Development of Web Stiffener Arrangements for Enhanced Web Crippling Strength

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Abstract

The governing capacity of a cold-formed steel flexural member depends on the relative capacities in bending, shear, web crippling, etc. and the combinations thereof. Out of these possible failure modes, perhaps the web crippling governing mode results in an inefficient (uneconomical) design of such members, since web crippling is a localized failure. The design efficiency can be improved if this failure mode can be shifted to a favourable mode of failure by increasing the web crippling capacity through the use of stiffeners. The objective of this investigation is to establish appropriate stiffener arrangement for single web cold-formed lipped channel steel sections that would enhance the web crippling capacity of such sections. The experimental investigation considered a total of 40 tests, subjected to interior two-flange (ITF), interior one-flange (IOF), end two-flange (ETF) and end one-flange (EOF) web crippling loads. The study also considered the impact of number of stiffeners and the number of screw fasteners. The first test series focused on single web elements subjected to ITF loading, where results showed that stiffened specimens gained about 25% in web crippling strength over corresponding unstiffened specimens. The same trend was found in IOF loading. The ETF tests had 106% increase in strength because the failure mode changed from web buckling to web yielding. The EOF tests had an increase in strength of 68%, and failed due to web buckling. Based on these studies, it is concluded that the most effective and economical method to increase the web crippling strength of the CFS lipped channel sections would be to attach a single stiffener to the inside of the web using three screws.

Keywords

Cold Formed Steel, Web Crippling Capacity, Experimental, Stiffeners, Number of Screws, Design Efficiency

1. Introduction

Cold-Formed Steel (CFS) structural members are widely used in the construction of low-rise buildings and houses, as a replacement to wood, masonry, etc. Such structural members are often formed to shape at room temperature from thin steel sheet (< 3mm) by machines that either roll or press the steel sheet into the desired shape. Resulting members are light weight, which provides advantages such as high strength-to-weight ratio, high stiffness-to-weight ratio, ease of shipping, each of construction, etc.

Even though the CFS sections come in different shapes (C-section, Z-section, Hat-section, I-section, Deck-section, etc.) lipped channel sections are widely used as columns (studs) and beams (joists). Depending on the span length and the loading arrangements, the capacity of the beam is governed by one of bending capacity, shear capacity, web crippling capacity, and the combination thereof. The web crippling failure potential arises when a concentrated load is applied on the flange of the channel section. Since this is a local failure, the design efficiency of the member can be improved if this failure mode can be shifted to a favorable failure mode by increasing the web crippling capacity of cold-formed steel section through the use of web stiffeners. The objective of this experimental investigation is to develop an appropriate stiffener arrangement for single web cold-formed lipped channel steel sections steel that would enhance the web crippling capacity of such sections.

2. Web Crippling of Cold-Formed Steel Channel Sections

Broadly speaking, the web crippling of cold-formed steel beams may arise due to four different loading situations. Figure 1 illustrates these situations, which are given in the North American Specification for the Design of Cold-Formed Steel Structural Members (CSA, 2016). When a load or a reaction is applied on one of the flanges at the interior flange or at the ends, then the web crippling may arise at these locations, which are identified as interior one-flange (IOF) and end one-flange (EOF), respectively. At times, the column above the floor may transfer the loads to the column (stud) below through the beam then the load is applied at both flanges. This situation may arise at the interior location or at the ends, which are identified herein as interior two-flange (ITF) and end two-flange (ETF), respectively.

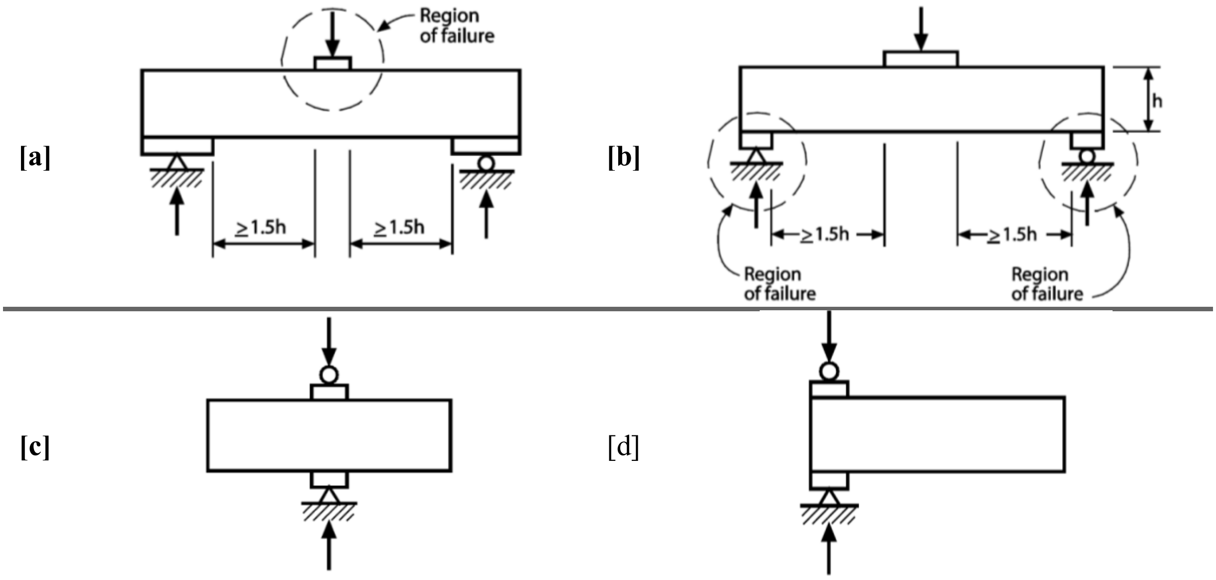


Figure 1 General Load Conditions for Web Crippling of Cold-Formed Steel Beams (CSA, 2016)
[a] Interior One-Flange [b] End One-Flange [c] Interior Two-Flange [d] End Two-Flange

The web crippling failure may be either due to web yielding, where the load bearing plate begins to crush the web causing a web failure at the web-flange intersection without significant out-of-plane deflection of the web, or due to web buckling, where the web buckles much like a slender column between the flanges. Furthermore, the web crippling resistance depends on whether the flanges are fastened to the support and on whether the flanges are stiffened (lipped). In general, a theoretical analysis for web crippling of cold-formed steel flexural members is rather complicated because it involves some or all of the following factors: (1) non-uniform stress distribution under the applied load and adjacent portions of the web, (2) elastic and inelastic stability of the web element, (3) local yielding in the immediate region of load application, (4) bending produced by eccentric load (or reaction) when it is applied on the bearing flange at a distance beyond the curved transition of the web, (5) initial out-of-plane imperfection of plate elements, (6) various edge restraints provided by beam flanges and the interaction effects between flange and web elements, and (7) inclined webs for decks and panels (CSA, 2016). For these reasons, the present design provision for web crippling is based on extensive experimental investigations conducted worldwide. The current design equation given in the North American Specification for the Design of Cold-Formed Steel Structural Members (CSA, 2016) for nominal web crippling strength of cold-formed steel section is as follows;

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

This is a unified web crippling equation with variable coefficients and is given in a normalized format, allowing for any consistent system of measurement to be used. In this equation, P_n = Nominal web crippling strength; C = General coefficient; t = Thickness; F_y = Yield strength; θ = Angle of web inclination; C_R = Inside bend radius coefficient; R = Inside bend radius; C_N = Bearing length coefficient; N = Bearing length; C_h = Web slenderness coefficient and h = Flat dimension of web.

This experimental investigation used lipped channel sections 600S162-54, with a depth of 152 mm, flange width of 41 mm, lip stiffeners depth of 12.7 mm, thickness of 1.438 mm and inside bend radius of 1.5t, having a minimum yield strength of F_y = 345MPa. As presented in the next section, the flanges of the specimens were not fastened to the support, and the test loads were applied through a bearing plate having a width of 100mm (N). Thus, F_y = 345MPa, $\theta=90^0$, t= 1.438mm, R= 2.157mm, N=100mm, and h = 145.21mm. The coefficients C, C_R, C_N, and C_h depend on the loading condition, and the corresponding values relevant to this experimental investigation are given in Table 1. The web crippling resistances of section under consideration were also calculated for the four loading conditions and are given in Table 1.

Table 1 Web Crippling Resistance of Test Specimens as per CSA, 2016

LOADING CONDITION	**C**	**C_R**	**C_N**	**C_H**	**P_n (kN)**
Interior Two-Flange (ITF)	24	0.52	0.15	0.001	13.9
Interior One-Flange (IOF)	13	0.23	0.14	0.01	13.0
End Two-Flange (ETF)	13	0.32	0.05	0.04	4.8
End One-Flange(EOF)	4	0.14	0.35	0.02	7.4

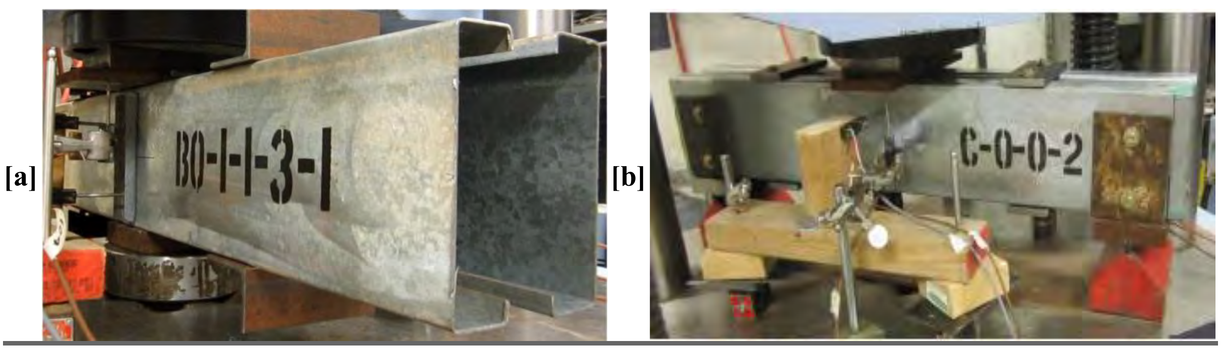
3. The Experimental Setup

The web crippling tests involve exertion of an increasing concentrated load applied on the flange of the steel section. In this investigation load was applied through an unfastened 100 mm bearing plate resting on the flange of the lipped channel section, at the zone of intended failure. However, direct application of a concentrated load to a single web C-section is difficult, since it is an unsymmetrical section and is susceptible for torsional loading. The torsional effects can only be avoided by loading the specimen through its shear center. American Iron and Steel Institute publication entitled "Standard Test Method for

Figure 2 Test Specimen Assembly

Determining the Web Crippling Strength of Cold-Formed Steel Beams" (AISI, 2013) gives precise conditions for testing such unsymmetrical members. As shown in Figure 2, following the AISI (2013) guidelines, the actual test specimens were assembled and loaded in pairs such that the resultant load passes through the theoretical shear center of the assembly, which is the midpoint of the bearing plate. Two similar pieces of lipped channel sections were connected together using rigid steel elements (L64x64x5 mm steel angles or 64x10 mm steel plates) at the 1/4 and 3/4 points along the specimen lengths to form the test specimen assembly. Figure 2 shows the test specimen BI-1-1-3-1, which is a stiffened cross-section and is subjected to interior two-flange loading. It is assumed that each channel carries one half of the applied load.

The investigation considered four different loading arrangements as defined by the CFS Standard S136-16 (CSA, 2016), namely; Interior Two-Flange (ITF), Interior One-Flange (IOF), End Two-Flange (ETF) and End One-Flange (EOF). Each of these test groups required somewhat different setup to accommodate the position of bearing plates and support conditions to ensure that failure occurred at the desired location. Figure 3 shows the photographic images of these experimental setups corresponding to these four loading arrangements. Figure 3 (a) shows the setup for an Interior Two-Flange (ITF) test, which is perhaps the easiest setup whereby a 900mm long specimen assembly was loaded at the mid-span through two 100 mm wide bearing plates located on the mid-span top and bottom flanges. The bearing plates were aligned using a level and the specimen was centered and ensured that the centerlines of the bearing plates coincided with the centerline of the specimen. Figure 3 (b) shows the setup for an Interior One-Flange (IOF) test, where the specimen was simply supported at the ends and subjected to an increasing mid-span point load on the top-flange. In order to ensure failure under the middle load and to prevent end failure, as evident from Figure 3(b), the end supports were stiffened with 10mm steel plates. Figure 3 (c) shows the setup for an End Two-Flange (ETF) test, which is somewhat similar to the Interior Two-Flange (ITF) test, except that the loads were applied at the very end of the test specimen. As may be evident from Figure 3(c), the ETF specimens were also 900mm long, however, since the failure is limited to the very end, the same specimen was used for two tests, one test at each end. Figure 3 (d) shows the setup for an End One-Flange (EOF) test, which was a challenging setup, since the setup must cause a failure at one end while the load is applied at an interior location. In order to achieve this (i) the loading location was reinforced and the load was applied through a 10mm bracket fastened to the web, (ii) the load was applied as close as possible to the target end so as to impart a larger reaction (based on dimensions, the target end experiences 0.55P and the far end experiences 0.45P, where P is the applied load), and (iii) the far end was supported with a 40 mm overhang and the far end web was also reinforced with channels. These measures may be evident in Figure 3 (d), and as presented later, the test failures were at the target ends.



[c]  [d] 

Figure 3 Photographic Images of the Experimental Setup;
[a] Interior Two-Flange [b] Interior One-Flange [c] End Two-Flange [d] End One-Flange

Data Acquisition: An increasing point load was applied to test specimens using the universal testing machine. The machine was set to apply the load at a rate of 0.25 mm/min until visible failure of the test specimen, at which point the stroke rate was manually increased to 1.0 mm/min. The applied load was recorded by the testing machine. Except for End One-Flange (EOF) test, the test specimen web crippling load was the machine recorded load. As indicated earlier, the web crippling load for EOF tests was 0.55 times the machine recorded load. The resulting displacements of each member for the ITF, IOF and ETF test cases were collected using two lateral transducers and one vertical transducer placed on each member of the test specimen, resulting in a total of six displacement records. The second set of displacement transducers (LVDT) act as backup measurements, as well as measurements that will confirm the symmetric loading and symmetric failure of the tests. The vertical displacements used in the results given in the next section were taken as the average of the two vertical displacement readings on each side of the specimen. The End One-Flange (EOF) test specimens, however, included two more vertical displacement transducers, as well as a displacement reading of the test machine stroke, in order to establish the displacements directly at the failure location.

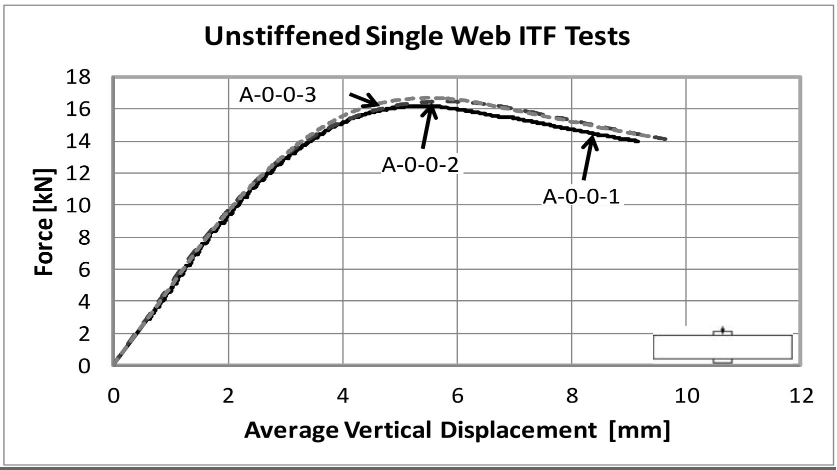


Figure 4 Load - Displacement Relations - Interior Two-Flange Tests

4. The Test Results

In order to establish the reliability and the consistency of the tests, first, three identical tests were conducted on three identical specimens. These were Interior Two-Flange (ITF) tests on regular unstiffened lipped channel sections 600S162-54, and identified herein as tests A-0-0-1, A-0-0-2 and A-0-0-3. Figure 4 shows the corresponding load-displacement relations, given for a single web, in which the load was obtained as machine load divided by 2. It is evident that three identical test specimens exhibited consistent behavior, and the corresponding ultimate loads were 16.2 kN, 16.5 kN, and 16.7 kN, respectively (Average 16.5 kN). As given in Table 1, the

Figure 5 Sample Stiffener Arrangements for Interior Two-Flange (ITF) Tests

Canadian Cold-Formed Steel Design Standard S136-16 (CSA, 2016) predicted web crippling resistance for ITF loading was 13.9 kN, which is about 15% less than the average test results.

<u>Stiffened Webs Under Interior Two-Flange (ITF) Loading:</u> This phase of the investigation considered different arrangements of web stiffeners fastened to the web using different screw pattern. In the interest of construction convenience and efficiency, regular bridging channels, which are widely available at cold-formed steel building construction sites, were used as web stiffeners in this investigation. These C- shaped bridging channels have a web width of 38 mm, and a lip depth of 13mm, and a thickness of 1.09mm. The length of the stiffeners was slightly less than the flat width of the test lipped channels and thus was 138mm. The investigation considered outside stiffeners and inside stiffeners, one stiffener and two stiffeners, and 2, 3, and 5 screws used to fasten each of the stiffener to the web. The corresponding specimens have been identified herein as follows; first letter indicating the stiffener location (ex. BO - B series outside stiffener and BI - B series inside stiffener), the first number indicates the number of stiffeners used in the test, the second number describes the number of columns of screws, the third number shows the number of screws in each column, and the final number refers to the iteration of the test. For example, specimen identification BI-2-2-5-1 signifies that the B series test specimen contains 2 inside stiffeners fastened to the web in two columns of screws and each column contains 5 screws. The last number indicates that this is the first test of this group.

Figure 5 shows sample photographic images of these stiffener and screw arrangements. The Figure 6 shows the representative experimental load-displacement behavior of test specimens containing different stiffener and screw arrangements. In order to facilitate comparison, the Figure 6 also shows the behavior of unstiffened web subjected to ITF loading. It is promptly evident that the outside stiffener does not enhance the web crippling resistance. Three tests considered outside stiffeners, with 2, 3, and 5 screws, respectively, and the corresponding failure loads for these specimens BO-1-1-2-1, BO-1-1-3-1 and BO-1-1-5-1 were 15.8 kN, 16.5 kN, and 16.3 kN, respectively. We observed that three or more screws improve the web crippling resistance as compared to two screws fastened stiffeners. This trend was observed even when the stiffeners were fastened to the inside face of web (between the flanges), and the corresponding results for BI-1-1-2-1, BI-1-1-3-1 and BI-1-1-5-1 were 20.1 kN, 20.8 kN, and 21.0 kN, respectively. When two parallel stiffeners were fastened on the inside with 2, 3, and 5 screws, respectively, the corresponding failure loads for these specimens BI-2-2-2-1, BI-2-2-3-1 and BI-2-2-5-1 were 19.7 kN, 19.6 kN, and 20.0 kN, respectively. We observed that two inside stiffeners do not increase the web crippling capacity as compared to one inside stiffener. These results show that one inside stiffener fastened to the web with three screws provides the optimum enhancement of the interior two flange (ITF) web crippling resistance. Therefore, the three screw fastened inside one stiffener test was repeated, and the corresponding results for three identical specimens BI-1-1-3-1, BI-1-1-3-2 and BI-1-1-3-3 were 20.8 kN, 20.5 kN, and 20.5 kN, respectively, giving an average capacity of 20.6 kN. This is about 25% increase in web crippling resistance as compared to the corresponding experimental resistance of 16.5 kN associated with the unstiffened lipped channel section subjected to interior two flange (ITF) web crippling loads.

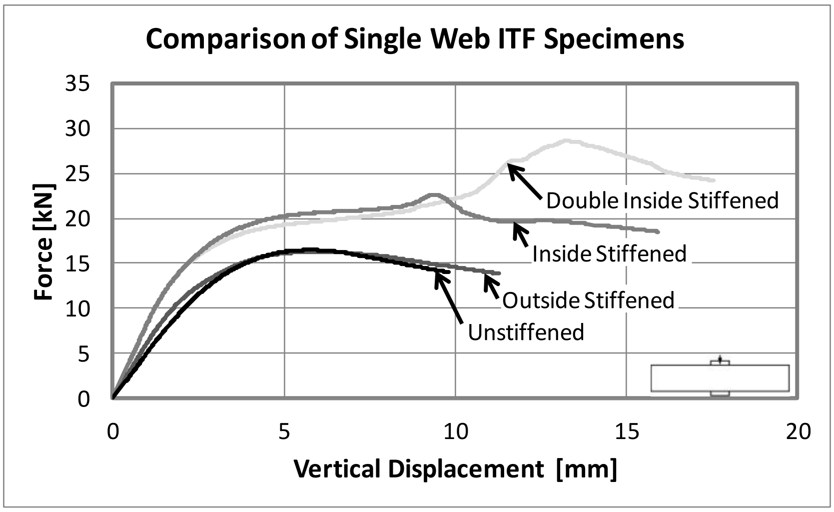


Figure 6 Representative Load - Displacement Relations - Interior Two-Flange Tests with Different Stiffener and Screw Arrangements

Interior One-Flange (IOF) Loading: This part of the investigation considered unstiffened and stiffnend webs subjected to interior one flange loading. Once again three identical tests were conducted for the unstiffened webs using lipped channel sections 600S162-54, and these tests are identified herein as tests C-0-0-1, C-0-0-2 and C-0-0-3. Even though the load-displacement relations are not given herein, the ultimate loads/single web associated with these tests were 15.0 kN, 14.7 kN, and 14.7 kN, respectively, giving an average capacity of 14.8 kN. This value may be compared to the design values given in Table 1, and accordingly, the experimental results are 14% higher than the Canadian Cold-Formed Steel Design Standard S136-16 (CSA, 2016) predicted IOF web crippling resistance, which was 13.0 kN. Based on earlier test observations, this series of tests focused on enhancement of interior one-flange web crippling resistance through an inside stiffener. One stiffener was centered and screw fastened to the lipped channel section, right under the loading bearing plate. Three tests considered stiffeners, with 2, 3, and 5 screws, respectively, and the corresponding failure loads for these specimens DI-1-1-2-1, DI-1-1-

3-1 and DI-1-1-5-1 were 17.6 kN, 18.5 kN, and 18.0 kN, respectively. Once again, three screws fastening arrangement gives optimum results. The three screws fastened inside one stiffener test was repeated, and the corresponding results for three identical specimens DI-1-1-3-1, DI-1-1-3-2 and DI-1-1-3-3 were 18.5 kN, 18.0 kN, and 18.5 kN, respectively, giving an average capacity of 18.3 kN, which is 25% higher than the corresponding experimental resistance of 14.8 kN associated with the unstiffened lipped channel section subjected to interior one flange (IOF) web crippling loads.

End Two-Flange (ETF) Loading: The next phase of the investigation focused on enhancement of exterior two flange loading web crippling resistance using interior stiffeners fastened along the centerline of the end bearing plates. The bench mark web crippling resistance of unstiffened section under this loading was 7.2 kN, which was based on three identical tests. The Canadian Cold-Formed Steel Design Standard S136-16 (CSA, 2016) predicted ETF web crippling resistance which was 4.8 kN, which is obviously, 66% of the experimental resistance. Three identical specimens having a single interior stiffener screw fastened at three locations and identified as FI-1-1-3-1, FI-1-1-3-2 and FI-1-1-3-3 were 15.0 kN, 14.8 kN, and 14.8 kN, respectively, giving an average capacity of 14.9 kN, which is more than double the experimental web crippling resistance associated with the unstiffened lipped channel section subjected to End Two Flange (ETF) web crippling loads. Figure 7 shows representative load displacement relations associated with these tests. Once again, it is evident that interior stiffener with three screws provide the best improvement in the web crippling resistance.

End One-Flange (EOF) Loading: The final phase of this investigation considered the exterior one flange loading web crippling resistance. As presented in the previous section, the load was applied off-center, and the loading point and the far end were reinforced to prevent failure at these locations. This setup ensured that the failure occurs at the near end. Based on the geometry and equilibrium, the near end experiences 0.55 P, where P is the machine load. Since, the test specimen consists of two webs the load resisted by each web can be taken as 0.275P, which is used in the following discussions.

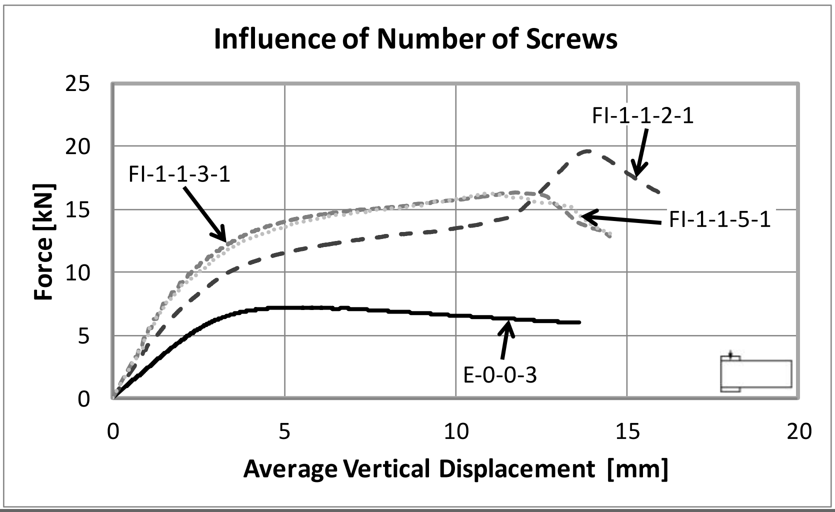


Figure 7 Representative Load - Displacement Relations - End Two-Flange Tests with Interior Stiffener and Different Screw Arrangements

Similarly to the other tests, first, three identical End One Flange (EOF) tests were conducted on three identical specimens fabricated from regular lipped channel sections 600S162-54. These specimens are identified herein as tests G-0-0-1, G-0-0-2 and G-0-0-3, and the corresponding web crippling capacities were 7.9 kN, 7.9 kN, and 8.1 kN, respectively, giving an average capacity of 8.0 kN. This value may be compared to the design values given in Table 1, and accordingly, the experimental results are 8% higher than the Canadian Cold-Formed Steel

Design Standard S136-16 (CSA, 2016) predicted EOF web crippling resistance which was 7.4kN. As in the previous test series, two, three and five screws fastening arrangements were investigated, however, only the unstiffened specimens and inside stiffened specimens with three screws were verified by three identical tests. Figure 8 shows the representative force-displacement relations. Note that the force shown in this figure is associated with the force experienced by one of the flanges at the target end (end that failed), which was established from machine loading and basic mechanics as 0.275P. It can be observed that the impact of various screw arrangements is negligible. The specimens HI-1-1-3-1, HI-1-1-3-2 and HI-1-1-3-3, which are the three identical specimens having a single interior stiffener screw fastened at three locations and subjected to end one flange loading, carried loads of 13.3 kN, 13.4 kN, and 13.9 kN, respectively, prior to failure. Thus, the experimental average stiffened EOF web crippling resistance is 13.5 kN, which is 69% more than the experimental web crippling resistance associated with the unstiffened lipped channel section subjected to End One Flange (EOF) web crippling loads.

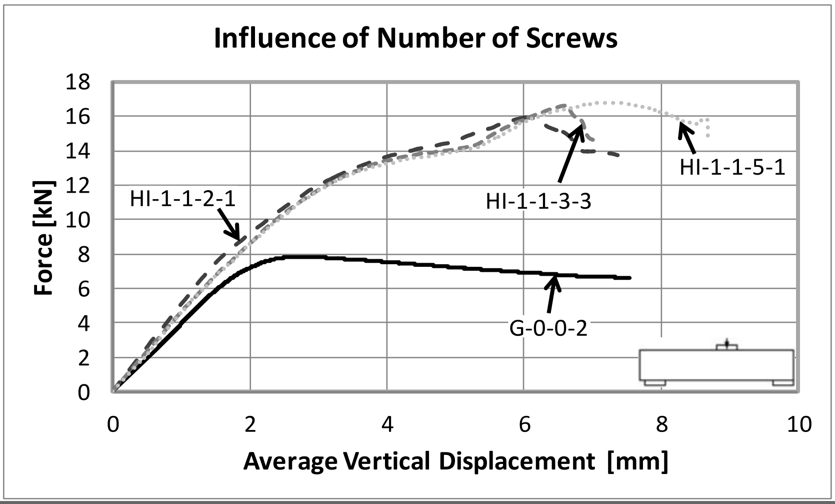


Figure 8 Representative Load - Displacement Relations - End One-Flange Tests with Interior Stiffener and Different Screw Arrangements

5. Concluding Remarks

Cold-Formed Steel (CFS) structural beams (joists) are widely used in the construction of low-rise buildings and houses. Such beams may fail in many different modes, however, the web crippling failure is an inefficient governing mode, since web crippling is a localized failure. The objective of this experimental investigation was to develop an appropriate stiffener arrangement for single web cold-formed lipped channel steel sections steel that would enhance the web crippling capacity of such sections. The experimental investigation considered a total of 40 tests, subjected to interior two-flange (ITF), interior one-flange (IOF), end two-flange (ETF) and end one-flange (EOF) web crippling loads. The investigation also established the impact of number of stiffeners and the number of screw fasteners. The following conclusions were made based on this experimental investigation; (i) The outside stiffener does not enhance the web crippling resistance, as compared to an inside stiffener. (ii) Two inside stiffeners do not increase the web crippling capacity as compared to one inside stiffener. (iii) One inside stiffener fastened with three screws provides an optimum enhancement of web crippling resistance as compared to two screws and five screws. (iv) Even though attachment of a single stiffener to the inside of the web using three screws provided different amount of web crippling strength gains based on the loading situation, such a reinforcement increases the web crippling capacity of the cold-formed steel section under consideration by at least 25%. Additional tests on sections with different dimensions are required prior to prescribing a universal recommendation.

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