Web Crippling of Cold-formed Steel Members

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Abstract

The North American Specification for the Design of Cold-Formed Steel Structural Members (NAS 2001) has recently adopted a new web crippling approach, which is the approach contained in the Canadian S136 Standard (CSA 1994). The objective of this work was to develop new design coefficients for the web crippling strength design expression currently used in the Canadian S136 Standard (CSA 1994) and the North American Specification (NAS 2001). An extensive statistical analysis was performed using published test data up to 1999, from the United States, Canada and Australia. The resulting web crippling coefficients, calibrated resistance factors and respective factors of safety of this study, have been adopted by the North American Specification (NAS 2001).

The new coefficients were developed based on section geometry, loading case and two different support conditions, fastened to the support and not fastened to the support during testing. The new coefficients showed excellent agreement with the test data for a wide range of cross section dimensions, yield strengths, bearing lengths and angle of web inclination.

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1- Introduction

Cold-formed steel members generally have large web slenderness ratios. As a consequence, their webs may cripple due to the high local intensity of load or reaction. Web crippling is one of the most important failure modes in the design of cold-formed steel members. Many factors affect the web crippling resistance, including section geometry, section parameters, load cases and bearing length.

Section Geometry

There are many geometric shapes in the market place, the following being the most common in the building construction industry:

- I-Sections
- C-Sections
- Z-Sections
- Single Hat Sections
- Multi-Web Sections (decks)

Web crippling is affected by the degree of restraint of the web against rotation. The web-flange interaction affects the resistance of this mode of failure. Stiffened and unstiffened flanges also play an important role in the web crippling resistance. The AISI Specification (AISI 1996a) and the S136 Standard (CSA 1994) separate stiffened and unstiffened sections in the design equations.

Section Parameters

The following section parameters have direct impact on the web crippling resistance:

- Yield strength of steel (F_y)
- Web thickness (t)
- Inside bend radius (r)
- Web height (h)
- Angle between plane of web and plane of bearing surface (θ)

The web crippling resistance increases as the thickness, the yield strength and the web inclination angle θ increase, and decreases as the web height and inside bend radius increase.

Load Categories

There are four different load cases based on whether the concentrated load is acting on both flanges or only on one flange, and whether the load is applied at the end of the member or somewhere in the middle of the span of the member. These four load cases can be summarized as follows (See Figure 1):

- End-One-Flange Loading (EOF)
- End-Two-Flange Loading (ETF)
- Interior-One-Flange Loading (IOF)
- Interior-Two-Flange Loading (ITF)

Bearing Length

The length over which the load is distributed, n, will influence the web crippling resistance, i.e., the web crippling resistance increases with and increase in bearing width,.

2- Objective and Scope

The main objective of this study was to develop new improved design coefficients for the web crippling strength expression currently used in the North American Specification (NAS 2001), taking into consideration all of the tests conducted up to 1999 for each section geometry and

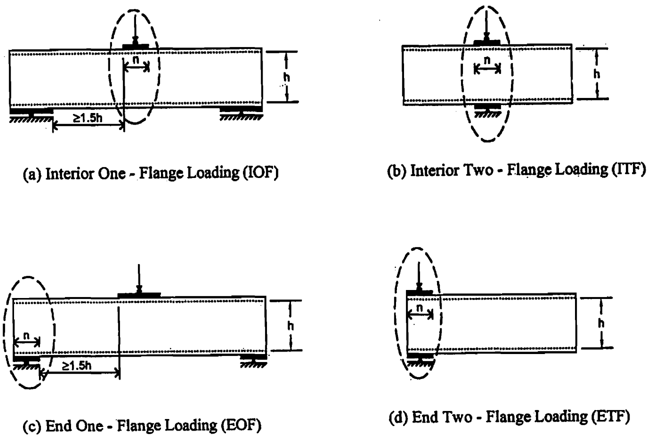

Figure 1: Load Categories for Web Crippling

loading case. More than one thousand tests were collected from eleven different sources from the United States, Canada and Australia. A non-linear regression analysis was used to develop the new web crippling coefficients. The non-linear procedures were mainly based on the minimum of squared errors, SEE. Separate coefficients were developed for each individual section geometry and load case, as well as for sections fastened or not fastened to the support during testing. Furthermore, the web crippling expression, using the coefficients of this study, was calibrated for the safety requirements of both the AISI Specification (AISI 1996) and the S136 Standard (CSA 1994).

3- Current North American Web Crippling Provisions

The web crippling design expressions used in the AISI Specification (AISI 1996), were developed by using the data up to 1978 (Hetrakul and Yu 1978). They were based on test data of I, C-and single hat sections. The AISI Specification (AISI 1996) separated the sections into two categories, I-sections and shapes having single webs. C-and Z-sections as well as single hat and multi-web sections are considered in the second category, single web category. The AISI Specification (AISI 1996) treats stiffened and unstiffened sections the same by using the same design expressions for both, except for the end one flange loading case for shapes having a single web. Furthermore, the design expressions were primarily based on data where the specimens were not fastened to the supports during testing, a situation that rarely exists in practice. It has been shown (Bhakta et al. 1992) that there is an effect of flange restraint on web crippling strength.

The current S136 Standard (CSA 1994) is based on the available data up to 1993 (Prabakaran 1993) and considers C-and Z-sections as single web shapes and hat and deck sections as multi-web type shapes. A unified web crippling expression with separate coefficients for each section type and load case was introduced by the S136 Standard (CSA 1994). The expression includes all major parameters that affect the web crippling resistance mentioned above and is non-dimensional. The coefficients were developed mainly using data of specimens not fastened to the supports during testing (the same data as was used by the AISI Specification (AISI 1996).

However, in the case of multi-web sections, data by (Wing 1981) was used, where the specimens were fastened to the support during testing.

4- Development of New Web Crippling Coefficients

As stated before, there are five major parameters that govern the web crippling resistance of cold formed steel members (Prabakaran 1993; Hetrakul and Yu 1978), and they are: thickness of the web element, t, yield strength, F_y, the web slenderness ratio, H = h/t, the inside bend ratio, R = r/t and the bearing plate length to thickness ratio, N = n/t. (Prabakaran and Schuster 1998) introduced the following unified expression currently used in the S136 Standard (CSA 1994) and the North American Specification (NAS 2001), which includes the above-mentioned parameters:

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

Where P_n is the nominal calculated web crippling resistance, C, C_R, C_N and C_H are the web crippling coefficients that depend on the section geometry and load condition. These coefficients were determined by using test data in a regression analysis. Each term within the brackets of Eq. (1) can be thought of as a correction factor, i.e. the first term is the inside bend radius correction factor, the second term is the bearing width correction factor and the third term is the web slenderness correction factor. Similarly, the term sinθ is the web inclination correction factor. Since the web crippling resistance increases with an increase in the bearing width ratio, N, a plus sign is used in the bearing plate correction factor. On the other hand, the web crippling resistance decreases with an increase in inside bend radius ratio, R, and web slenderness ratio, H, hence, minus signs are used in both cases for their correction factors. The above equation is totally non-dimensional and can be used with any consistent units of measurements.

Based on the above discussion, Equation (1) was used in the development of the new web crippling coefficients for all section types and loading cases.

5- Test Data

More than one thousand web crippling test data points, for different section types and loading cases were collected from eleven different sources from 1953 to 1999 in four Universities from three countries, the United States, Canada and Australia. Table 1 shows the sources, the University, the country, as well as the number of tests that were used in the development of the new web crippling coefficients.

The test data were organized according to section type (I-sections, single web sections (C-and Z-sections), single hat sections and multi-web sections), stiffened or unstiffened sections and to the loading case (EOF, IOF, ETF, and ITF).

(Bhakta 1992) showed in his research that fastened sections resulted in a marginal increase in web crippling resistance in comparison to unfastened sections. Based on this, the data was separated in accordance with whether or not the section was fastened or unfastened to the support.

The number of tests from each researcher that were used to develop the web crippling coefficients for the AISI Specification (AISI 1996), the S136 Standard (CSA 1994) and the new coefficients for each section are listed in Tables 2 to 5 of the Appendix. Parameter ranges for the test data used to develop the new coefficients are shown in Tables 6 to 9 of the Appendix.

Table 1 Test Data Used in Development of New Web Crippling Coefficients

Source Name, Year	University	Country	No. of Tests
1- Winter, 1953	Cornell	USA	193
2- Hetrakul, 1978	Missouri-Rolla	USA	283
3- Yu 1981	Missouri-Rolla	USA	18
4- Wing, 1981	Waterloo	Canada	219
5- Bhakta, 1992	Missouri-Rolla	USA	44
6- Langan, 1994	Missouri-Rolla	USA	31
7- Cain, 1995	Missouri-Rolla	USA	40
8- Gerges, 1997	Waterloo	Canada	67
9- Wu, 1997	Missouri-Rolla	USA	51
10- Young, 1998	Sydney	Australia	56
11- Beshara, 1999	Waterloo	Canada	72
Total			**1074**

6- Regression Analysis

Non-linear regression analysis procedures were used to develop the new coefficients using (Eq. 1). The statistical analysis software package "SAS" was used to perform the non-linear regression analysis, which was based on the minimum of squared errors, SEE. A comparison between the tested and the predicted failure loads, using the new coefficients, indicates excellent agreement. Tables 10 to 13 show the new coefficients for each section and load case, as well as the mean values for the failure test values in comparison to the calculated values and the coefficient of variation (COV).

7- Calibration of New Coefficients

Procedures for calculating both the resistance factor, ϕ, for the Load and Resistance Factor Design method (LRFD) and the factor of safety, Ω, for Allowable Stress Design, ASD, are well described by (Hsiao and Galambos 1998; Supornsilaphachai et al. 1979 and Gerges 1997). Calibration calculations depend on the reliability index value, β, the dead load to live load ratio, dead, and live load factors. For the AISI Specification (AISI 1996), the ratio between dead and live load is D/L = 1/5 and the load factors for dead and live load are $\alpha_D = 1.20$, and $\alpha_L = 1.60$, respectively. The following two equations give the values of Ω and ϕ for any β value.

$$\Omega = \frac{e^{\beta\sqrt{0.0554+V_P^2}}}{(1.091P_m)}, \qquad \text{Eq. (2)}$$

$$\phi = \frac{1.673\ P_m}{e^{\beta\sqrt{0.0553+V_P^2}}} \qquad \text{Eq. (3)}$$

For the S136 Standard (CSA 1994), the ratio between dead and live load is D/L = 1/3 and the load factors for dead and live load are $\alpha_D = 1.25$, and $\alpha_L = 1.50$, respectively. The following equation gives the value ϕ for any β value:

$$\phi = \frac{1.562\,P_m}{e^{\beta\sqrt{0.0475+V_P^2}}} \qquad \text{Eq. (4)}$$

In Eq.(4), P_m and V_P are the mean value and the coefficient of variation of the prediction of the ultimate resistance, respectively. The recommended value for β is 2.5 for the AISI Specification (AISI 1996) and 3.0 for the S136 Standard (CSA 1994). By substituting the values of P_m, V_P and β into the above equations, the factor of safety and the resistance factor for each section and loading case are obtained, as shown in Tables 10 to 13.

8- Conclusions

An extensive web crippling investigation of cold-formed steel members was carried out, using the experimental test data available in the literature up to 1999. The objective of this study was to develop improved coefficients for the web crippling strength expression currently used in the S136 Standard, (CSA 1994) and the North American Specification (NAS 2001). Test data were organized and separated according to section type, loading case, whether the section was stiffened or unstiffened, and whether the specimen was fastened or not fastened to the supports during testing. Non-linear regression analysis was used to develop the new coefficients. The predicted failure loads, using the new coefficients, indicated excellent agreement with the tested failure loads.

Finally, the proposed new web crippling coefficients were used in the calibration of the safety requirement in accordance with the AISI Specification (AISI 1996) and the S136 Standard (CSA 1994). The resistance factors and factors of safety contained in the North American Specification (NAS 2001) were based on the values summarized in Tables 10 to 13, rounded to the nearest 0.05 value.

8- References

AISI (1996a) American Iron and Steel Institute, *Specification for the Design of Cold-Formed Steel Structural Members,* 1996 Edition, Washington, DC, USA, 1996 – Including Supplement No.1, July 30, 1999.

AISI (1996b) American Iron and Steel Institute, *Commentary on the 1996 Edition of the Specification for the Design of Cold-Formed Steel Structural Members*, 1996 Edition, Washington, DC, USA

Beshara, B. (1999), "Web Crippling of Cold Formed Steel Members", M.A.Sc. Thesis, University of Waterloo, Waterloo, Canada, 1999

Bhakta, B.H., R.A. LaBoube and W.W. Yu (1992), "The Effect of Flange Restraint on Web Crippling Strength," Final Report, Civil Engineering Study 92-1, University of Missouri-Rolla, Rolla, MO, USA, March 1992.

Cain, D.E., R.A LaBoube, and W.W. Yu (1995), "The Effect of Flange Restraint on Web Crippling Strength of Cold Formed Steel Z-and I-Sections," Final Report, Civil Engineering Study 95-2, University of Missouri-Rolla, Rolla, MO, May 1995.

Cornell University, "65th and 66th Progress Reports on Light Gage Steel Beams of Cold Formed Steel", Cornell University, New York, NY, September 1952 and January 1953, respectively (unpublished), USA.

CSA (1994), *Cold Formed Steel Structural Members*, CSA S136-94, Canadian Standards Association, Rexdale, Ontario, Canada, December 1994.

Gerges, R. R. (1997), "Web Crippling of Single Web Cold Formed Steel Members Subjected to End One-Flange Loading," M.A.Sc. Thesis, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario, Canada.

Hetrakul, N. and W.W. Yu (1978), "Structural Behavior of Beam Webs Subjected to Web Crippling and a Combination of Web Crippling and Bending," Final Report, Civil Engineering Study 78-4, University of Missouri-Rolla, Rolla, MO, USA, June 1978.

Hsaio, L., W.W. Yu and T.V. Galambos (1998), "Load and Resistance Factor Design of Cold Formed Steel, Calibration of the AISI Design Provisions," Ninth Progress Report, Civil Engineering Study 88-2, University of Missouri-Rolla, Rolla, MO, February 1998.

Langan, J.E., R.A. LaBoube and W.W. Yu (1994), "Structural Behavior of Perforated Web Elements of Cold Formed Steel Flexural Members Subjected to Web Crippling and a Combination of Web Crippling and Bending," Final Report, Civil Engineering Study 94-3, University of Missouri-Rolla, Rolla, MO, USA, May 1994.

Parabakaran, K. (1993), "Web Crippling of Cold Formed Steel Sections," Project Report, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario, Canada, April 1993.

Parabakaran, K. and R.M. Schuster (1998), "Web Crippling of Cold Formed Steel Sections", *Fourteenth International Specialty Conference on Cold-Formed Steel Structures*, University of Missouri-Rolla, Rolla, MO, USA, October 1998.

Supornsilaphachai, B., T.V. Galambos and W.W. Yu (1997), "Load and Resistance Factor Design of Cold Formed Steel, Calibration of the Design Provisions on Beam Webs," Fifth Progress Report, Civil Engineering Study 79-5, University of Missouri-Rolla, Rolla, MO, USA, September 1979.

Wing, B.A. (1981), "Web Crippling and the Interaction of Bending and Web Crippling of Unreinforced Multi-Web Cold Formed steel Sections," M.A.Sc. Thesis, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario, Canada.

Wu, S., W.W. Yu and R.A. LaBoube (1997), "Strength of Flexural Members Using Structural Grade 80 of A653 Steel (Web Crippling Tests)," Civil Engineering Study 97-3, Cold Formed Steel Series, Third Progress Report, University of Missouri-Rolla, Rolla, MO, USA, February 1997.

Young, B. and G.J. Hancock (1998), "Web Crippling Behavior of Cold Formed Unlipped Channels," *Proceedings of the 14th International Specialty Conference on Cold Formed Steel Structures*, University of Missouri-Rolla, Rolla, MO, USA, October 1998.

Yu, W.W. (1981), "Web Crippling and Combined Web Crippling and Bending of Steel Decks," Civil Engineering Study 81-2, Structural Series, University of Missouri-Rolla, Rolla, MO, USA, April 1981.

APPENDIX

Table 2 Researcher Names and Number of Tests Used to Develop Design Expressions for I-Sections

Section			(CSA 1994)		(AISI 1996)		New Coefficients	
			Researcher Name	No. of Tests	Researcher Name	No. of Tests	Researcher Name	No. of Tests
i) Stiffened	a) Fastened	1) EOF	No Coefficients	----	No Expression	----	Bhakta,UMR, 1992	6
		2) IOF	No Coefficients	----	No Expression	----	Cain,UMR, 1995	12
	b) Unfastened	1) EOF	Cornell, 1953	30	Cornell, 1953	30	Cornell, 1953	30
			Hetrakul, UMR, 1978 (38 Stiff.+ 4 Unstiff.)	42	Hetrakul, UMR, 1978 (42 Stiff.+ 4 Unstiff.)	46	Hetrakul, UMR, 1978	50
			Total	72	Total	76	Bhakta, UMR, 1992	6
							Total	86
		2) IOF	Cornell, 1953	10	Cornell, 1953	10	Cornell, 1953	10
			Hetrakul, UMR, 1978 (15 Stiff.+ 2 Unstiff.)	17	Hetrakul, UMR, 1978 (19 Stiff.+ 2 Unstiff.)	21	Hetrakul, UMR, 1978	19
			Total	27	Total	31	Total	29
		3) ETF	Cornell, 1953	27	Cornell, 1953	27	Cornell, 1953	27
			Hetrakul, UMR, 1978	26	Hetrakul, UMR, 1978	30	Hetrakul, UMR, 1978	30
			Total	53	Total	57	Total	57
		4) ITF	Cornell, 1953	36	Cornell, 1953	36	Cornell, 1953	36
			Hetrakul, UMR, 1978	26	Hetrakul, UMR, 1978	30	Hetrakul, UMR, 1978	30
			Total	62	Total	66	Total	66
ii) Unstiffened	Unfastened	1) EOF	Same expression for Stiffened	----	Same expression for Stiffened	----	Hetrakul, UMR, 1978 (Same Coeff. For stiff. Unfast.)	4
		2) IOF	Same expression for Stiffened	----	Same expression for Stiffened	----	Hetrakul, UMR, 1978 (Same Coeff. For stiff. Unfast.)	2

Table 3 Researcher Names and Number of Tests Used to Develop Design Expressions for Single Web Sections

Section			(CSA 1994) Researcher Name	(CSA 1994) No. of Tests	(AISI 1996) Researcher Name	(AISI 1996) No. of Tests	New Coefficients	New Coefficients No. of Tests
i) Stiffened	a) Fastened	1) EOF	No Coefficients	----	No Expression	----	For C: Hetrakul,UMR,1978	8
							Bhakta,UMR,1992	6
							Gerges,UW,1997	67
							Total	81
							For Z: Bhakta,UMR,1992	4
							Cain,UMR,1995	14
							Total	18
							(Total Tests Used in Regression)	99
		2) ETF	No Coefficients	----	No Expression	----	For C: Beshara,UW,1999	18
							For Z: Beshara,UW,1999	18
		2) ITF	No Coefficients	----	No Expression	----	For C: Beshara,UW,1999	18
							For Z: Beshara,UW,1999	18
	b) Unfastened	1) EOF	Hetrakul, UMR, 1978 - C (Stiff.-Unfast.)	22	Hetrakul, UMR, 1978 - C (Stiff.-Unfast.)	26	For C: Hetrakul,UMR,1978	34
			Hetrakul, UMR, 1978 - C (Stiff.-Fast.)	8	Hetrakul, UMR, 1978 - C (Stiff.-Fast.)	8	Bhakta,UMR,1992	6
			Cornell,1953 - Single Hat	38	Hetrakul, UMR, 1978 - C (Unstiff.-Unfast.)	8	Langan,UMR,1994	23
			Total	68	Cornell,1953 - Single Hat	36	Total	63
					Total	78	For Z: Bhakta,UMR,1992	4
							Cain,UMR,1995	14
							Total	18
		2) IOF	Hetrakul, UMR, 1978 - C (Stiff.-Unfast.)	16	Hetrakul, UMR, 1978 - C (Stiff.-Unfast.)	20	For C: Hetrakul,UMR,1978	24
			Hetrakul, UMR, 1978 - C (Stiff.-Fast.)	4	Hetrakul, UMR, 1978 - C (Stiff.-Fast.)	4	Langan,UMR,1994	8
			Hetrakul, UMR, 1978 -C (Unstiff.-Unfast.)	4	Hetrakul, UMR, 1978 - C (Unstiff.-Unfast.)	4	Total	32
			Cornell,1953 - Single Hat	30	Cornell,1953 - Single Hat	30		
			Total	54	Total	58		
		3) ETF	Hetrakul, UMR, 1978 - C (Stiff.-Unfast.)	22	Hetrakul, UMR, 1978 - C (Stiff.-Unfast.)	26	For C: Hetrakul,UMR,1978	26
			Hetrakul, UMR, 1978 - C (Unstiff.-Unfast.)	4	Hetrakul, UMR, 1978 - C (Unstiff.-Unfast.)	4		
			Total	26	Total	30		
		4) ITF	Hetrakul, UMR, 1978 - C (Stiff.-Unfast.)	22	Hetrakul, UMR, 1978 - C (Stiff.-Unfast.)	26	For C: Hetrakul,UMR,1978	26
			Hetrakul, UMR, 1978 - C (Unstiff.-Unfast.)	4	Hetrakul, UMR, 1978 - C (Unstiff.-Unfast.)	4		
			Total	26	Total	30		

Table 3 (Continued) Researcher Names and Number of Tests Used to Develop Design Expressions for Single Web Sections

Section			(CSA 1994)		(AISI 1996)		New Coefficients	
			Researcher Name	No. of Tests	Researcher Name	No. of Tests	New Coefficients	No. of Tests
i) Unstiffened	Unfastened	1) EOF	Hetrakul, UMR, 1978 - C (Unstiff.-Unfast.)	8	Hetrakul, UMR, 1978 - C (Unstiff.-Unfast.)	8	For C: Hetrakul, UMR, 1978	18
			Cornell, 1953 - Single Hat	22	Cornell, 1953 - Single Hat	24	Young, Sydney, 1998	14
			Total	30	Total	32	Total	32
		2) IOF	Same Stiffened Coefficients	----	Same Stiffened Expression	----	For C: Hetrakul,UMR,1978	4
							Young, Sydney, 1998	16
							Total	20
		3) ETF	Same Stiffened Coefficients	----	Same Stiffened Expression	----	For C: Hetrakul, UMR, 1978	4
							Young,Sydney,1998	12
							Total	16
		4) ITF	Same Stiffened Coefficients	----	Same Stiffened Expression	----	For C: Hetrakul, UMR, 1978	4
							Young, Sydney, 1998	14
							Total	18

Table 4 Researcher Names and Number of Tests Used to Develop Design Expressions for Single Hat Sections

Section		(CSA 1994)		(AISI 1996)		New Coefficients	
		Researcher Name	No. of Tests	Researcher Name	No. of Tests	Researcher Name	No. of Tests
a) Fastened	1) EOF	No Coefficients	----	No Expression	----	Bhakta, UMR, 1992	2
						Wu, UMR, 1997	3
						Total	5
						(Same Coeff. For Unfastened)	
	2) IOF	No Coefficients	----	No Expression	----	Wing, UW, 1981	25
						(used with the unfastened data in regression)	
	3) ETF	No Coefficients	----	No Expression	----	Wing, UW, 1981	17
	4) ITF	No Coefficients	----	No Expression	----	Wing, UW, 1981	24
b) Unfastened	1) EOF	Included in Single Web Expression	----	Included in Single Web Expression	----	Cornell, 1953	60
						Bhakta, UMR, 1992	2
						Total	62
	2) IOF	Included in Single Web Expression	----	Included in Single Web Expression	----	Cornell, 1953	30
						(used with the fastened data in regression)	

Table 5 Researcher Names and Number of Tests Used to Develop Design Expressions for Multi-Web Sections

Section		(CSA 1994) Researcher Name	(CSA 1994) No. of Tests	(AISI 1996) Researcher Name	(AISI 1996) No. of Tests	New Coefficients Researcher Name	New Coefficients No. of Tests
a) Fastened	1) EOF	Bhakta, UMR, 1992 - Fastened Single Hat	2	No Expression	----	Bhakta, UMR, 1992 (Same coefficients for unfastened)	2
		Bhakta, UMR, 1992 - Fastened Multi-Web	2				
		Total	4				
	2) IOF	Cornell, 1953 - Unfastened Single Hat	31	No Expression	----	Wing, UW, 1981	34
		Wing, UW, 1981 - Fastened Single Hat	26			Bhakta, UMR, 1992	2
		Wing, UW, 1981 - Fastened Multi-Web	33			Total (used with the unfastened data in regression)	36
		Total	90				
	3) ETF	Wing, UW, 1981 - Fastened Single Hat	17	No Expression	----	Wing, UW, 1981	63
		Wing, UW, 1981 - Fastened Multi-Web	63				
		Total	80				
	4) ITF	Wing, UW, 1981 - Fastened Single Hat	25	No Expression	----	Wing, UW, 1981	57
		Wing, UW, 1981 - Fastened Multi-Web	57				
		Total	82				
b) Unfastened	1) EOF	No Coefficients	----	Included in Single Web Expression	----	Yu, UMR, 1981	18
						Bhakta, UMR, 1992	2
						Wu, UMR, 1997	16
						Total	36
	2) IOF	No Coefficients	----	Included in Single Web Expression	----	Bhakta, UMR, 1992	2
						Total (used with the fastened data in regression)	42
	3) ETF	No Coefficients	----	Included in Single Web Expression	----	Wu, UMR, 1997	16
	4) ITF	No Coefficients	----	Included in Single Web Expression	----	Wu, UMR, 1997	16

Table 6 I-Section Data Parameters

Section			Researcher's Name	No. of Tests	t min to t max (mm)	Fy min to Fy max (MPa)	h/t min to h/t max (ratio)	r/t min to r/t max (ratio)	n/t min to n/t max (ratio)
i) Stiffened	a) Fastened	1) EOF	Bhakta, UMR, 1992	6	1.600 to 2.769	390.8 to 431.8	68.2 to 134.0	1.4 to 5.0	48.2 to 83.3
		2) IOF	Cain, UMR, 1995	12	1.702 to 2.159	421.6 to 436.3	88.3 to 112.0	1.8 to 2.3	61.8 to 78.4
	b) Unfastened	1) EOF	Cornell, 1953	30	1.168 to 3.754	208.0 to 259.0	25.5 to 170.4	1.0 to 1.0	6.8 to 54.4
			Hetrakul, UMR, 1978	50	1.168 to 2.743	230.5 to 370.5	46.9 to 249.8	1.0 to 2.7	13.3 to 123.2
			Bhakta, UMR, 1992	6	1.600 to 2.769	390.8 to 431.8	68.2 to 131.2	1.4 to 5.0	48.2 to 83.3
		2) IOF	Cornell, 1953	10	1.168 to 3.124	208.0 to 259.0	61.9 to 168.2	1.0 to 1.0	8.1 to 38.6
			Hetrakul, UMR, 1978	19	1.156 to 1.308	230.5 to 370.5	139.0 to 247.0	1.8 to 2.6	19.4 to 65.9
		3) ETF	Cornell, 1953	27	1.168 to 3.754	208.0 to 259.0	25.5 to 170.4	1.0 to 1.0	6.8 to 54.4
			Hetrakul, UMR, 1978	30	1.168 to 2.743	230.5 to 324.6	47.0 to 260.7	1.0 to 2.7	13.3 to 65.2
		4) ITF	Cornell, 1953	36	1.168 to 3.754	208.0 to 259.0	25.5 to 170.4	1.0 to 1.0	6.8 to 54.4
			Hetrakul, UMR, 1978	30	1.168 to 2.743	230.5 to 324.6	46.9 to 254.7	1.0 to 2.7	13.3 to 65.2
ii) Unstiffened	Unfastened	1) EOF	Hetrakul, UMR, 1978	4	1.232 to 1.245	249.8 to 249.8	95.7 to 195.1	1.0 to 1.0	61.2 to 61.9
		2) IOF	Hetrakul, UMR, 1978	2	1.245 to 1.245	249.8 to 249.8	192.7 to 193.1	1.0 to 1.0	61.2 to 61.2

Table 7 Single Web Data Parameters

Section			Researcher's Name	No. of Tests	t min to t max (mm)	Fy min to Fy max (MPa)	h/t min to h/t max (ratio)	r/t min to r/t max (ratio)	n/t min to n/t max (ratio)
i) Stiffened	a) Fastened	1) EOF	Hetrakul, UMR, 1978	8	1.270 to 1.295	324.6 to 324.6	91.7 to 141.6	1.7 to 1.9	19.7 to 60.0
			Bhakta, UMR, 1992	10	1.600 to 2.769	390.8 to 447.0	68.3 to 132.7	1.4 to 5.0	24.1 to 41.7
			Gerges, UW, 1997	67	1.280 to 1.280	321.0 to 321.0	96.1 to 222.7	5.0 to 9.3	23.4 to 78.9
			Cain, UMR, 1995	14	1.499 to 2.108	391.9 to 508.2	69.9 to 150.5	3.0 to 4.2	31.6 to 44.5
		2) ETF	Beshara, UW, 1999	36	1.160 to 1.450	323.0 to 448.0	60.1 to 195.2	4.8 to 12.1	20.7 to 69.7
		3) ITF	Beshara, UW, 1999	36	1.160 to 1.450	323.0 to 448.0	60.1 to 195.2	4.8 to 12.1	20.7 to 87.1
	b) Unfastened	1) EOF	Hetrakul, UMR, 1978	34	1.194 to 1.321	254.0 to 370.5	73.1 to 253.2	1.2 to 2.8	19.6 to 140.9
			Bhakta, UMR, 1992	10	1.600 to 2.769	390.8 to 447.0	68.8 to 132.6	1.4 to 5.0	24.1 to 41.7
			Langan, UMR, 1994	23	0.838 to 1.956	234.2 to 640.6	33.6 to 192.3	2.0 to 4.7	13.0 to 30.3
			Cain, UMR, 1995	14	1.499 to 2.108	391.9 to 508.2	69.9 to 150.5	3.0 to 4.2	31.6 to 44.5
		2) IOF	Hetrakul, UMR, 1978	24	1.207 to 1.283	301.8 to 324.6	116.7 to 249.2	1.7 to 2.8	19.9 to 62.5
			Langan, UMR, 1994	8	0.838 to 1.143	365.1 to 495.9	72.4 to 167.6	3.5 to 4.7	66.7 to 121.2
		3) ETF	Hetrakul, UMR, 1978	26	1.168 to 1.308	301.8 to 324.6	90.0 to 255.1	1.8 to 2.7	19.4 to 63.8
		4) ITF	Hetrakul, UMR, 1978	26	1.194 to 1.326	301.8 to 324.6	88.7 to 252.6	1.7 to 2.7	19.3 to 63.8
ii) Unstiffened	Unfastened	1) EOF	Hetrakul, UMR, 1978	18	1.232 to 1.295	249.8 to 283.7	94.4 to 193.1	0.9 to 1.6	20.4 to 140.0
			Young, Sydney, 1998	14	3.820 to 4.740	275.0 to 415.0	16.9 to 38.3	0.9 to 1.1	7.9 to 19.4
		2) IOF	Hetrakul, UMR, 1978	4	1.245 to 1.245	249.8 to 249.8	96.1 to 192.2	1.0 to 1.0	61.2 to 61.2
			Young, Sydney,1998	16	3.810 to 4.740	275.0 to 415.0	16.9 to 38.4	0.9 to 1.1	7.9 to 19.5
		3) ETF	Hetrakul, UMR, 1978	4	1.232 to 1.245	249.8 to 249.8	96.7 to 192.9	1.0 to 1.0	61.2 to 61.9
			Young, Sydney, 1998	12	1.470 to 4.830	275.0 to 550.0	16.2 to 62.7	0.6 to 1.2	7.9 to 51.0
		4) ITF	Hetrakul, UMR, 1978	4	1.245 to 1.257	249.8 to 249.8	94.2 to 193.9	1.0 to 1.0	60.6 to 61.2
			Young, Sydney, 1998	14	1.460 to 4.820	275.0 to 550.0	16.2 to 62.7	0.6 to 1.2	7.9 to 51.0

Table 8 Single Hat Data Parameters

Section		Researcher's Name	No. of Tests	t min to t max (mm)	Fy min to Fy max (MPa)	h/t min to h/t max (ratio)	r/t min to r/t max (ratio)	n/t min to n/t max (ratio)
a) Fastened	1) EOF	Bhakta, UMR, 1992	2	1.245 to 1.245	301.8 to 301.8	145.4 to 145.5	4.1 to 4.1	53.6 to 53.6
		WU, UMR, 1997	3	0.737 to 0.737	715.7 to 715.7	51.0 to 155.3	4.3 to 4.3	34.5 to 34.5
	2) IOF	Wing, UW, 1981	25	0.549 to 1.524	230.8 to 317.5	62.0 to 204.0	1.6 to 17.4	16.7 to 208.3
	3) ETF	Wing, UW, 1981	17	0.610 to 1.539	230.8 to 317.5	28.5 to 323.9	1.6 to 9.1	16.7 to 81.0
	4) ITF	Wing, UW, 1981	23	0.610 to 1.539	230.8 to 317.5	28.2 to 157.2	1.6 to 10.1	16.7 to 125.0
b) Unfastened	1) EOF	Cornell, 1953	60	1.130 to 1.839	186.0 to 413.3	37.1 to 193.1	1.0 to 3.0	10.9 to 56.2
		Bhakta, UMR, 1992	2	1.245 to 1.245	301.8 to 301.8	145.3 to 145.4	4.1 to 4.1	53.6 to 53.6
	2) IOF	Cornell, 1953	30	1.491 to 1.699	212.8 to 384.4	83.0 to 195.0	1.0 to 3.0	11.3 to 42.6

Table 9 Multi-Web Data Parameters

Section		Researcher's Name	No. of Tests	t min to t max (mm)	Fy min to Fy max (MPa)	h/t min to h/t max (ratio)	r/t min to r/t max (ratio)	n/t min to n/t max (ratio)
a) Fastened	1) EOF	Bhakta, UMR, 1992	2	0.660 to 0.660	396.0 to 396.0	102.8 to 102.9	6.6 to 6.6	101.0 to 101.0
	2) IOF	Wing, UW, 1981	34	0.508 to 1.549	230.8 to 317.5	72.3 to 207.2	1.5 to 13.0	16.4 to 161.9
		Bhakta, UMR, 1992	2	0.660 to 0.660	396.0 to 396.0	102.8 to 102.9	6.6 to 6.6	201.9 to 201.9
	3) ETF	Wing, UW, 1981	63	0.610 to 1.575	230.8 to 337.5	20.6 to 324.3	1.3 to 10.1	16.4 to 125.0
	4) ITF	Wing, UW, 1981	57	0.610 to 1.539	230.8 to 337.5	20.6 to 207.2	1.3 to 10.0	16.7 to 125.0
b) Unfastened	1) EOF	Yu, UMR, 1981	18	0.721 to 1.240	270.7 to 343.7	38.0 to 99.3	3.1 to 7.1	61.1 to 208.1
		Bhakta, UMR, 1992	2	0.660 to 0.660	396.0 to 396.0	102.7 to 102.9	6.6 to 6.6	101.0 to 101.0
		WU, UMR, 1997	16	0.432 to 0.737	715.7 to 774.9	25.9 to 208.3	2.2 to 5.5	34.5 to 58.8
	2) IOF	Bhakta, UMR, 1993	2	0.660 to 0.660	396.0 to 396.0	102.8 to 103.0	6.6 to 6.6	201.9 to 201.9
	3) ETF	WU, UMR, 1997	16	0.432 to 0.737	715.7 to 774.9	25.9 to 208.3	2.2 to 5.5	34.5 to 58.8
	4) ITF	WU, UMR, 1997	16	0.432 to 0.737	715.7 to 774.9	25.9 to 208.3	2.2 to 5.5	34.5 to 58.8

Table 10 New Coefficients, Resistance Factors and Factors of Safety for I-Sections

Support and Flange Conditions		Load Cases		C	C_R	C_N	C_H	No. of Tests	Mean Value	C.O.V.	S136	AISI	
											ϕ	Ω	ϕ
FASTENED TO SUPPORT	Stiffened or Partially Stiffened Flanges	One - Flange Loading or Reaction	Interior	20	0.15	0.05	0.003	18	1.01	0.06	0.80	1.67	0.92
UNFASTENED	Stiffened or Partially Stiffened Flanges	One - Flange Loading or Reaction	End	10	0.14	0.28	0.001	86	1.00	0.21	0.62	2.03	0.75
			Interior	20.5	0.17	0.11	0.001	29	1.01	0.13	0.75	1.74	0.88
		Two - Flange Loading or Reaction	End	15.5	0.09	0.08	0.04	57	1.01	0.21	0.63	2.01	0.76
			Interior	36	0.14	0.08	0.04	66	1.00	0.19	0.65	1.98	0.77

Table 11 New Coefficients, Resistance Factors and Factors of Safety for Single Web Sections

Support and Flange Conditions		Load Cases		C	C_R	C_N	C_H	Tests No.	Section Type	Mean Value	C.O.V.	S136	AISI	
												ϕ	Ω	ϕ
FASTENED TO SUPPORT	Stiffened or Partially Stiffened Flanges	One - Flange Loading or Reaction	End	4	0.14	0.35	0.02	99	C &Z	1.00	0.11	0.75	1.75	0.88
		Two - Flange Loading or Reaction	End	7.5	0.08	0.12	0.048	18	C	1.03	0.12	0.77	1.72	0.89
				9	0.05	0.16	0.052	18	Z	1.00	0.12	0.74	1.78	0.86
			Interior	20	0.10	0.08	0.031	18	C	1.01	0.13	0.74	1.78	0.86
				24	0.07	0.07	0.04	18	Z	1.03	0.18	0.69	1.88	0.82
UNFASTENED	Stiffened or Partially Stiffened Flanges	One - Flange Loading or Reaction	End	4	0.14	0.35	0.02	63	C	1.00	0.16	0.70	1.86	0.83
				5	0.09	0.02	0.001	18	Z	1.01	0.13	0.74	1.78	0.86
			Interior	13	0.23	0.14	0.01	32	C	1.02	0.07	0.80	1.66	0.92
		Two - Flange Loading or Reaction	End	13	0.32	0.05	0.04	26	C	1.01	0.06	0.80	1.67	0.92
			Interior	24	0.52	0.15	0.001	26	C	1.02	0.19	0.67	1.92	0.80
	Unstiffened Flanges	One - Flange Loading or Reaction	End	4	0.40	0.60	0.03	32	C	1.01	0.14	0.72	1.80	0.85
			Interior	13	0.32	0.10	0.01	20	C	1.01	0.15	0.71	1.82	0.84
		Two - Flange Loading or Reaction	End	2	0.11	0.37	0.01	16	C	1.01	0.20	0.65	1.96	0.78
			Interior	13	0.47	0.25	0.04	18	C	1.00	0.19	0.66	1.94	0.79

Table 12 New Coefficients, Resistance Factors and Factors of Safety for Single Hat Sections

Support Conditions	Load Cases		C	C_R	C_N	C_H	Tests No.	Mean Value	C.O.V.	S136	AISI	
										ϕ	Ω	ϕ
FASTENED TO SUPPORT	One - Flange Loading or Reaction	Interior	17	0.13	0.13	0.04	25	1.01	0.17	0.68	1.89	0.81
	Two - Flange Loading or Reaction	End	9	0.10	0.07	0.03	17	1.02	0.11	0.76	1.73	0.89
		Interior	10	0.14	0.22	0.02	23	1.0	0.12	0.73	1.79	0.86
UNFASTENED	One - Flange Loading or Reaction	End	4	0.25	0.68	0.04	62	1.01	0.21	0.64	2.00	0.77
		Interior	17	0.13	0.13	0.04	30	1.05	0.14	0.76	1.71	0.90

Table 13 New Coefficients, Resistance Factors and Factors of Safety for Multi-Web Sections

Support Conditions	Load Cases		C	C_R	C_N	C_H	Tests No.	Mean Value	C.O.V.	S136	AISI	
										ϕ	Ω	ϕ
FASTENED TO SUPPORT	One - Flange Loading or Reaction	Interior	8	0.10	0.17	0.004	36	1.02	0.12	0.75	1.76	0.87
	Two - Flange Loading or Reaction	End	9	0.12	0.14	0.040	63	1.00	0.14	0.71	1.83	0.84
		Interior	10	0.11	0.21	0.020	57	1.01	0.11	0.76	1.75	0.88
UNFASTENED	One - Flange Loading or Reaction	End	3	0.08	0.70	0.055	36	1.00	0.28	0.53	2.29	0.67
	Two - Flange Loading or Reaction	End	6	0.16	0.15	0.050	16	1.01	0.05	0.81	1.65	0.93
		Interior	17	0.10	0.10	0.046	16	1.01	0.05	0.81	1.65	0.93