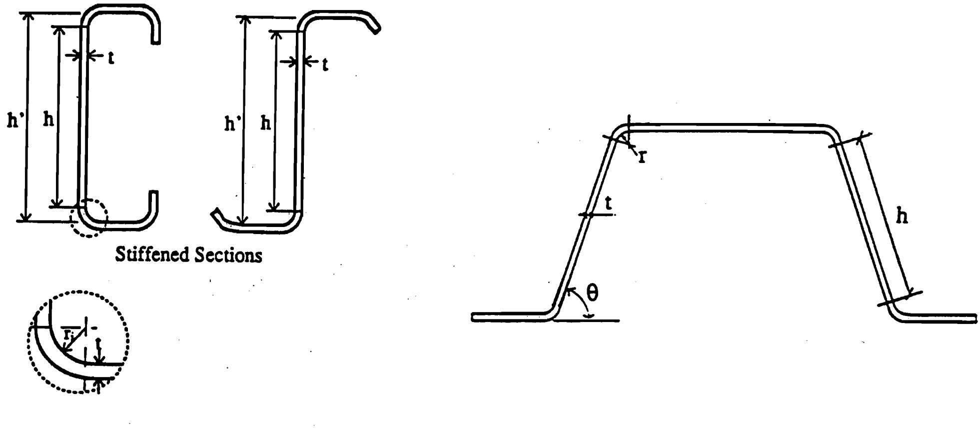


(b) Exterior One-Flange Loading (EOF)



(c) Exterior Two-Flange Loading (ETF)

Figure 1: Web Crippling Loading Cases [9]



(a) C and Z-Section **(b) Multiple Web Section (Deck)**

Figure 2: Definition of Parameter (h)

OBJECTIVE AND SCOPE

The objective of this investigation was to develop a new simplified and totally non-dimensional web crippling expression without the (k) term and incorporating the new definition of (h). Presented in this paper are the results of the final recommended design expression which was chosen from eight possible expressions investigated by Prabakaran[5]. In addition, statistical comparisons were made using the S136[3] and AISI[1] web crippling expressions to substantiate the new recommended design expression.

The study was restricted to the investigation of the web crippling strength of cold formed steel members subjected to web crippling load only, even though in practice most cold formed steel members are subjected to web crippling and bending.

DEVELOPMENT OF NEW EXPRESSION

The following eight web crippling expressions were considered by Prabakaran[5] in the statistical analysis of I-sections, single web and multiple web (deck-type) sections:

$$P_n = Ct^2F_y(1 - C_R R)(1 + C_N N)(1 - C_H H) \qquad \text{(Eq.1)}$$

$$P_n = Ct^2F_y(1 - C_R\sqrt{R})(1 + C_N N)(1 - C_H H) \qquad \text{(Eq.2)}$$

$$P_n = Ct^2F_y(1 - C_R\sqrt{R})(1 + C_N\sqrt{N})(1 - C_H H) \qquad \text{(Eq.3)}$$

$$P_n = Ct^2F_y(1 - C_R\sqrt{R})(1 + C_N\sqrt{N})(1 - C_H\sqrt{H}) \qquad \text{(Eq.4)}$$

$$P_n = Ct^2F_y(1 - C_R R)(1 + C_N\sqrt{N})(1 - C_H H) \qquad \text{(Eq.5)}$$

$$P_n = Ct^2F_y(1 - C_R R)(1 + C_N\sqrt{N})(1 - C_H\sqrt{H}) \quad \text{(Eq.6)}$$

$$P_n = Ct^2F_y(1 - C_R\sqrt{R})(1 + C_N N)(1 - C_H\sqrt{H}) \quad \text{(Eq.7)}$$

$$P_n = Ct^2F_y(1 - C_R R)(1 + C_N N)(1 - C_H\sqrt{H}) \quad \text{(Eq.8)}$$

For multiple web sections (decks), the above expressions were multiplied by the term *(sinθ)* to account for the web inclination.
Since a statistical approach is being used with experimental data, it should be kept in mind that any resulting web crippling expression is primarily a function of the data being used.

I-SECTIONS

The data was taken from Reference 9, which is reproduced in Reference 7.

Exterior One-Flange Loading (EOF)

A total of 72 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 7:

F_y = 30.2 ksi (208 MPa) to 53.79 ksi (371 MPa)
t = 0.046 in. (1.168 mm) to 0.148 in. (3.759 mm)
N = 6.80 to 65.2
H = 23.5 to 208
R = 0.96 to 2.72

Interior One-Flange Loading (IOF)

A total of 27 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 7:

F_y = 30.2 ksi (208 MPa) to 53.79 ksi (371 MPa)
t = 0.046 in. (1.168 mm) to 0.123 in. (3.124 mm)
N = 8.10 to 65.9
H = 59.9 to 202
R = 0.96 to 2.60

Exterior Two-Flange Loading (ETF)

A total of 53 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 7:

F_y = 30.2 ksi (208 MPa) to 47.13 ksi (325 MPa)
t = 0.046 in. (1.168 mm) to 0.148 in. (3.759 mm)
N = 6.80 to 65.2
H = 27.5 to 205
R = 1.01 to 2.60

Interior Two-Flange Loading (ITF)

A total of 62 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 7:

F_y = 30.2 ksi (208 MPa) to 47.13 ksi (325 MPa)
t = 0.046 in. (1.168 mm) to 0.148 in. (3.759 mm)
N = 6.80 to 65.2
H = 25.5 to 209
R = 1.00 to 2.72

SINGLE WEB SECTIONS

The web crippling expressions used in S136[3] and AISI[1] are based on data of C and Z-sections as well as single hat and deck-type sections. Furthermore, the data used was primarily based on specimens that were not fastened to the supports during testing, a situation that rarely exists in practice. It has been shown by Bhakta[2] that there is an effect of flange restraint on the web crippling strength. In this investigation, only the available C and Z-section data was used in the category of single web sections. The data used was taken from Reference 7.

Exterior One-Flange Loading (EOF)

a) Stiffened Flanges

A total of 68 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, for sections having *stiffened* flanges, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 7:

F_y = 27.0 ksi (186 MPa) to 55.4 ksi (382 MPa)
t = 0.0445 in. (1.130 mm) to 0.0724 in. (1.839 mm)
N = 11.2 to 61.2
H = 37.1 to 203
R = 1.00 to 3.00

b) Unstiffened Flanges

A total of 30 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, for sections having *unstained* flanges, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 7:

F_y = 30.0 ksi (207 MPa) to 56.1 ksi (387 MPa)
t = 0.0409 in. (1.039 mm) to 0.0691 in. (1.755 mm)
N = 10.9 to 61.9
H = 95.9 to 193
R = 0.94 to 3.00

Interior One-Flange Loading (IOF)

A total of 54 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 7:

F_y = 30.9 ksi (213 MPa) to 55.8 ksi (385 MPa)
t = 0.0475 in. (1.207 mm) to 0.0669 in. (1.699 mm)
N = 11.3 to 62.5
H = 83.1 to 203
R = 0.96 to 3.00

Exterior Two-Flange Loading (ETF)

A total of 26 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 7:

F_y = 36.26 ksi (250 MPa) to 47.12 ksi (325 MPa)
t = 0.0460 in. (1.168 mm) to 0.0515 in. (1.308 mm)
N = 19.4 to 63.2
H = 90.0 to 208
R = 0.96 to 2.72

Interior Two-Flange Loading (ITF)

A total of 26 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 7:

F_y = 36.26 ksi (250 MPa) to 47.12 ksi (325 MPa)
t = 0.0470 in. (1.194 mm) to 0.0522 in. (1.326 mm)
N = 19.3 to 63.8
H = 88.8 to 205
R = 0.95 to 2.66

MULTIPLE WEB SECTIONS (DECKS)

This category exists only in S136[3] and not in AISI[1]. The data used was taken primarily from Reference 8.

Exterior One-Flange Loading (EOF)

Only four experimental data for restrained flanges were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 8:

F_y = 43.82 ksi (302 MPa) to 57.49 ksi (396 MPa)
t = 0.0260 in. (0.660 mm) to 0.0490 in. (1.245 mm)
N = 53.6 to 101
H = 89.6 to 137
R = 4.14 to 6.62
θ = 90°

Interior One-Flange Loading (IOF)

A total of 90 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 8:

F_y = 30.9 ksi (213 MPa) to 55.8 ksi (385 MPa)
t = 0.0216 in. (0.549 mm) to 0.0669 in. (1.699 mm)
N = 11.3 to 208
H = 62.1 to 209
R = 1.00 to 17.4
θ = 50° to 90°

Exterior Two-Flange Loading (ETF)

A total of 80 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 8:

F_y = 33.5 ksi (231 MPa) to 49.0 ksi (338 MPa)
t = 0.0240 in. (0.610 mm) to 0.0620 in. (1.575 mm)
N = 16.4 to 125
H = 21.4 to 328
R = 1.34 to 10.1
θ = 45° to 90°

Interior Two-Flange Loading (ITF)

A total of 82 experimental data were used to develop the web crippling coefficients C, C_R, C_N and C_H of the new expression, as summarized in Table 1. Table 2 gives the computed statistical information, such as the mean, standard deviation, coefficient of variation and the corrected sum of squares. The following parametric variations were summarized from Reference 8:

F_y = 33.5 ksi (231 MPa) to 49.0 ksi (338 MPa)
t = 0.0240 in. (0.610 mm) to 0.0606 in. (1.539 mm)
N = 16.7 to 125
H = 21.4 to 209
R = 1.34 to 10.1
θ = 45° to 90.5°

CONCLUSIONS

An extensive statistical web crippling investigation of cold formed steel sections was carried out, using the experimental data available in the literature. The object of this study was to develop a new simplified and consistent expression for the prediction of the web crippling strength of cold formed steel members, which has been accomplished.

Based on the results of this research, Expression 4 is recommended for the design of I-sections, single web sections and multiple web sections (decks). The new expression is presented in Table 1 with the corresponding web crippling coefficients for the four typical load cases of end one flange loading (EOF), interior one flange loading (IOF), end two flange loading (ETF) and interior two flange loading (ITF).

The parameter limits are based on the test data used and should remain as presently specified in S136 [1], i.e.,

a) for I-sections and shapes having single webs are H < 200, N < 200, n/h < 1 and R < 4 and

b) for multiple web sections (decks) H < 200, N < 200, n/h < 2 and R < 10.

The statistical results of the recommended Expression 4 are given in Table 2. As can be observed, the statistical parameters are within the range of those found when using AISI[1] - see Table 3 and S136[3] - see Table 4. The recommended Expression 4 has already been adopted in the 1994 edition of S136. Since the time of this work, additional data has been generated by Cain and LaBoube at the University of Missouri-Rolla. This data should also be included in a follow-up statistical evaluation in the future.

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NOTATIONS

C	coefficient
C_H	web slenderness coefficient
C_N	bearing length coefficient
C_R	inside bend radius coefficient
C.S.S.	corrected sum of squares
C.V.	coefficient of variation
EOF	exterior one-flange loading
ETF	exterior two-flange loading
F_y	yield strength of steel
h	flat dimension of web measured in the plane of the web
H	web slenderness ratio, h/t
IOF	interior one-flange loading
ITF	interior two-flange loading
k	$F_y/33$ (ksi) ; $F_y/228$ (N/mm^2)
n	bearing length of load
N	bearing length to thickness ratio, n/t
P	applied load per web
P_a	computed ultimate web crippling load per web using AISI [1] expression
P_n	computed ultimate web crippling load or reaction per web using new expression
P_s	computed ultimate web crippling load per web using S136 [3] expression
P_t	test ultimate web crippling load per web
r	inside bend radius
R	inside bend radius to thickness ratio, r/t
S.D.	standard deviation
SI	system international
t	web thickness
θ	angle between plane of web and plane of bearing surface in degrees

TABLE 1

RECOMMENDED EXPRESSION

$$P_n = Ct^2F_y(\sin\theta)(1 - C_R\sqrt{R})(1 + C_N\sqrt{N})(1 - C_H\sqrt{H}) \qquad \text{(Eq.4)}$$

	C	C_R	C_N	C_H
I-SECTIONS				
a) EOF	9.85	0.185	0.315	0.001
b) IOF	18.0	0.001	0.075	0.001
c) ETF	15.0	0.001	0.100	0.050
d) ITF	28.0	0.001	0.035	0.025
SINGLE WEB SECTIONS				
a) EOF				
i) Stiffened Flanges				
ii) Unstiffened Flanges	4.00	0.230	0.650	0.035
b) IOF	7.20	0.250	0.120	0.030
c) ETF	17.0	0.130	0.130	0.040
d) ITF	17.0	0.400	0.064	0.045
	29.5	0.135	0.080	0.060
MULTIPLE WEB SECTIONS (DECKS)				
a) EOF	4.00	0.070	0.200	0.001
b) IOF	21.0	0.120	0.065	0.040
c) ETF	9.00	0.180	0.200	0.044
d) ITF	10.0	0.140	0.210	0.020

Note: *See Fig. 1 for description of EOF, IOF, ETF, ITF.*
Expression 4 applies to I-sections and single web sections when $R<4$, $N<200$, $H<200$ *and* $n/h<1$. *Expression 4 applies to multiple web sections when* $R<10$, $N<200$, $H<200$ *and* $n/h<2$.

TABLE 2
STATISTICAL RESULTS OF RECOMMENDED EXPRESSION GIVEN IN TABLE 1

	MEAN OF P_t/P_n	S.D. OF P_t/P_n	C.V. OF P_t/P_n	C.S.S. OF P_t/P_n	Tests Used / Total Tests
I-SECTIONS					
a) EOF	1.073	0.215	0.200	3.095	68 / 72
b) IOF	1.035	0.168	0.162	0.649	24 / 27
c) ETF	1.044	0.245	0.235	3.127	53 / 53
d) ITF	1.048	0.221	0.211	2.790	58 / 62
SINGLE WEB SECTIONS					
a) EOF					
i) Stiffened Flanges	1.000	0.122	0.121	0.944	65 / 68
ii) Unstiffened Flanges	1.096	0.247	0.225	1.763	30 / 30
b) IOF	1.095	0.140	0.128	1.025	53 / 54
c) ETF	1.000	0.061	0.061	0.079	22 / 26
d) ITF	1.072	0.081	0.075	0.137	22 / 26
MULTIPLE WEB SECTIONS (DECKS)					
a) EOF	1.073	0.017	0.016	0.001	4 / 4
b) IOF	1.023	0.167	0.163	2.151	78 / 90
c) ETF	1.046	0.166	0.159	1.900	70 / 80
d) ITF	1.078	0.143	0.133	1.558	77 / 82

Note: *See Fig. 1 for description of EOF, IOF, ETF, ITF.*
Where P_t = ultimate test web crippling load per web
P_n = ultimate computed web crippling load per web using the parameters of Expression 4 given in Table 1.

TABLE 3
STATISTICAL RESULTS OF CURRENT EXPRESSIONS GIVEN IN AISI[1] (WITH AISI LIMITS APPLIED)

	MEAN OF P_t/P_n	S.D. OF P_t/P_n	C.V. OF P_t/P_n	C.S.S. OF P_t/P_n	Tests Used / Total Tests
I-SECTIONS					
a) EOF	1.105	0.210	0.190	2.944	68 / 72
b) IOF	0.951	0.133	0.140	0.406	24 / 27
c) ETF	1.005	0.130	0.130	0.882	53 / 53
d) ITF	1.025	0.127	0.124	0.916	58 / 62
SINGLE WEB SECTIONS					
a) EOF					
i) Stiffened Flanges	0.995	0.119	0.120	0.923	66 / 68
ii) Unstiffened Flanges	1.008	0.192	0.190	1.063	30 / 30
b) IOF	0.979	0.109	0.112	0.622	53 / 54
c) ETF	0.982	0.085	0.087	0.153	22 / 26
d) ITF	0.953	0.099	0.104	0.205	22 / 26
MULTIPLE WEB SECTIONS (DECKS)					
a) EOF	1.651	0.026	0.016	0.002	4 / 4
b) IOF	0.912	0.117	0.128	0.929	69 / 90
c) ETF	1.717	0.448	0.261	12.43	63 / 80
d) ITF	1.034	0.267	0.258	4.930	70 / 82

Note: *See Fig. 1 for description of EOF, IOF, ETF, ITF.*
Where P_t = test ultimate web crippling load per web
P_n = computed ultimate web crippling load per web using the Expressions given in AISI[1]

TABLE 4
STATISTICAL RESULTS OF EXISTING EXPRESSIONS GIVEN IN S136[3] (WITH S136 LIMITS APPLIED)

	MEAN OF P_t/P_n	S.D. OF P_t/P_n	C.V. OF P_t/P_n	C.S.S. OF P_t/P_n	Tests Used / Total Tests
I-SECTIONS					
a) EOF	1.105	0.210	0.190	2.944	68 / 72
b) IOF	0.951	0.133	0.140	0.406	24 / 27
c) ETF	1.005	0.130	0.130	0.882	53 / 53
d) ITF	1.025	0.127	0.124	0.916	58 / 62
SINGLE WEB SECTIONS					
a) EOF					
i) Stiffened Flanges	0.988	0.112	0.113	0.803	65 / 68
ii) Unstiffened Flanges	1.003	0.190	0.190	1.052	30 / 30
b) IOF	1.003	0.112	0.112	0.652	53 / 54
c) ETF	0.974	0.086	0.089	0.156	22 / 26
d) ITF	1.028	0.135	0.132	0.385	22 / 26
MULTIPLE WEB SECTIONS (DECKS)					
a) EOF	1.397	0.024	0.017	0.002	4 / 4
b) IOF	0.895	0.119	0.133	1.083	78 / 90
c) ETF	1.001	0.160	0.159	1.748	70 / 80
d) ITF	0.938	0.108	0.115	0.881	77 / 82

Note: *See Fig. 1 for description of EOF, IOF, ETF, ITF.*
Where P_t = test ultimate web crippling load per web
P_n = computed ultimate web crippling load per web using the Expressions given in S136[3]