International Specialty Conference on Cold-Formed Steel Structures

(1988) - 9th International Specialty Conference on Cold-Formed Steel Structures

Nov 8th, 12:00 AM

Some Studies on Cold-formed Steel Sections with Web Openings

K. S. Sivakumaran

Recommended Citation

Sivakumaran, K. S., "Some Studies on Cold-formed Steel Sections with Web Openings" (1988). *International Specialty Conference on Cold-Formed Steel Structures*. 3.
https://scholarsmine.mst.edu/isccss/9iccfss-session1/9iccfss-session6/3

Ninth International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, U.S.A., November 8-9, 1988

SOME STUDIES ON COLD-FORMED STEEL SECTIONS WITH WEB OPENINGS

K.S. Sivakumaran*

ABSTRACT

This paper concerns with the influence of a web opening on the (a) strength of compressive elements and (b) web crippling strength of cold-formed steel sections. The first part of the paper summarizes the relevent provisions as given in the corresponding Canadian design standard. Then the problem has been examined through experimental research on C-shaped lipped channel section. 48 stub column tests were carried out on sections with a web opening of various sizes and shapes and the load-deflection relationships and ultimate loads were established. 103 web crippling tests on specimens with web openings subjected to interior one flange loading condition also were undertaken. This paper briefly describes the above tests procedures and presents the observed ultimate strengths. The parameters covered in this study include opening size, opening shape and web slenderness. Based on these results prediction equations for the influence of a web opening have been derived using non-linear least square curve fitting technique. The author's observations and conclusions based on these investigations have been included at the end of the paper.

1. INTRODUCTION

The use of cold-formed thin-walled steel members in civil engineering applications has been increasing in recent years primarily due to its high strength- to-weight ratio and high stiffness-to-weight ratio compared to other traditional civil engineering materials such as concrete, masonry, timber, etc. However, a major design consideration with such thin-walled members is the resistance against the local instability of plate elements when subjected to compressive, shearing, bending and bearing loads. Unlike, the design of hot-rolled steel members where buckling constitutes a failure, the design of cold-formed steel members includes the post-local buckling strength. In fact, the actual strength (including post-buckling strength) of cold-formed steel members can be many times larger than the actual buckling loads. Thus, in order to achieve maximum benefit it is necessary to include the post-buckling strength in design. However, in developing such a design guidelines, a theoretical analysis of cold-formed steel members, including post-buckling strength, is rather complicated because it may include the following factors: (a) non-uniform stress distribution under the applied loads, (b) possibility of elastic and inelastic instability, (c) initial imperfections, and (d) various edge restraints provided by elements (flanges, web, lips, etc.) and the interaction between them. Primarily for this reason, the present day design provisions [1,4,5], which involve post-buckling strength, are based on experimental investigations. Two such provisions, which are relevant to the subject matter discussed in this paper, are the ones dealing with the design of compressive elements and the other in regards to the design of unreinforced web of member against web crippling. In Canada, the design of buildings using cold-formed steel members is governed by "Cold Formed Steel Structural Members, CAN3-S136-M84" published by Canadian Standards Association [5].

---

* Assistant Professor, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, CANADA L8S 4L7

For the benefit of the reader, the aforementioned two provisions as given in the Canadian standard have been summarized below

1.1 Strength of Compressive Elements

The strength (including post-buckling strength) of individual compressive thin plate element can be efficiently calculated using the effective width concept first proposed by Von Karman et al. [10]. However, the effective width postulated by Von Karman et al. [10] was later found to be unsafe for plates which exhibit inelastic buckling mode of failure. Hence, the Von Karman's effective width formulation was modified by many investigators based primarily upon the results of experimental studies. Excellent reviews of various theoretical and experimental studies on the effective width of plates can be found in a report by Roorda and Venkataramiah [8] and in a book byYu [9]. The CAN3-S136-M84 [5] effective width formulae for compressive elements grew out of essentially the experimental work of Winter [11]. Accordingly, in CAN3-S136-M84 [5] the compressive elements are considered fully effective up to a limiting value of flat width W_{lim} given by

$$W_{lim}/t = 0.644\sqrt{k\,E/f} \tag{1}$$

For compressive elements with flat width W larger than W_{lim}, the flat width W shall be replaced by an effective width B given by

$$B/t = 0.950\sqrt{\frac{kE}{f}}\left[1 - \frac{0.208}{(W/t)}\sqrt{\frac{kE}{f}}\right] - R \tag{2}$$

In equations (1) and (2), f is the maximum stress in the compressive element computed on the basis of the effective width and not exceeding F_y. The value of k reflects the edge conditions and taken as $k = 4.0$ for stiffened compressive elements and $k = 0.5$ for unstiffened compressive elements. The value of R, which reflects the flexibility of unusually wide compression elements ($W/t \geq 60$) that are not stiffened at each edges by means of either a web or flange, shall be taken as $R = 0.1\,(W/t) - 6$. When more than one element of a section is subjected to compressive load, the strength of the section may be obtained by summing the strength of individual compressive thin elements.

1.2 Web Crippling Strength

The safe design load to avoid web crippling may be calculated using the clause 6.4.7 of the Code CAN3-S136-M84 [5]. The code [5] provides separate equations for the web crippling resistances of unreinforced sections such as built up sections (I-beams sections made of two channels back-to-back or similar sections), shapes having single web (channel and Z-sections) and multiple web sections (hat or deck sections). In addition, equations have been provided for both one- and two-flange loading and for both end and interior load locations. Incidentally, for the case of shapes having single web and subjected to end one-flange loading or reaction, the code [5] gives two equations, one for sections having stiffened flanges and the other for sections having unstiffened flanges. So, in general, there are altogether 13 equations. For instance, the factored web crippling strength of unreinforced C-shaped channel section subjected to interior one-flange loading may be calculated as

$$Pr = \phi_s 16t^2 Fy\ (1.22 - 0.22\,k)(1.06 - 0.06\,R)(1 + 0.007\,N)^{\dagger}(1 - 0.0014\,H) \quad (3)$$

The equation (3) for web crippling resistance grew out of essentially the experimental work by Hetrakul and Yu [7]. Hence, limits have been placed on the various parameters to reflect the experimental limitations. Thus, the equation (3) applies only when $R \leq 4$, $N \leq 200$, and $n/h \leq 1$

1.3 Objective and Scope of the Investigation

The code [5] provisions for the compressive element resistance and web crippling resistance are strictly applicable to cold-formed steel sections without any web opening. However, often in practice, openings are either pre-punched or punched on-site on the web and/or flange of the cold-formed steel sections in order to pass through conduits, duct work, etc. When such openings are provided the resistances of such members can only be obtained by conducting performance tests in accordance with the procedures described in CAN3-S136-M84 [5], which obviously results in an increase in cost. Thus, the objective of this investigation is to gather experimental data on the strength of cold-formed steel sections with opening, with a view to developing prediction equations for the resistances of such sections. The experimental investigation consisted of two parts. One dealt with the influence of an opening on the strength of compressive elements and the other dealt with the influence of an opening on the web crippling strength of channel sections subjected to interior one flange loading. The former consisted of a total of 48 stub column tests and the latter consisted of 103 web crippling tests. The study addressed the important parameters such as (a) opening size (b) opening shape (c) web slenderness. The next two sections briefly describe the test procedures and the test results while the last two sections document the author's observations and conclusions. Further details on the investigation discussed in this paper can be found in Ref. [3, 12].

2. EXPERIMENTAL PROGRAM

2.1 Test Specimens

All specimens were cut to length from C-shaped lipped channel cold-formed steel members supplied by a local manufacturer. Figure 1 shows such a cross- section along with the geometric notations that have been used in the paper. The geometric dimensions and the mechanical properties of the sections described in this paper are listed in Table 1. The sections which are termed as A through E were chosen such that to have a wide range of web slenderness (web height/thickness ratio). The corresponding values have also been shown in Table 1. W_w, W_f and W_ℓ in Table 1 and in Figure 1 are the flat widths, which means the width of an element exclusive of rounded corners. As shown in Figure 1, the internal radius of the corners of these sections is roughly 2 times the base metal thickness. Table 1 also shows the base metal thicknesses which have been obtained in accordance with ASTM test procedures [2]. Specimens of series A and B were used in stub column tests, thus the lengths of the specimens were chosen such as to satisfy the stub column test procedures described in Ref. [6]. Specimen series C, D and E were used in web cripping tests. The lengths of these specimens were such that they satisfy the code CAN3-S136-M84 [5] requirements for one flange interior loading conditions. The remaining column in Table 1 gives the yield strength F_y of the flat walls of the sections. These values are the weighted average of the strengths of standard tensile coupons taken longitudinally from each flat portion (web and two flanges) of the section. As expected, the steel exhibited gradual yielding and 0.2% offset method was used to

---

† When $N > 60$ the factor $(1 + 0.007\,N)$ may be increased to $(0.75 + 0.011\,N)$

TABLE 1

Properties of the Specimens*

Specimen Series	W_w (mm)	W_f (mm)	W_ℓ (mm)	t (mm)	W_w/t	L (mm)	F_y (MPa)
A	83	32	8	1.60	52	200	341
B	145	34	9	1.29	112	265	262
C	197	32	8	1.52	130	770	337
D	148	29	7	0.91	163	620	270
E	88	34	9	1.22	72	432	260

*- 1mm = 0.039 inch; 1 MPa = 0.145 ksi

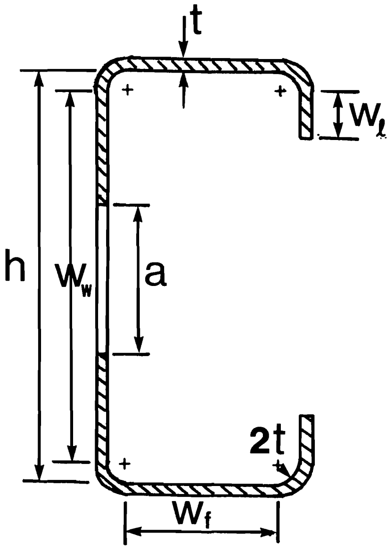

FIGURE 1. Typical Cross Section of a C-shaped lipped channel section.

define the yield stress. The specimens under consideration contained various sizes and shapes of web openings. The dimensions of the cut-outs are shown in Tables 2 and 3 along with the test results. The type of openings under discussion can also be seen in Figures 2 and 3 which show the permanent deformation shapes of the specimens of the stub column tests and of the web crippling tests respectively. The manufacturer of these sections usually pre-punches oval shaped openings and the test program included these openings as well. In order to obtain reliable results the tests were repeated on three identical specimens.

2.2 Test Procedure and Results

2.2.1 Strength of Compressive Elements

In this part of the test program stub column tests were performed as a means of studying the strength of compressive elements with opening. The tests were conducted on the channel sections described before in accordance with the stub column test procedures described in Ref. [6]. A total of 48 (16 groups × three identical specimens) stub columns were tested accordingly. The specimens were well aligned (see Ref. [6] for necessary conditions for alignment) so that the specimens may be subjected to concentric loading. The alignment was facilitated by the use of strain gauges. The strain gauges were helpful in detecting buckling loads as well. The results of which are not given here but may be found in Ref. [3]. In order to document the extent of the local deformations, including out-of-plane and axial, the displacements were measured at strategic points. Typically, the stub column tests consisted of the following steps. The well prepared specimen was placed on the testing machine and was centered. The necessary dial gauges and displacement transducers were placed at the appropriate locations. Small increments of loads were applied and the readings were recorded, until the peak load was reached. Beyond the peak load, though the readings may not be accurate, displacements were recorded as the load dropped off. Tests were terminated once the specimen exhibited the exaggerated buckled shape (see Figure 2).

Table 2 shows the experimental ultimate loads of the specimens under consideration. The table also shows the opening shape and the size. The failure load as shown in Table 2 is the average of the maximum loads recorded during the tests on three identical specimens. The results on three identical specimens showed excellent consistency As a matter of fact, the maximum deviation of any individual test result from the mean value of three identical specimens is less than 3%. A study of the results given in Table 2, indicates that the ultimate load capacity decreases with increasing opening sizes. Comparison of the results of specimens having comparable size of circular and square hole indicates that the shape of the cut-out does not influence the strength significantly. Table 2 also shows the ultimate strengths of the specimens (without opening) calculated using CAN3-S136-M84 [5] provisions (equations (1) and (2)). The calculated values are in general more than the experimental ultimate loads. The load versus out-of-plane deflections and load versus axial shortening relationships were also plotted for all the specimens (which are not shown here but may be found in Ref. [3] and on the average, the out-of-plane deflections at the ultimate load levels were about 1.5 times the thickness of the member.

2.2.2 Web Crippling Strength

In this part of the test program simple beam tests were performed as a means of studying the web crippling strength of interior one flange loaded members with web opening. A special test rig was constructed for this study and Figure 4 shows the test arrangement. By this arrangement two equal loads were applied at the ends of the sample while the entire sample was supported at the mid span. This particular arrangement was necessitated in

TABLE 2

Stub Column Test Results*

Specimen Series (opening shape)	Opening Dimensions		Experimental Failure Load (CAN3-S136-M84 Ultimate Load) [kN]	
	a (mm)	b (mm)		
A	0	0	85.3	(89.6)
A (Circular)	17	17	85.8	
A (Square)	17	17	84.7	
A (Circular)	33	33	81.7	
A (Square)	33	33	81.6	
A (Circular)	50	50	78.1	
A (Square)	50	50	77.6	
A (oval)†	38	102	72.6	
B	0	0	54.0	(56.3)
B (Circular)	29	29	54.0	
B (Square)	29	29	53.2	
B (Circular)	58	58	53.4	
B (Square)	58	58	51.0	
B (Circular)	87	87	47.1	
B (Square)	87	87	47.0	
B (oval)†	38	102	51.6	

*- 1mm = 0.039 inch; 1 kN = 0.225 kips;
† - manufacturer's pre-punched opening

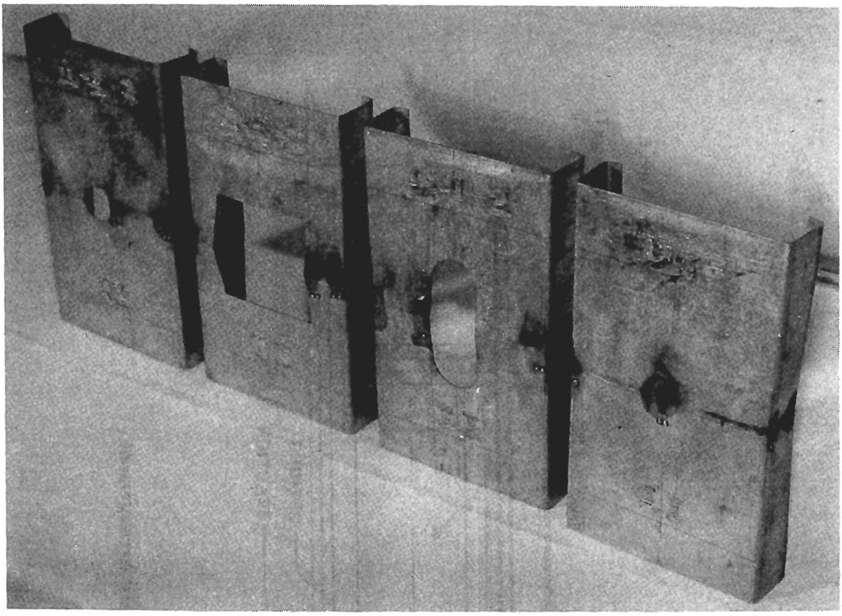

FIGURE 2. Stub Column Test Specimens Afer Failure

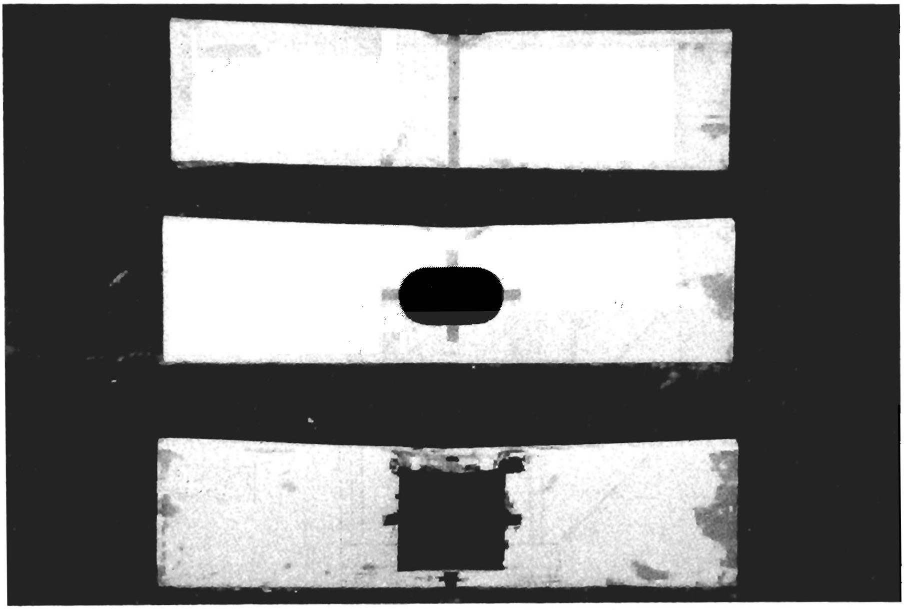

FIGURE 3. Web Crippling Test Specimens After Failure

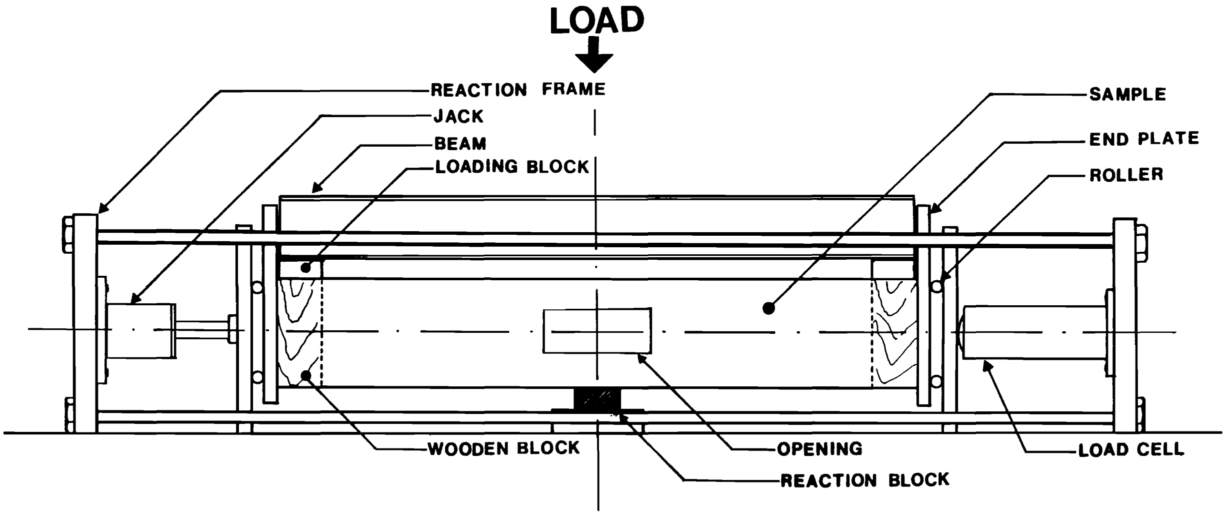

FIGURE 4. The Web Crippling Test Arrangement

order to (a) fulfill the interior one flange condition as given in CAN3-S136-M84 [5] and to assure failure at the interior support location (b) avoid the possibility of out-of-web plane loads that may be caused by the rotation of loading blocks due to excessive flange curling (c) reduce the overall rotational instability. Due ot the geometry of loading, shown in Figure 4, it is impossible to produce a web crippling load test setup without at least some influence of bending moment. However, the test moment ratio (maximum test moment/computed ultimate moment capacity) was found to be less than 0.3, which is the maximum ratio below which the interaction between web crippling and bending moment is negligible [7]. Typically, the web crippling tests consisted of the following steps. Once the specimen has been placed on the test rig it was levelled horizontally, prior to and after placing of a stiff steel beam through which the test load was transmitted to the specimen via end loading blocks. A nominal confining horizontal axial force was also applied using a hydraulic jack, which further stabilized the specimen. Now, the test load was applied in small increments using a fixed head Tinius-Olson universal testing machine. By virtue of the loading arrangement, the whole specimen would move downwards, which was facilitated by the use of rollers at the ends. Out-of-plane deflections of the web and the vertical deflections of flanges were monitored using displacement transducers (LVDT). Generally, the test was terminated once the peak load is reached, but occasionally the test was continued until the specimen exhibited permanent deformed shapes, as shown in Figure 3. A total of 103 (24 groups × three identical specimens and 31 single specimens) web crippling tests were performed accordingly, under this test program.

Table 3 shows the experimental interior one flange web crippling ultimate loads of the channel section specimens under consideration. The table also shows the opening sizes, which were primarily rectangular in shape. Failure loads as shown in Table 3 are the average of the failure loads of three identical specimens. The cases where only one specimen was tested have been clearly identified in the table. The results on three identical specimens showed excellent consistency. In fact, the spread of any individual test result from the average value was found to be less than 3%. Thus, the results based on a signal specimen can also be treated with confidence. As expected, the results in Table 3 show that the ultimate load capacity decreases with increasing opening sizes. Table 3 also shows the calculated ultimate strengths. These values are the unfactored web crippling resistances (P_r/ϕ_S) and have been calculated for specimens without opening, using equation (3) of this paper. The code [5] values are in general 15% less than the experimental ultimate loads. The load verses out-of-plane deflection relationships were also obtained, but for brevity they have not been included in this paper but may be found in Ref. [12].

3. OBSERVATIONS

In evaluating the experimental results, first of all they have been compared with the ultimate loads calculated using the CAN3-S136-M84 [5] provisions. Then, a prediction equation has been developed based on non-linear least square best fit of the current experimental data.

3.1 Strength of Compression Elements

In the case of sections without any openings, Table 2 shows both the experimental ultimate loads and the CAN3-S136-M84 [5] calculated ultimate loads. It can be noticed that the calculated strengths are larger than the corresponding experimental failure loads. This implies that the effective design width equations as given in the design code CAN3-S136-M84 [5] may overestimate the strength of compressive elements. As indicated earlier, the present

TABLE 3

Web Crippling Test Results*

Specimen Series	Opening Size		Experimental Failure Load (CAN3-S136-M84 Ultimate Load) [N]
	a (mm)	b (mm)	
C	0	0	12375 (10550)
C[1]	6	51	11750
C[1]	6	102	11125
C[1]	6	152	10875
C[1]	51	6	11850
C[1]	51	51	11500
C	51	152	10850
C[1]	102	6	11750
C[1]	102	51	11050
C[1]	102	114	10450
C	102	152	10375
C[1]	152	6	10625
C	152	25	10158
C	152	51	9758
C	152	102	9800
C	152	152	7500
C[†]	64	114	11508
D	0	0	4075 (3445)
D[1]	6	51	3750
D[1]	6	102	3500
D[1]	6	152	3250
D	19	114	3950
D[1]	38	6	4000
D[1]	38	51	3900
D	38	114	3875
D[1]	38	152	3775
D[1]	76	6	3850

TABLE 3 (Cont'.d)

Specimen Series	Opening Size		Experimental Failure Load (CAN3-S136-M84 Ultimate Load) [N]
	a (mm)	b (mm)	
D[1]	76	51	3500
D	76	114	3750
D[1]	76	152	3100
D[1]	114	6	3700
D	114	25	3883
D	114	51	3575
D	114	114	3125
D[1]	114	152	2300
D†	64	114	3875
E	0	0	7625 (6523)
E[1]	3	51	7550
E[1]	3	102	6750
E[1]	3	152	6250
E	13	70	7350
E[1]	23	3	7150
E	25	70	7000
E[1]	23	101	6825
E[1]	23	152	6650
E[1]	45	3	6875
E	45	70	6950
E[1]	46	152	5050
E[1]	68	3	6500
E	70	25	7208
E	70	51	5842
E	70	70	5542
E[1]	68	101	3250
E[1]	68	152	2700
E†	38	102	6968

[1]- Only one identical specimen was tested;
* - 1 mm = 0.039 inch; 1N = 0.225 lbf;
† - Manufacturer's pre-punched opening

code [5] provisions are not suitable for cold-formed steel sections with web openings. However, a conservative estimation of the strength of compressive elements with openings may be made by considering the flat portion of the web on each side of the hole as two unstiffened elements. Thus, in equations (1) and (2) $k = 0.5$ shall be used. Such a calculation (which is not shown in this paper) resulted, in general, a value less than the corresponding experimental ultimate loads.

The influence of the web opening on the effective width of a compressive element may be represented by a ratio given by B(with opening)/B(without opening). Where, B is the effective web width which can be deduced from the experimental results by subtracting the contributions due to flanges, lips and rounded corners. Now, the above ratio should be related to the opening dimensions and the opening shape. It was indicated earlier that the influence due to a circular and a square openings having the same dimension were quite comparable. Thus, in this study the above ratio was related only to a non-dimensional parameter (a/W), where, a is the width-wise dimension of an opening and W is web flat width. Based on a non linear least square best fit of the experimental results, the prediction equation for the influence of an opening on the strength of a compressive element may be given as

$$\frac{\text{B (with opening)}}{\text{B (without opening)}} = \left[1 - 0.895\left(\frac{a}{W}\right)^{1.87}\right] \tag{4}$$

Until further results become available, equation (4) may be used to establish the influence of an opening on the effective width of a compressive element. However, the equation (4) is valid for opening having a/W less than 0.6.

3.2 Web Crippling Strength

Similar to Table 2, Table 3 shows both experimental and CAN3-S136-M84 [5] calculated ultimate web crippling loads for sections without any openings. It may be noticed that although the Canadian cold-formed steel code [5] values are lower bound, they are about 15% lower than the corresponding experimental results. Once again the code provisions for web crippling are inapplicable when the web contains an opening. The influence of the web opening on the web crippling strength may be represented by a ratio given by P_r(with opening)/P_r(without opening), where, P_r is the experimental failure load. The above influence is also dependent on (a/W) and (b/n), where, a and b are the width-wise and length-wise dimensions of the opening respectively, W is the web width and n is the bearing length. Based on this assumption and a non-linear least square best fit of the experimental results, the prediction equation for the influence of an opening on the web crippling strength of interior one flange loaded single web may be given as

$$\frac{P_r\text{ (with opening)}}{P_r\text{ (without opening)}} = \left[1 - 0.45\left(\frac{a}{W}\right)^{3.5}\right]\left[1 - 0.0145\left(\frac{b}{n}\right)^{2.25}\right] \tag{5}$$

The limits for the use of equation (5) are $a/W \leq 0.75$ and $b/n \leq 3.0$.

4. CONCLUSIONS

A series of tests on cold-formed channel shaped steel sections with web opening has been described. The study consisted of two parts (a) the effect of web opening on the strength of compressive element and (b) the effect of web opening on the web crippling strength of sections when subjected to interior one flange loading. Although the experimental observations included the loads and deflections, only the ultimate strengths were presented in this paper. Based on non-linear least square best fit of the experimental results prediction equation for the influence of an opening has been established. Based on the limited experimental results and the associated analysis presented in this paper, the following remarks can be made.

4.1 Strength of Compression Elements

The effective design width equation as given in the Canadian design code [5] may overestimate the strength. The web opening reduces the strength and the influence should be considered in the design. However, the shape of an opening does not appear to be a governing parameter. The effect of an opening (preferably circular or square) on the strength of a compressive element may be established using the prediction equation (4), provided $a/W \leq 0.6$.

4.2 Web Crippling Strength

The web crippling strength calculated in accordance with the Canadian code [5] is as expected a lower bound solution (15% lower than the experimental results). The web opening certainly reduces the web crippling capacity. The effect of such an opening on the web crippling strength of interior one flange loaded section having single web may be estimated using the prediction equation (5), provided $a/W \leq 0.75$ and $(b/n) \leq 3.0$. It may be also worth reminding that during the web crippling tests the loads were applied right over the opening. Therefore, the results represent the worst possible scenario. Nevertheless, the prediction equation indicates that the width-wise openings (larger a values) effect significantly more than the length-wise (larger b values) openings.

ACKNOWLEDGEMENTS

The investigation on the strength of compressive elements reported in this paper also forms a part of Mr. A.S. Bainwait's M.Eng. thesis. The investigation on the web crippling strength reported in this paper also forms a part of Mr. K.M. Zielonka's M.Eng. thesis. The cold-formed steel members used in this study were kindly provided by Bailey Metal Products Ltd., Toronto, Ontario, Canada. The financial support provided by the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged.

REFERENCES

[1] American Iron and Steel Institute, Specification for the Design of Cold-Formed Steel Structural Members, American Iron and Steel Institute, Washington, D.C., U.S.A., 1986.

[2] American Society for Testing and Materials, ASTM Standard Test Method for Weight of Coating on Zinc-Coated (Galvanized) Iron or Steel Artices, A90-81, Annual book of ASTM Standards, Philadelphia, PA, U.S.A., 1986.

[3] Banwait, A.S., Axial Load Behaviour of Thin-Walled Steel Sections with Openings, M.Eng Thesis, McMaster University, Hamilton, Ontario, Canada, 1987.

[4] British Standards Institute, Structural Use of Steel Work in Buildings, Part 5. Code of practice for design of cold formed sections, BS5950: Part 5: 1987, British Standards Institution, London, 1987.

[5] Canadian Standards Association, Cold-Formed Steel Structual Members, CAN3-S136-M84, Canadian Standards Association, Rexdale, Ontario, Canada, 1984.

[6] Column Research Council, Guide to Stability Criteria for Metal Structures. Edited by T.V. Galambos, Wiley-Interscience, New York, NY, 1988.

[7] Hetrakul, N. and Yu, W.W., Structural Behaviour of Beam Webs Subjected to Web Crippling and Combination of Web Crippling and Bending, Final Report, Civil Engineering Study 78-4, University of Missouri-Rolla, Rolla, Missouri, U.S.A., 1978.

[8] Roorda, J., and Venkataramaiah, K.R., Effective Width of Stiffened Steel Plate Components. Solid Mechanics Division, University of Waterloo, Waterloo, Ontario, Paper No. 148, 1978.

[9] Yu, W.W., Cold-Formed Steel Design, John Wiley and Sons Inc., New York, 1985.

[10] Von Karman, T., Sechler, E. and Donnell, L.H., The Strength of Thin Plates in Compression. Transactions of the American Society of Mechanical Engineers, 54 (2), pp. 53-57, 1932.

[11] Winter, G., Strength of Thin Steel Compression Flanges. Transactions of the American Society of Civil Engineers, 112:, pp. 527-554, 1947.

NOTATIONS

a - Width-wise dimension of an opening

B - Effective width of a compressive element (equation 2)

b - Length-wise dimension of an opening

E - Modulus of elasticity of steel

F_y - Yield strength of steel

f - Maximum stress

h - Clear distance between flats of flanges

H - Web slenderness ratio ($= h/t$)

k - Buckling coefficient (equations 1 and 2)

K - Coefficient in equation 3 ($= 883\ F_y/E$)

n - Bearing length

N - Ratio of bearing length to thickness ($= n/t$)

P_r - Factored web crippling resistance

r - Inside bend radius

R - Ratio of inside bend radius to thickness ($= r/t$)

R - Coefficient in equation 2 ($= 0.1\ (W/t) - 6$ when $W/t \geq 60$)

t - Base metal thickness

W - Flat width of elements

W_{lim} - Limiting flat width for fully effective compressive elements

Φ_s - Resistance factor for web crippling ($= 0.8$)