Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Toronto, Canada, March 25-28, 2014

Direct Strength Method for Web Crippling of Cold-Formed Steel C- and Z- Sections Subjected to Two-Flange Loading

M.Y. Choy[1], X.F. Jia[2], X. Yuan[3], J. Zhou[4], H.S. Wang[5], C. Yu[6]

Abstract

Direct Strength Method (DSM) is a design method for cold-formed steel members recently adopted by the North American Specification for the Design of Cold-Formed Steel Structural Members (AISI S100, 2007). DSM uses the elastic buckling solutions and the yield loads of the entire section instead of the effective section modulus to predict the nominal strength of cold-formed steel members. With the help of advanced computation tools such as the Finite Strip Analysis, DSM offers quicker, simpler, and more reliable calculations compared with the traditional Effective Width Method. However, the DSM is currently capable of determining the nominal strength of flexural and compressive strength only. This paper presents an effort to expand the DSM to the web crippling strength of cold-formed steel C- and Z- sections subjected to two-flange loading. The proposed DSM equations use simplified elastic buckling solution and the yield load for the web to predict the nominal web crippling strength. The research shows that the proposed DSM equations have good agreement with industrial standard cold-formed steel C- and Z- sections. This paper proves the concept that DSM can be used to determine the web crippling strength of cold-formed steel flexural members.

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[1] PhD Student, Tsinghua University, <mycesther@yahoo.com.hk>

[2] Master Student, Tsinghua University, <jiaxiangfu@foxmail.com>

[3] PhD Student, Tsinghua University, <emylf@163.com>

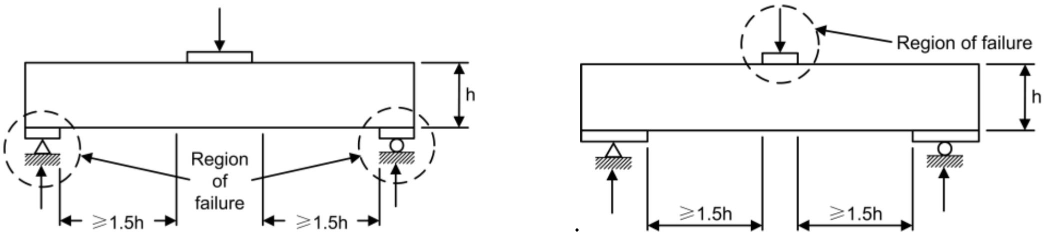
[4] Master Student, Tsinghua University, <snakejian2005@163.com>

[5] Undergraduate Student, Tsinghua University, <whs11@mails.tsinghua.edu.cn>

[6] Assoc. Professor, University of North Texas, <cheng.yu@unt.edu>

1. Introduction

Web crippling is an important limit state in the structural design of cold-formed steel (CFS) flexural members. Due to the large slenderness ratio, the web element of CFS members tends to cripple at the areas of compression loads or bearing supports. The North American Specification for Cold-Formed Steel Structural Members (AISI S100, 2012) defines four loading cases for web crippling: End One-Flange (EOF) loading, Interior One-Flange (IOF) loading, End Two-Flange (ETF) loading and Interior Two-Flange (ITF) loading as shown in Fig.1. The current AISI S100 design provision for web crippling is based on extensive experimental results by Winter and Pian (1946), Zetlin (1955a), Hetrakul and Yu (1978), Yu (1981), Santaputra (1986), Santaputra, Parks and Yu (1989), Bhakta, LaBoube and Yu (1992), Wing (1981), Wing and Schuster (1982), Prabakaran (1993), Beshara and Schuster (2000 and 2000a) and Young and Hancock (1998). In the 1996 AISI Specification and previous editions, different equations were adopted for web crippling strength. Since the 2001 edition, the AISI Specification began using a unified equation with different coefficients for determining the nominal web crippling strength for different cases. The unified design method was developed by Prabakaran (1993), Prabakaran and Schuster (1998) and Beshara (1999).



(a) EOF Loading (b) IOF Loading

(c) ETF Loading (d) ITF Loading

Figure 1. Four loading conditions for web crippling tests

As per the North American Specification for the Design of Cold-Formed Steel Structure Members (AISI S100, 2012), the normal web crippling strength can be calculated as follows.

$$P_n = Ct^2 F_y (\sin\theta)\left(1 - C_R\sqrt{\frac{R}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\sqrt{\frac{h}{t}}\right) \quad (1)$$

where C is the web crippling coefficient, C_H is the web slenderness coefficient, C_N is the bearing length coefficient, C_R is the inside bend radius coefficient, F_y is the yield strength of steels, h is the flat dimension of web measured in plane of web, N is the bearing length, R is the inside bend radius, t is the web thickness and θ is the angle between plane of web and plane of bearing surface

The Direct Strength Method (DSM) is a newly developed methodology for CFS design. The method has been formally adopted by the North American Specification for the Design of Cold-Formed Steel Structure Members and the Australian/New Zealand Standard for CFS design.

Compared with the Effective Width Method, DSM is more reliable and has specific advantage on solving complicated section problems and distortional buckling cases. DSM is currently capable of determining the nominal strength of members under flexural, compression, and shear forces. It is therefore meaningful to expand DSM to address the web crippling strength. As an initial research effort, the objective of this paper is to develop DSM equations for the web crippling strength of CFS steel C- and Z- sections subjected to two-flange loading. The goal is to prove the concept that DSM works for the limit state of web crippling.

2. Elastic buckling of C- and Z- sections subjected to web crippling failures

2.1 Equivalent plate model

According to the AISI S100 (2012), the assumed reaction or load distributions of two flange loading cases (ITF and ETF) are illustrated in Fig.2 and Fig.3, respectively. It can be seen from the two figures that the stress distribution of the two flange load cases can be assumed to be the combination of the two one-flange-loading results. The web crippling of CFS sections under two-flange loading is essentially a buckling issue of a plate element under compression stresses. Fig.2 and Fig.3 indicate that the two flange loading situation can be treated as a plate subjected to compression stresses (equivalent plate model). The plate width shall be greater than the bearing length due to the constraint provided by the section’s web outside the stress distribution area. For the boundary conditions of the equivalent plate models, simply-simply supported condition is appropriate for the ITF case, and the simply-free supported condition is applicable to the ETF case.

The equivalent width of the web is an important parameter in determining the web crippling strength of the CFS member. Since the stress can be assumed to be distributed at a 45° angel, the equivalent width (defined as the most influential area), therefore, can be determined as (N+h) for ITF and (N+0.5h) for ETF, where N is the bearing length and h is flat web depth.

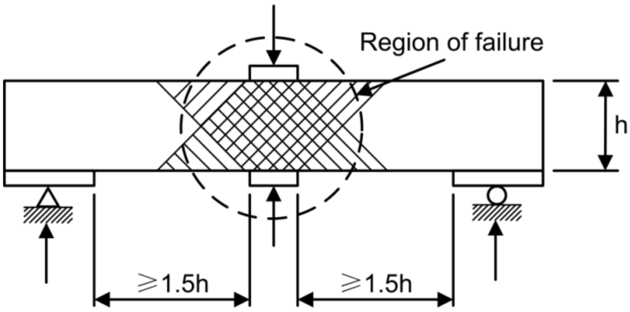


Figure 2: Load distribution of CFS member subjected to two flange interior loading

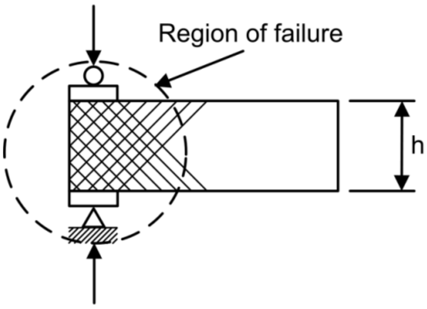


Figure 3: Load distribution of CFS member subjected to two flange end loading

2.2 Plate Buckling

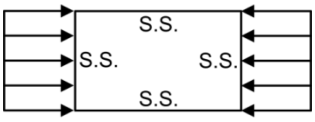
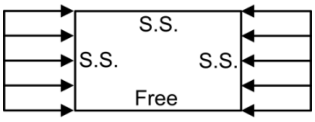
The elastic buckling stress of thin plates can be determined by Eq. 2.

$$f_{cr} = \frac{k\pi^2 E}{12(1-\mu^2)(w/t)^2} \qquad (2)$$

where k is the plate buckling coefficient, E is the modulus of elasticity of steel, μ is the poisson's ratio (0.3 for steel in the elastic range), w is the flat width of the compression element and t is the thickness of the compression element.

The values of plate buckling coefficients are shown in Table 1. For simply-simply supported plates, the value of k is 4.0; For simply-free supported plates, the value of k is 0.43.

Table 1: Values of plate buckling coefficients

Case	Boundary condition	Type of stress	Value of k for long plate
(a)		Compression	4.0
(b)		Compression	0.43

3. Proposed DSM for web crippling

3.1 Theory

The idea of DSM is to use the elastic buckling solution and the yield load of the entire section to predict the nominal strength of CFS members for each specific buckling mode. Eq. 3 is the key DSM equation for calculating the nominal axial strength of CFS columns in local buckling mode.

$$P_{nl} = \left[1 - 0.15\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4}\right]\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4} P_{ne} \tag{3}$$

where P_{crl} is the critical elastic local buckling load and P_{ne} is the nominal axial strength in the global buckling model ($P_{ne} = P_y$ for stocky columns).

By extending the DSM to the calculation of web crippling strength, it is our purpose to use the same theory and similar function to predict the nominal web crippling strength. Eq. 4 shows the proposed DSM function for web crippling.

$$P_n = c\left[1 - a\left(\frac{P_{cr}}{P_y}\right)^{b}\right]\left(\frac{P_{cr}}{P_y}\right)^{b} P_y \tag{4}$$

where P_{cr} is the critical elastic buckling load of the equivalent plate model, P_y is the yield load of the equivalent plate model and a/b/c are the parameters obtained from the regression analysis.

The yield load of the equivalent plate P_y can be calculated by Eq. 5.

$$P_y = F_y w_e t \tag{5}$$

where F_y is the yield stress of the whole section, w_e is the equivalent width of the web ($w_e = N+h$ for ITF case, $w_e = N+0.5h$ for ETF case), t is the thickness of the web and N is the bearing length, h is the flat web depth.

The critical elastic buckling load of the equivalent plate P_{cr} can be obtained by Eq. 6.

$$P_{cr} = f_{cr} w_e t = \frac{k\pi^2 E}{12(1-\mu^2)(w_e/t)^2} w_e t \tag{6}$$

where f_{cr} is the elastic critical buckling stress (refer to Eq. 2), k is the plate buckling coefficient (refer to Table 1), E is the modulus of elasticity of steel, μ is the poisson's ratio (0.3 for steel in the elastic range), w_e is the equivalent width of the web ($w_e = N+h$ for ITF case, $w_e = N+0.5h$ for ETF case), t is the thickness of the web, N is the bearing length and h is the flat web depth.

3.2 Regression analysis and results

In order to identify the parameters in Eq. 4, a regression analysis using Matlab is carried out. A total of 416 industrial standard CFS C- and Z- sections are used in the analysis, those sections' geometric and material properties are obtained from the AISI Design Manual (AISI D100, 2008). The purpose of the regression process is to obtain the most appropriate parameters for the DSM in order to make the DSM formula statistically close to the AISI formula (Eq. 1) as much as possible. With this purpose, the nonlinear regression method is adopted in the regression process and the most appropriate values for parameters, a, b and c are determined.

The proposed DSM design for CFS web crippling of C and Z sections under two-flange loading is listed below.

For the ITF:

$$P_{DSM} = \frac{1}{2.5}[1-0.075(\frac{P_{cr}}{P_y})^{0.63}](\frac{P_{cr}}{P_y})^{0.63}P_y \tag{7}$$

For the ETF:

$$P_{DSM} = [1-0.24(\frac{P_{cr}}{P_y})^{0.83}](\frac{P_{cr}}{P_y})^{0.83}P_y \tag{8}$$

Fig.4 and Fig. 5 respectively show the comparison of the proposed DSM method with the current AISI design method for ITF and ETF respectively. Table 2 shows the statistical results of the comparison. The proposed DSM method has good agreement with the AISI predictions, and it yields appropriate but conservative prediction. It can be concluded that the DSM concept works for the two flange loading cases of web crippling.

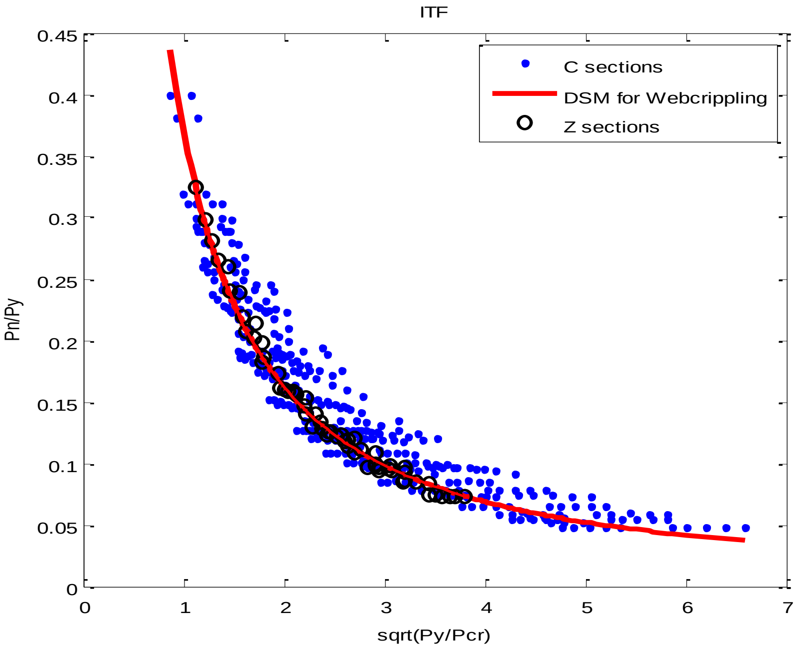


Figure 4: Interior case for C- and Z- Sections

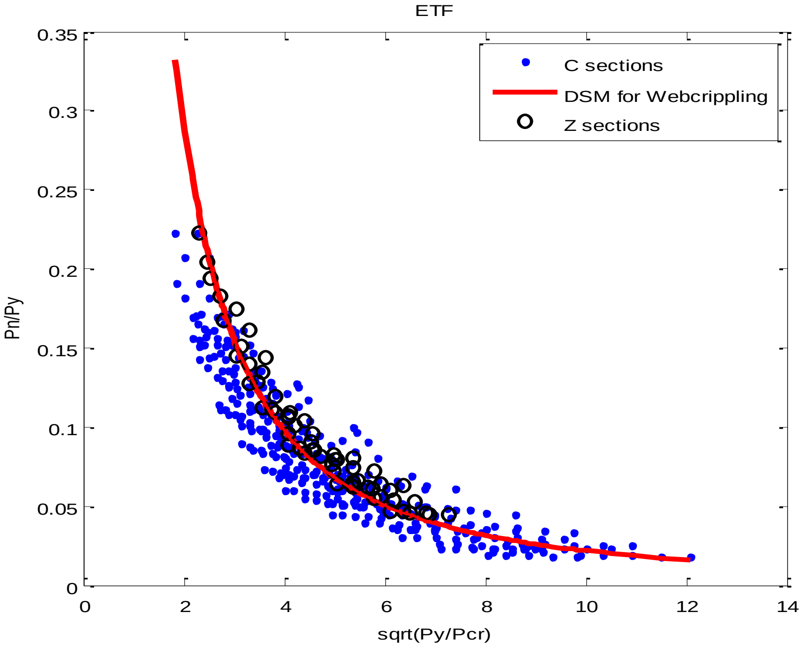


Figure 5: End case C- and Z- Sections

Table 2 shows the statistical results of the index in determining whether the parameter is good or not. The average web crippling strength calculated by AISI formula and DSM is given. The covariance of the web crippling strength calculated by different formula is also given.

Table 2: Results of the nonlinear regression for all sections

	Number of Sections	**Average P_{AISI}/P_{DSM}**	**C.O.V. (P_{AISI}/P_{DSM})**
ITF	415	1.0429	0.007
ETF	415	1.0249	0.0232

4. Validation of the proposed formula

The proposed DSM equations for web crippling are obtained from a regression analysis against the current AISI design method. It is important to validate the new approach by using experimental data. In the past 25 years, more than five hundred web crippling tests were done in different countries including the United States, Canada and Australia. Table 3 is the summary of most recent tests.

Table 3: Summary of recent web crippling tests

Researcher, Year	**Country**	**Institution**	**No. of tests**
Santaputra, Parks and Yu, 1989	USA	University of Missouri	210
Young and Hancock, 1998	Australia	Sydney University	56
Beshara and Schuster, 1999	Canada	University of Waterloo	72
Tryland, Langseth and Hopperstad, 1999	Norway	Norwegian University of science and technology	52
Holesapple and LaBoube, 2003	USA	University of Missouri	29
Zhou and Young, 2008	China	University of Hong Kong	150
Zhou and Young, 2013	China	University of Hong Kong	90

The 72 tests by Beshara and Schuster (1999) is used herein to verify the newly proposed DSM formula and the results are shown in Table 4~Table 7. The results show that the proposed DSM method has good agreement with the test results and it yield conservative predictions.

5. Conclusions

This paper aims at extending the Direct Strength Method to predict the web crippling strength of cold-formed C- and Z- sections, the following conclusions can be drawn:

(1) The web crippling of CFS sections can be treated as a buckling issue of an equivalent plate.

(2) The DSM methodology works for the web crippling strength.

(3) The proposed DSM equations have good agreement with the AISI design method and the experimental data.

The research is underway to develop DSM provisions for the one-flange loading cases and CFS sections with web openings.

Acknowledgments

The authors gratefully acknowledge the Tsinghua Visiting Scholarship Program and the National Natural Science Foundation of China Research (Grant No. 51261120377) for supporting the research. The authors also would like to thank Assoc. Prof. Xiaodong Ji of Tsinghua University for his technical advises.

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Table 4: Single Web C-Sections End Two Flange Loading（ETF）

No.	Specimen	t(mm)	Fy(MPa)	h(mm)	R(mm)	N(mm)	H(mm)	W_e(mm)	P_y(MPa)	P_{cr}(MPa)	P_{DSM}(kN)	P_t(kN)	P_t/P_{DSM}
1	C-120-7-30-ETF	1.45	332	118	7	30	101.1	80.55	38776.77	3026.99	4.53	3.84	0.85
2	C-120-7-60-ETF	1.45	332	118	7	60	101.1	110.55	53218.77	2205.55	3.72	4.74	1.27
3	C-120-10-30-ETF	1.45	332	117	10	30	94.1	77.05	37091.87	3164.49	4.66	3.75	0.80
4	C-120-10-60-ETF	1.45	332	117	10	60	94.1	107.05	51533.87	2277.66	3.80	4.17	1.10
5	C-120-14-100-ETF A	1.45	332	115	14	100	84.1	142.05	68382.87	1716.47	3.18	4.77	1.50
6	C-120-14-100-ETF-B	1.45	332	115	14	100	84.1	142.05	68382.87	1716.47	3.18	4.68	1.47
7	C-200-7-30-ETF	1.16	328	197	7	30	180.68	120.34	45786.96	1037.38	1.95	2.07	1.06
8	C-200-7-60-ETF	1.16	328	197	7	60	180.68	150.34	57201.36	830.37	1.69	2.46	1.45
9	C-200-10-30-ETF	1.16	328	197	10	30	174.68	117.34	44645.52	1063.90	1.99	2.01	1.01
10	C-200-10-60-ETF	1.16	328	197	10	60	174.68	147.34	56059.92	847.28	1.72	2.19	1.28
11	C-200-14-30-ETF	1.16	328	198	14	30	167.68	113.84	43313.84	1096.61	2.03	1.95	0.96
12	C-200-14-60-ETF	1.16	328	198	14	60	167.68	143.84	54728.24	867.89	1.74	2.13	1.22
13	C-300-7-30-ETF	1.45	448	297	7	30	280.1	170.05	110464.48	1433.84	2.98	2.85	0.96
14	C-300-7-60-ETF	1.45	448	297	7	60	280.1	200.05	129952.48	1218.81	2.68	3.27	1.22
15	C-300-10-30-ETF	1.45	448	297	10	30	274.1	167.05	108515.68	1459.59	3.02	2.76	0.92
16	C-300-10-60-ETF	1.45	448	297	10	60	274.1	197.05	128003.68	1237.37	2.71	3.06	1.13
17	C-300-14-30-ETF	1.45	448	296	14	30	265.1	162.55	105592.48	1499.99	3.07	2.67	0.87
18	C-300-14-60-ETF	1.45	448	296	14	60	265.1	192.55	125080.48	1266.29	2.75	2.91	1.06

Mean Value	1.12
S.D	0.21
C.O.V.	0.04

Table 5: Single Web C-Sections Interior Two Flange Loading（ITF）

No.	Specimen	t(mm)	F_y(MPa)	h(mm)	R(mm)	N(mm)	H(mm)	W_e(mm)	P_y(MPa)	P_{cr}(MPa)	P_{DSM}(kN)	P_t(kN)	P_t/P_{DSM}
1	C-120-7-30-ETF	1.45	332	118	7	30	101.1	131.1	63111.54	17300.76	10.80	10.7	0.99
2	C-120-7-60-ETF	1.45	332	118	7	64	101.1	165.1	79479.14	13737.91	10.26	11.8	1.15
3	C-120-10-30-ETF	1.45	332	117	10	30	94.1	124.1	59741.74	18276.63	10.93	9.96	0.91
4	C-120-10-60-ETF	1.45	332	117	10	60	94.1	154.1	74183.74	14718.56	10.42	11	1.06
5	C-120-14-100-ETF A	1.45	332	115	14	100	84.1	184.1	88625.74	12320.10	10.01	9.06	0.91
6	C-120-14-100-ETF-B	1.45	332	115	14	100	84.1	184.1	88625.74	12320.10	10.01	10.1	1.01
7	C-200-7-30-ETF	1.16	328	197	7	30	180.68	210.68	80159.53	5512.07	5.85	7.2	1.23
8	C-200-7-60-ETF	1.16	328	197	7	60	180.68	240.68	91573.93	4825.01	5.67	7.56	1.33
9	C-200-10-30-ETF	1.16	328	197	10	30	174.68	204.68	77876.65	5673.65	5.90	6.57	1.11
10	C-200-10-60-ETF	1.16	328	197	10	60	174.68	234.68	89291.05	4948.37	5.70	7.08	1.24
11	C-200-14-30-ETF	1.16	328	198	14	30	167.68	197.68	75213.29	5874.56	5.95	6.72	1.13
12	C-200-14-60-ETF	1.16	328	198	14	60	167.68	227.68	86627.69	5100.50	5.74	7.08	1.23
13	C-300-7-30-ETF	1.45	448	297	7	30	280.1	310.1	201440.96	7314.19	9.88	11	1.11
14	C-300-7-60-ETF	1.45	448	297	7	60	280.1	340.1	220928.96	6669.01	9.66	11.6	1.20
15	C-300-10-30-ETF	1.45	448	297	10	30	274.1	304.1	197543.36	7458.50	9.93	9.99	1.01
16	C-300-10-60-ETF	1.45	448	297	10	60	274.1	334.1	217031.36	6788.77	9.70	10.9	1.12
17	C-300-14-30-ETF	1.45	448	296	14	30	265.1	295.1	191696.96	7685.97	10.01	10.3	1.03
18	C-300-14-60-ETF	1.45	448	296	14	60	265.1	325.1	211184.96	6976.71	9.77	10.6	1.09

Mean Value	1.10
S.D.	0.11
C.O.V.	0.013

Table 6: Single Web Z-Sections End Two Flange Loading（ETF）

No.	Specimen	t(mm)	F_y(MPa)	h(mm)	R(mm)	N(mm)	H(mm)	W_e(mm)	P_y(MPa)	P_{cr}(MPa)	P_{DSM}(kN)	P_t(kN)	P_t/P_{DSM}
1	Z-120-7-30-ETF	1.45	332	117	7	30	100.1	80.05	38536.07	3045.90	3.07	5.43	1.77
2	Z-120-7-60-ETF	1.45	332	117	7	60	100.1	110.05	52978.07	2215.57	2.84	6.18	2.18
3	Z-120-10-30-ETF	1.45	332	117	10	30	94.1	77.05	37091.87	3164.49	3.10	5.31	1.71
4	Z-120-10-60-ETF	1.45	332	117	10	60	94.1	107.05	51533.87	2277.66	2.86	6.09	2.13
5	Z-120-14-30-ETF A	1.45	332	117	14	100	86.1	143.05	68864.27	1704.47	2.66	5.25	1.97
6	Z-120-14-60-ETF-B	1.45	332	117	14	100	86.1	143.05	68864.27	1704.47	2.66	5.85	2.20
7	Z-200-7-30-ETF	1.16	323	197	7	30	180.68	120.34	45088.99	1037.38	1.66	2.73	1.64
8	Z-200-7-60-ETF	1.16	323	197	7	60	180.68	150.34	56329.39	830.37	1.57	2.88	1.83
9	Z-200-10-30-ETF	1.16	323	197	10	30	174.68	117.34	43964.95	1063.90	1.67	2.64	1.58
10	Z-200-10-60-ETF	1.16	323	197	10	60	174.68	147.34	55205.35	847.28	1.58	2.67	1.69
11	Z-200-14-30-ETF	1.16	323	200	14	30	169.68	114.84	43028.25	1087.06	1.68	2.64	1.57
12	Z-200-14-60-ETF	1.16	323	200	14	60	169.68	144.84	54268.65	861.90	1.59	2.58	1.62
13	Z-300-7-30-ETF	1.45	446	297	7	30	280.1	170.05	109971.34	1433.84	2.84	3.36	1.18
14	Z-300-7-60-ETF	1.45	446	297	7	60	280.1	200.05	129372.34	1218.81	2.73	3.78	1.39
15	Z-300-10-30-ETF	1.45	446	297	10	30	274.1	167.05	108031.24	1459.59	2.86	3.3	1.16
16	Z-300-10-60-ETF	1.45	446	297	10	60	274.1	197.05	127432.24	1237.37	2.74	3.69	1.35
17	Z-300-14-30-ETF	1.45	446	297	14	30	266.1	163.05	105444.44	1495.39	2.87	3.36	1.17
18	Z-300-14-60-ETF	1.45	446	297	14	60	266.1	193.05	124845.44	1263.01	2.75	3.66	1.33

Mean Value	1.64
S.D.	0.33
C.O.V.	0.11

Table 7: Single Web Z-Sections Interior Two Flange Loading（ITF）

No.	Specimen	t(mm)	F_y(MPa)	h(mm)	R(mm)	N(mm)	H(mm)	W_e(mm)	P_y(MPa)	P_{cr}(MPa)	P_{DSM}(kN)	P_t(kN)	P_t/P_{DSM}
1	Z-120-7-30-ETF	1.45	332	117	7	30	100.1	130.1	62630.14	17433.74	10.82	11.7	1.08
2	Z-120-7-60-ETF	1.45	332	117	7	60	100.1	160.1	77072.14	14166.96	10.33	13.1	1.27
3	Z-120-10-30-ETF	1.45	332	117	10	30	94.1	124.1	59741.74	18276.63	10.93	11.6	1.06
4	Z-120-10-60-ETF	1.45	332	117	10	60	94.1	154.1	74183.74	14718.56	10.42	12.6	1.21
5	Z-120-14-30-ETF A	1.45	332	117	14	100	86.1	186.1	89588.54	12187.69	9.98	11.3	1.13
6	Z-120-14-60-ETF-B	1.45	332	117	14	100	86.1	186.1	89588.54	12187.69	9.98	15.1	1.51
7	Z-200-7-30-ETF	1.16	323	197	7	30	180.68	210.68	78937.58	5512.07	5.82	7.83	1.35
8	Z-200-7-60-ETF	1.16	323	197	7	60	180.68	240.68	90177.98	4825.01	5.63	8.16	1.45
9	Z-200-10-30-ETF	1.16	323	197	10	30	174.68	204.68	76689.50	5673.65	5.86	7.65	1.31
10	Z-200-10-60-ETF	1.16	323	197	10	60	174.68	234.68	87929.90	4948.37	5.67	7.86	1.39
11	Z-200-14-30-ETF	1.16	323	200	14	30	169.68	199.68	74816.10	5815.72	5.90	6.93	1.18
12	Z-200-14-60-ETF	1.16	323	200	14	60	169.68	229.68	86056.50	5056.09	5.70	7.65	1.34
13	Z-300-7-30-ETF	1.45	446	297	7	30	280.1	310.1	200541.67	7314.19	9.87	10.3	1.04
14	Z-300-7-60-ETF	1.45	446	297	7	60	280.1	340.1	219942.67	6669.01	9.64	10.8	1.12
15	Z-300-10-30-ETF	1.45	446	297	10	30	274.1	304.1	196661.47	7458.50	9.92	9.48	0.96
16	Z-300-10-60-ETF	1.45	446	297	10	60	274.1	334.1	216062.47	6788.77	9.69	9.78	1.01
17	Z-300-14-30-ETF	1.45	446	297	14	30	266.1	296.1	191487.87	7660.01	9.98	8.88	0.89
18	Z-300-14-60-ETF	1.45	446	297	14	60	266.1	326.1	210888.87	6955.32	9.75	9.99	1.03

Mean Value	1.18
S.D.	0.17
C.O.V.	0.03