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Experimental Study on Web Crippling of Lapped Cold-Formed Steel Channels Subjected To Interior Two-Flange Loading

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Abstract

This investigation focused on the effects of lapped channels on the web crippling capacity of cold-formed steel members. The current design recommendations in North America Specifications specifies expressions for web crippling strength of different joist geometries in case of exterior end and concentrated load locations. However, it does not permit an increase in web crippling capacity when lapped cold-formed steel channels are subjected to interior two-flange loading. This may be attributed to the lack of experimental data on web crippling strength at interior support locations. Thus, the objective of the current research is to generate experimental data for CFS channels where both flanges of channel members are lapped at the interior support location and being loaded simultaneously. This paper summarizes the results of investigation. Test specimens were loaded to failure and load history and the failure pattern were recorded. Recommendations for further testing were drawn to establish design equations for web crippling strength of lapped CFS channels at interior support location when subjected to two flange loading. The test specimen used for the investigation is single web C-section.

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Introduction

Web crippling is a form of localized buckling that occurs at points of transverse concentrated loading or supports of thin walled structural members. Cold-formed channels that are unstiffened against this type of loading are susceptible to structural failure caused by web crippling [2]. Web crippling may occur when there is no end or load stiffener in cold-formed steel members under concentrated force or reaction [7]. The computation of the web crippling strength by means of theoretical analysis is quite complex, as it involves a large number of factors, such as the initial imperfection of web element, local yielding in the region of load application, instability of the web element, and other factors. Hence, the current design rules found in most specifications for cold-formed steel structures are empirical in nature and may not adequately account for sections outside the range of variables tested [2]. Due to the appearance of new materials and the improvement of cold-forming techniques, the material strength and sheet thickness of such channels may be increased. Thus, the applicability of the current web crippling design rules needs to be investigated [7]. This study focused on an interior two flange loading condition with the specimen load capacity governed by a web crippling failure. Fig. 1 illustrates the necessary conditions for an interior two flange loading.

The principal benefit of this project is to develop more liberal design expression for the joist lap at support, thereby potentially making cold formed steel framing more economical. In addition, this work will give the design professional and building code officials added confidence in the reliability of steel joist construction. The current web crippling design guidelines do not permit an increase in capacity when lap is present. This investigation will enhance these guidelines by providing a modification to the interior two flange web crippling design equation to account for the lap.

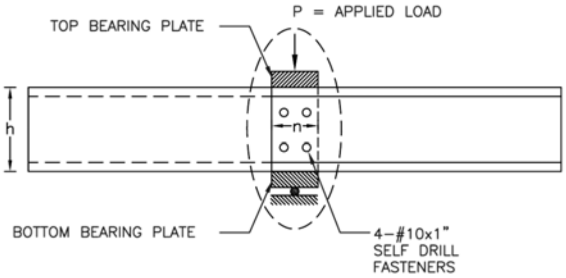


Fig.1 Interior Two Flange Loading Condition

Current Design Equation

At university of waterloo in 1993 Prabakaran performed an extensive statistical analysis of the web crippling capacity of cold formed steel section. Based on his research he developed a unified equation for the web crippling capacity of cold-formed steel section. This equation (1) is used in North American Specifications for determination for web crippling resistance.

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

Where
P_n = nominal web crippling strength
C = regression analysis coefficient
C_h = web slenderness coefficient
C_N = bearing length coefficient
C_R = inside bend radius coefficient
F_y = yield strength
h = flat dimension of the web measured in the plane of the web
N = bearing length (lap length)
R = inside bend radius
t = web thickness
θ = angle between the plane of the web and the plane of the bearing surface

Experimental Study

An experiment study performed at the Ryerson University, studied the web crippling capacity of a single web section loaded under an interior two flange condition with a variance in a lap length at support. Following is the summary of the test performed.

Test Specimen

The specimens consisted of edge-stiffened “C” section. (Fig 2) The sections have average yield stress of 53ksi (370Mpa). A nominal depth of web ranging from 8” (203mm) to 10” (254mm), and thickness of channel ranging from 0.068” (1.7mm) to 0.045” (1.14mm). The key cross sectional parameters for each tested cross-section are summarized in Table 1.

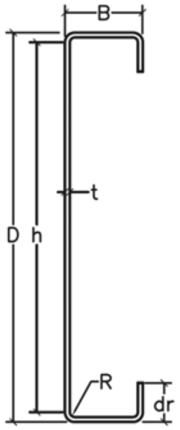


Fig. 2 Typical C-Section

Bearing Plate

The loads were applied by means of bearing plates. All bearing plates were machined to specified dimensions. The thickness of bearing plates was 0.5" (12.7mm). The bearing plates were designed to act across the full flange width of the channels. The length of bearing plate was equal to the lap length (N). The flanges of the channel specimens were restrained by the bearing plate.

Specimen Labelling

Total 24 specimens were tested. Each specimen was labeled such that the depth, thickness and lap length could be identified from the label. For example, the labels "10C14 250" define the following specimens.

- The first two letters shows the over all depth of the web in "inches".
- The letter "C" shows that specimen cross section is "C".
- The next two digits show the thickness of section in "gauge".
- The last three digits shows the lap length in "inches"

Material Properties

The material properties of the test specimens were determined by tensile coupon test. For each section tested, the three coupons were taken from the center of the

Table 1. Typical "C" Section Properties

Specimen	D (in)	h (in)	t (in)	B (in)	R (in)	df (in)	Fy (ksi)	N (in)
10C14	10	9.52	0.067	1.62	3.38	0.787	51.80	2.5
	10	9.52	0.067	1.62	3.38	0.787	51.80	3.625
	10	9.52	0.067	1.62	3.38	0.787	51.80	6
10C16	10	9.68	0.056	1.62	2.77	0.708	54.70	2.5
	10	9.68	0.056	1.62	2.77	0.708	54.70	3.625
	10	9.68	0.056	1.62	2.77	0.708	54.70	6
8C16	8	7.63	0.055	1.62	2.77	0.708	53.16	2.5
	8	7.63	0.055	1.62	2.77	0.708	53.16	3.625
	8	7.63	0.055	1.62	2.77	0.708	53.16	6
8C18	8	7.75	0.047	1.62	1.78	0.708	56.50	2.5
	8	7.75	0.047	1.62	1.78	0.708	56.50	3.625
	8	7.75	0.047	1.62	1.78	0.708	56.50	6

web plate in the longitudinal direction of the undisturbed specimens. The tensile coupons were prepared and tested according to American Society of Testing and Materials (ASTM A370, 2005). To measure the actual thickness of specimen the galvanized coating was removed by hydrochloric acid solution. The averages of three coupon tests for each specimen were used in the formula. Table2 shows the material mechanical properties of tested specimens.

Table 2. Mechanical Properties

Specimen	Test #	t (in)	Fy (ksi)	Fu (ksi)	% Elongation *
10C14	1	0.0678	51.90	68.50	34.5
	2	0.0676	52.20	69.00	34.5
	3	0.0677	51.40	68.50	34.0
	Average	**0.0677**	**51.80**	**68.70**	**34.3**
10C16	1	0.0564	54.90	69.50	32.5
	2	0.0562	54.30	70.10	33.0
	3	0.0564	54.90	70.20	32.5
	Average	**0.0563**	**54.70**	**69.90**	**32.7**
8C16	1	0.0555	53.20	69.70	34
	2	0.0549	53.20	70.00	34
	3	0.0552	53.10	70.00	34
	Average	**0.0552**	**53.16**	**69.90**	**34**
8C18	1	0.0467	56.10	73.00	22
	2	0.0476	56.80	73.20	22
	3	0.0468	56.60	73.00	22
	Average	**0.0470**	**56.50**	**73.06**	**22**

* Based on 2” gauge length

Test Procedure

The channel specimens were tested using interior two flange loading conditions (ITF) according to AISI specification. The test setup of ITF is shown in Fig 3. The channels at lapped was attached together with 4 self drilling screws size #10x1”. It should be noted that the two rows of screws are located at the third point of the web depth. Two identical bearing plates of the same width were placed top and bottom of channel at lap. Length of bearing plate was equal to length of lap. Channels’ sectional rotation at there ends were restrained by inserting their ends into a U-shape steel support system. In this case, the channel member is considered unbraced between this end rotational restraint and the interior support location. A 50 kip (222kN) capacity hydraulic jack was used to apply a compressive force to the test specimens over the interior support. Web lateral deflection and vertical movement of the channel top flange were recorded using LVDT’s. Each specimen was loaded incrementally till complete collapse. Failure was considered at the point at which the specimens could not accept a further load. Table 3. Shows the test results of all the tested specimen.

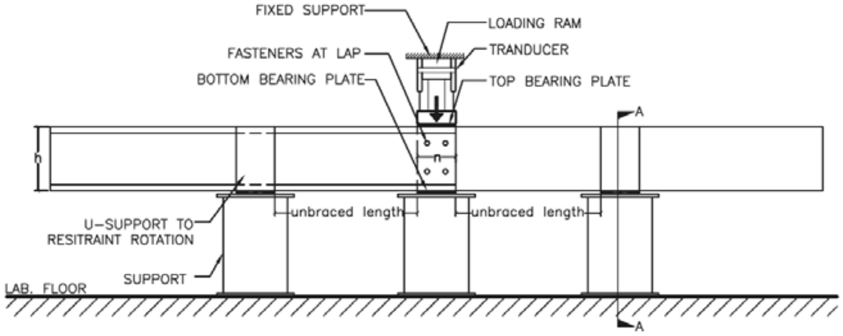


Fig 3. Schematic diagram of loading condition

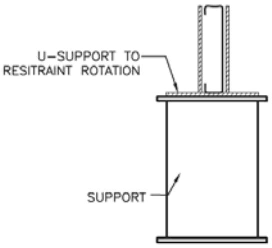


Fig 4. Section at “A-A”

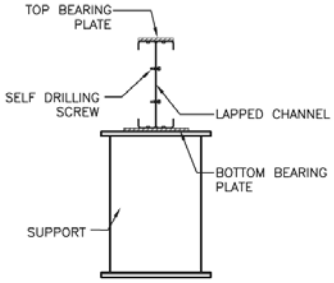
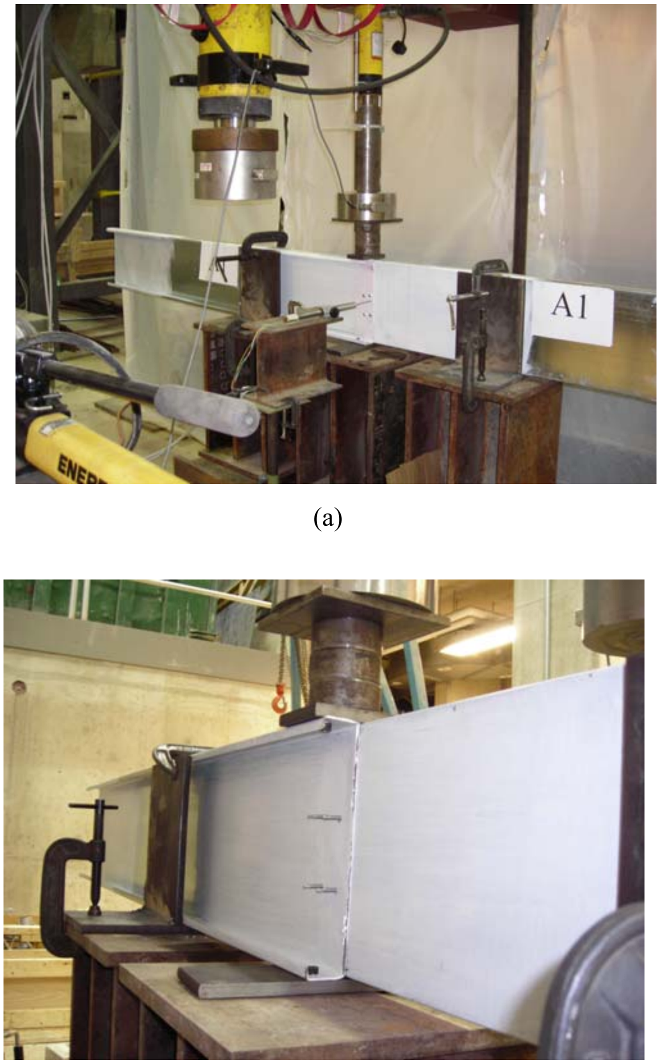


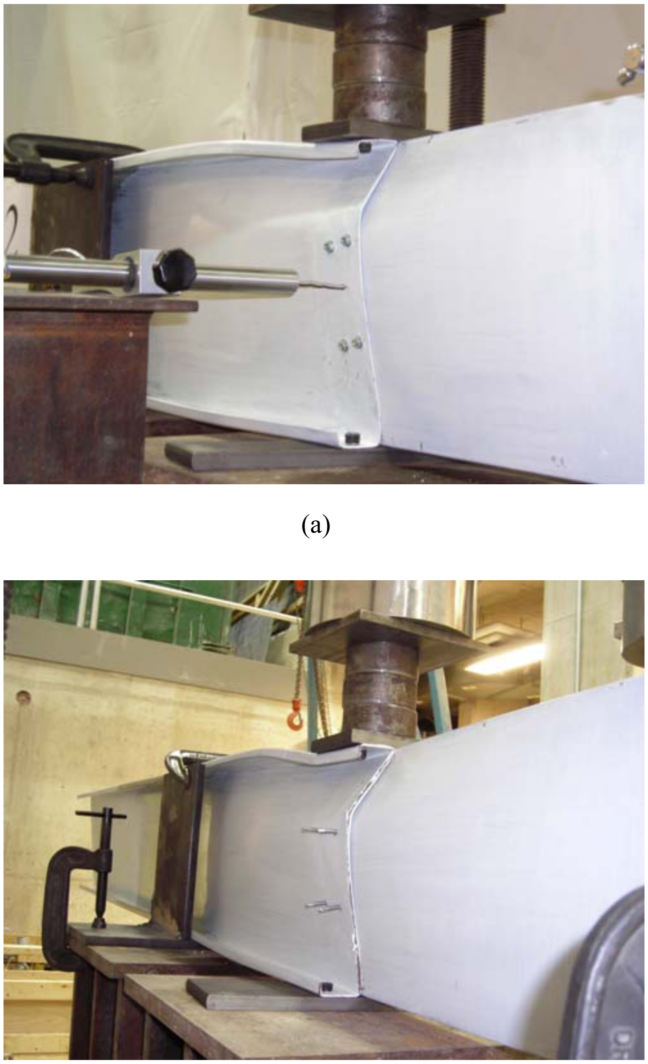
Fig 5. Section at lap



(a)

(b)

Fig 6. Specimen sample before test



(a)

(b)

Fig 7. Specimen after failure

Table 3. Interior two flange loading Test Results

Section	Lap Length “N” (mm)	Test #1 P_{t1} (kip)	Test #2 P_{t2} (kip)	Average $P_{t\ avg}$ (kip)
10C14	2.5”	4.65	4.50	4.57
	3.625”	4.63	5.17	4.90
	6”	6.23	6.24	6.24
10C16	2.5”	2.84	3.20	3.02
	3.625”	3.65	3.42	3.53
	6”	5.06	5.40	5.22
8C16	2.5”	3.64	3.40	3.52
	3.625”	4.12	4.15	4.14
	6”	5.32	4.92	5.11
8C18	2.5”	2.62	2.86	2.74
	3.625”	3.00	3.57	3.30
	6”	3.60	3.94	3.76

Development of New Coefficients

A nonlinear regression analysis was performed by using the unified web crippling expression to update the fastened case coefficients for single web “C” section subjected to ITF loading. For the regression analysis, the results of studies were analyzed using “MinRes” computer software. New proposed correction coefficients are shown in table 4.

Table 4. New Coefficients for Single Web Section

Support and Flange Conditions		Load Cases		C	C_R	C_N	C_h
Fastened To Support	Stiffened Flanges	Two Flange Loading	Interior Lap	2.5	0.02	1.01	0.001

Notes: The above coefficient apply when $h/t \leq 172$, $N/t \leq 127$, $N/h \leq 0.78$, $R/t \leq 1.97$ and $\theta = 90°$

Evaluation of Test Results

For the recommendation of this study, the recorded failure load for each specimen P_t was normalized by division of the corresponding design strength P_n. P_n was calculated by using equation 1 with new coefficient calculated. P_t/P_n values greater than unity for most of the specimens, meaning that the tested web-crippling values are greater than the predicted web-crippling values. This makes the analytical approaches conservative. The P_t/P_n ratio used for analysis of the test data.

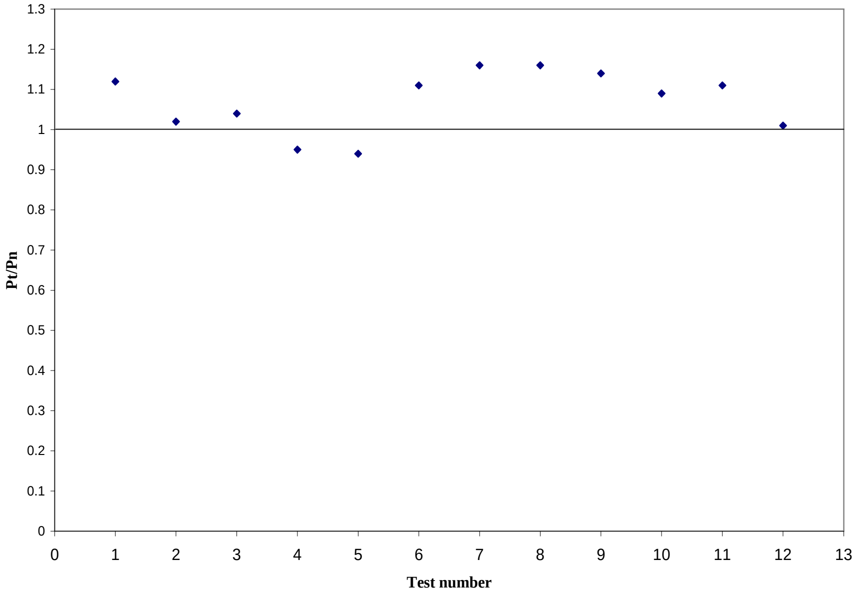


Fig 8. P_t/P_n for “C” Section

New Safety Coefficient

The objective of structural design and construction is to produce safe, serviceable, economic, durable and aesthetic structures. Structures must be able to withstand the loads acting on them during a reasonable lifetime. For cold formed steel member design there are two different methods, Limit State Design (LSD) and Allowable Stress Design (ASD). Based on a probabilistic concept, the structural safety can be measured in terms of a reliability index, β. The theory of probability can be applied to both design methods to achieve the same degree of structural safety.

Procedure for calculating both the resisting factor, ϕ, for load resistance factored design (LRFD), and the factor of safety, Ω, for allowable stress design (ASD), are well described in North American Specifications. The resistance factor ϕ and factor of safety Ω can be calculated as follows. Table 5. Shows the new proposed resistance factor and factor of safety.

$$\phi = C_\phi \left(M_m F_m P_m\right) e^{-\beta_0 \sqrt{V_M^2 + V_F^2 + C_P V_P^2 + V_Q^2}} \tag{2}$$

$$\Omega = 1.6 / \phi \tag{3}$$

Where

C_ϕ = Calibration coefficient and is equal to 1.52 for the United States and Mexico and 1.42 for Canada

M_m = Mean value of material factor, "$M_m = 1.10$"

F_m = Mean value of fabrication factor, "$F_m = 1.00$"

P_m = Mean value of professional factor, "$P_m = 1.0$"

β_o = Target reliability index and is equal to 2.5 for structural members and 3.5 for connections for the United States and Mexico, and 3.0 for structural members and 4.0 for connections for Canada

V_M = Coefficient of variation of material factor "$V_M = 0.10$"

V_F = Coefficient of variation of fabrication factor "$V_F = 0.05$"

C_P = Correction factor and is equal to $(1+1/n)m/(m-2)$ for $n \geq 4$, and 5.7 for $n = 3$

m = Degrees of freedom and is equal to (n-1)

n = Number of tests

V_P = Coefficient of variation of test results, "$V_P = 10.94\%$"

V_Q = Coefficient of variation of load effect = 0.21

e = Natural logarithmic base (2.718)

Table 5 Resistance Factors and Factors of Safety

Support and Flange Conditions		Load Cases		Tests No.	Mean Value	C.O.V	S136		AISI	
							Ω	ϕ	Ω	ϕ
Fastened To Support	Stiffened Flanges	Two Flange Loading	Interior Lap	24	1.045	0.109	2.30	0.70	1.90	0.85

Conclusions

A test program on cold-formed stiffened lapped channels subjected to web crippling has been presented in this paper. Channel specimens having an average nominal yield stress of 53ksi (370Mpa) were tested. The specimens were tested using interior two flange loading condition according to American Iron and Steel Institute (AISI 2001) specification for cold-formed steel structures. The concentrated load or reaction forces were applied by means of bearing plate. New proposed correction coefficient for equation 1 is shown in this paper. New proposed resistance factor and safety factor is also shown in this paper.

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Notation

C	Coefficient depending on the section type
C_h	Web slenderness coefficient
C_N	Bearing length coefficient
C_R	Inside bend radius coefficient
C.O.V.	Coefficient of variation
D	Total depth of the Channel
Fy	Yield strength of steel
h	Flat dimension of web measured in plane of web

ITF	Interior Two Flange Loading
N	Bearing length
P_m	Mean
P_n	Computed web crippling strength
P_t	Web crippling strength in the test
R	Inside bend radius
t	Thickness of the web
V_P	Coefficient of variation
β	Reliability index
θ	Angle between the plane of the web and plane of bearing surface
Ω	Factor of safety
ϕ	Resistance factor

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