Effect of openings on the ultimate capacity of cold-formed channel steel beams

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In this paper, a 3-dimensional finite element model is presented. The model is capable to predict the ultimate load capacity for spatially loaded cold-formed steel beams of open cross-sections. The treatment of both material and geometrical non-linearities is included in the model. The results of the proposed model are verified with the available experimental and theoretical results. Hence, the model is used to demonstrate the effect of the presence of openings located in the web on the ultimate capacity of cold-formed channel steel beams. A parametric study on six beams of different channel cross-sections and different size and location of web openings is initiated. The openings are chosen so that the effects of both their size and location are examined. Three sizes of openings are included in this study as a ratio between the diameter of opening and the depth of the flat portion of the web. The chosen size ratios are 0.25, 0.50, and 0.75. For the three sizes of openings, the effect of the location of opening is examined as the second parameter; three locations are chosen in quarter, middle third and middle of the span. From the parametric study done, the effect of the presence of openings in the webs on the ultimate capacity of cold-formed channel beams is clearly evaluated. The results show that the two chosen parameters have considerable influence on both the ultimate capacity of beams as well as their modes of failure.

فى هذا البحث، تم تقديم نموذج ثلاثى الابعاد بطريقة العناصر المحددة لحساب السعة القصوى للكمرات الحديدية ذات القطاعات المفتوحة والمشكلة على البارد. وقد تم فى هذا النموذج معالجة كلا من لاخطية المادة ولاخطية الشكل. وقد تم اختبار النموذج المقترح وذلك بمقارنة النتائج بالنتائج المعملية والنظرية المتاحة. وقد تم استخدام النموذج فى دراسة تأثير وجود فتحات فى الاعصاب على السعة القصوى للكمرات الحديدية ذات قطاعات مجرى ([) والمشكلة على البارد. وقد تم عمل دراسة بارامترية على ٦ كمرات ذات قطاعات مجرى مختلفة وبمقاسات وأوضاع مختلفة للفتحات. وقد تم اختيار الفتحات لأختبار تأثير كلا من مقاسها ووضعها. ولذلك تم اختيار ثلاثة مقاسات للفتحات وذلك كنسبة بين قطر الفتحة وعمق العصب المستوى. وهذه النسب هى ٠,٢٥، ٠,٥٠ و ٠,٧٥. ولكل مقاس فتحة، تم تغيير وضع الفتحة كعامل آخر من عوامل الدراسة وقد تم اختيار ربع وثلث ومنتصف بحر الكمرة لدراسة تأثير هذا العامل. من نتائج الدراسة البارامترية التى تمت، تظهر النتائج مدى تأثر السعة القصوى للكمرات بوجود فتحات. كما تظهر النتائج أن العاملين المختارين فى الدراسة لهما تأثير كبير على كلا من السعة القصوى وأشكال الانهيار فى الكمرات.

Keywords: Cold-formed sections, Channels, Steel beams, Torsion, Crippling, Openings, and Finite element method

1. Introduction

Cold-formed steel members have been widely accepted as structural members in both commercial and residential applications as wall studs and floor joists. These members are commonly manufactured with prepunched holes in the web. Such openings provide easy installation of electrical and plumbing systems. However, when the prepunched hole is of inadequate size, a field cut hole may be used. Whether the hole is prepunched or field cut, the influence of the hole on the structural integrity of the stud or joist is not defined by the recognized design specifications [1, 2].

Since 1990, the center for Cold-Formed Steel Structures at the University of Missouri-Rolla (UMR) has been engaged in a comprehensive research study to define the behavior of web elements of flexural members that have a web opening (Langan et al. [3]; Shan et al. [4]; Deshmukh [5]; Uphoff [6];

LaBoube et al. [7]). The loading combinations of bending and/or shear and/or web crippling have been investigated. Although the UMR studies have focused on web elements of C-shaped cross sections, the recognized behavior and the design recommendations are applicable to the general family of cold-formed steel flexural members.

The use of theoretical analysis of web crippling for cold-formed steel members is rather complicated because it involves a number of factors, such as (1) a non-uniform stress distribution at the load application, (2) elastic and inelastic stability of the web element may occur, (3) local yielding may occur in the immediate region of load application, and (4) initial out-of-plane imperfections of the web elements [8]. One of the theoretical analyses of web crippling capacity of cold-formed steel members is the research done by Young and Hancock [9]. In this research, web crippling design equations based on a simple plastic mechanism model are derived. Because of the limited success of applying theoretical means, the majority of the web crippling researches are based on experimental studies. Hence, the Australian/ New Zealand Standard [10] for cold-formed steel structures was formulated with respect to experimental results conducted by Zhao and Hancock [11, 12]. While, the web crippling design rules in the North American Specification [13, 14] for the design of cold-formed steel structural members are based on a unified web crippling equation applicable for various section geometries developed by Prabakaran and Schuster [15] and Beshara and Schuster [16].

On the other hand, there has been limited research on the web crippling behaviour of sections with a web opening. LaBoube et al [17] and Sivakumaran and Zielonka [18] developed empirical formulae with reduction factors expressions based on experimental studies for circular and square holes in the webs of open sections. All of the test specimens were fabricated with the hole located and centred beneath the bearing plate.

2. Objective of study

The objective of this paper is:

1. To present a numerical model based on the finite element method to model cold-formed channel beams the proposed model allows the inclusion of material and geometrical non-linearities, local buckling and warping. Also, the model is capable of reproducing beam instability and bowing effect. In order to verify the results of the proposed model, the results are compared to the available experimental and theoretical results in the literature. Also, the results are compared to the Standard Association of Australia (AS/NZS) [10] and the North American Specification (NAS) [14].
2. To study the effect of the presence of openings in the webs on the ultimate capacity of cold-formed channel beams. Hereby, a parametric study has been carried out in order to evaluate this effect. Two main factors are examined in the study, the first is the ratio between the diameter of opening, a, and the depth of the flat portion of the web, h, representing the size of opening, a/h. The second parameter studies the location of opening, X/L, which is the ratio between the distance of opening from the support, X, and the total length of the beam, L.

Fig. 1 shows the definition of these parameters.

3. The finite element model

3.1. Finite element mesh

The powerful COSMOS/M (V2.6) finite element analysis program [19] is used for the non-linear 3-D analysis of the cold-formed channel beam. The surfaces of the beam's cross-section are modelled as quadrilateral flat thick shell elements while the rounded corners of the cross-sections are modelled as quadrilateral isoparametric thick shell elements. Each element (flat and isoparametric) consist of four nodes at the corners, each node has six degrees of freedom. In case of channels with openings, the finite element mesh is chosen to be quite fine around the opening where maximum stresses may occur. A reduced numerical integration scheme with a 2×2×2 Gauss point grid is employed. Figs. (2-a) and (2-b) show the finite element mesh of the analyzed beam without and with opening, respectively.

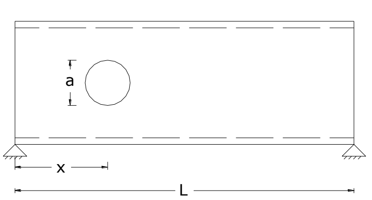


Fig. 1. Definition of parameters of beams with channel cross-sections.

3.2. Solution technique

In order to predict the behavior of the analyzed beams and to determine their mode of failure, the loads are applied in an incremental manner using the modified Newton-Raphson technique and the Arc-length method is used to pass the limit point in order to trace the behavior of beams till failure. The total Lagrangian procedure is used to encounter the problem of geometrical non-linearity while the material non-linearity is utilized using the Von Mises yield criterion which can represent the triaxial state of stresses in an equivalent effective stress, $\overline{\sigma}$.

4. Verification of the model results

To verify the results of the proposed model of channel beams without openings, six beams with different channel cross-sections are analyzed. For the comparison, the dimensions and the properties of the analyzed beams are taken the same as in the experimental study done by Young and Hancock [20]. The lengths of the beams are calculated according to NAS specification [13,14] and the AS/NZS Standard [10] which is equal to $3d+b$, where (d) is the overall depth of the web and (b) is the width of the flat portion of the flange to ensure that crippling failure mode will occur in these beams. Table 1 lists the dimensions and the material properties of the analyzed beams. For crippling failure mode, the loads are considered to act across the flat portion of the flange width. The length of bearing was generally chosen to be equal to the flat flange width (i.e. for all beams the bearing plates are of square shape) [20].

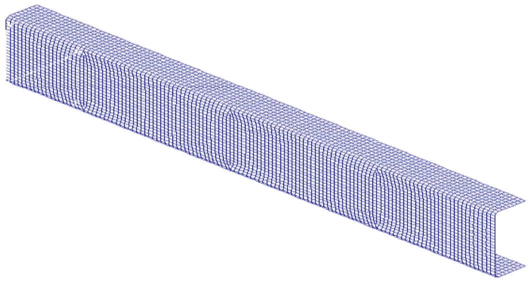
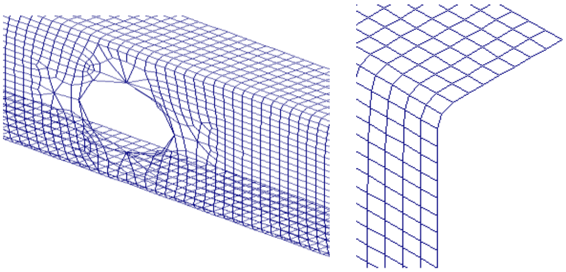


Fig. 2-a Finite element mesh of the analyzed beam without opening.



Modeling of the corner of the channel cross-section

Fig. 2-b. Finite element mesh at the region of opening in case of the analyzed beam with openings.

The results of the crippling capacities of the analyzed beams using the suggested finite element model, P_{model}, are compared to the experimental results conducted by Young and Hancock [20], P_{exp}, and the theoretical results based on a simple plastic mechanism model derived by Young and Hancock [9], P_{thr}, . Also, the results of the model are compared to the capacities calculated using the NAS Specification [14], P_{NAS}, and the AS/NZS Standard [10] for cold-formed steel structures, $P_{AS/NZS}$. Table 2 shows the comparisons of these results as a ratio from the experimental results.

From the comparison listed in table 2, the mean values of the calculated capacities, $P_{calculated}$, are plotted in fig. 3 against the experimental capacities, $P_{experimental}$. From the figure, it can be noticed that the design strengths predicted by the NAS Specification and the AS/NZS Standard are generally unconservative. The mean values of P_{NAS}/P_{exp} and $P_{AS/NZS}/P_{exp}$ ratios are 1.1342 and 1.3832 with the Coefficients Of Variation (COV) of 0.0188 and 0.0250 respectively. Also,

Table 1
Dimensions and material properties of the analyzed beams

Channel No.	Channel $d \times b_f \times t$ (mm)	Beam dimensions				Measured stresses and strains (Young and Hancock [20])		
		h/t	b/t	r (mm)	L (mm)	σ_y (MPa)	σ_u (MPa)	ε_u (%)
C-01	75×40×4	14.80	8.03	3.9	257.10	450	525	20
C-02	100×50×4	20.95	10.48	4.1	341.90	440	545	20
C-03	125×65×4	27.30	14.28	3.9	432.10	405	510	23
C-04	200×75×5	36.32	13.16	4.2	665.80	415	520	24
C-05	250×90×6	37.03	12.68	7.9	826.10	445	530	21
C-06	300×90×6	45.20	12.60	8.4	975.60	435	535	23

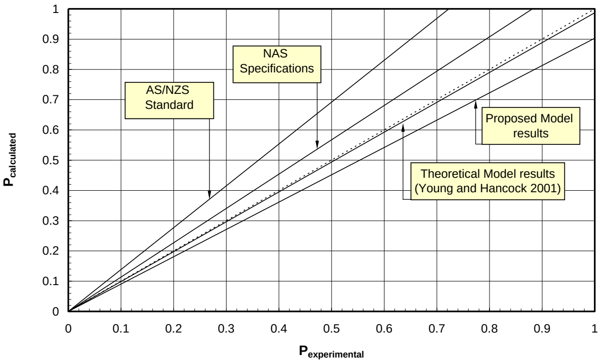


Fig. 3. Comparison between the mean values of the results of crippling capacities of channels without openings with respect to experimental results.

it can be noticed that the theoretical results depending on a simple plastic mechanism derived by young and Hancock [9] are generally conservative except for beam (C-03). The mean value of P_{thr}/P_{exp} ratio is 0.9870 with a coefficient of variation of 0.0113. The comparison shows that the results of the proposed model are always conservative for all beams analyzed in the parametric study. The mean value of P_{model}/P_{exp} ratio is 0.9029 with a coefficient of variation of 0.0010 which is the best COV in the comparison. This means that the results of the proposed model are homogeneous and the proposed finite element model simulates well the crippling failure mode.

5. Parametric study

In this study, finite element analyses are conducted for 60 beams with cold-formed channel cross-sections. Three parameters are studied through these analyses. These parameters are: depth of the flat portion of web, *h*, to thickness, *t*, ratio, *h/t*; size of opening represented as the ratio between the diameter of opening, *a*, and the depth of the flat portion of web, *h*, *a/h*; and the position of opening simulated as the ratio between the distance of the center of opening from the left support, *X*, and the total length of the beam, *L*, *X/L*. The first parameter, *h/t*, represents the web slenderness ratio and it has been considered to vary from comparatively stocky webs of 14.8 to relatively more slender webs of 45.2. While the second parameter, *a/h*, shows the effect of the diameter of opening relative to the depth of the flat portion of the web. Three ratios equal 0.25, 0.50 and 0.75 are considered in this case. The last parameter concerns with the effect of the position of opening as a ratio from the length of the beam. Three positions are studied; at the middle, middle third and quarter of the beam.
The channel cross-sections of the beams are taken as listed in table 1. The lengths of all beams, *L*, are taken equals to *L*=1200 mm to examine the beams under different modes of failure. The material properties used are yield stress, $\sigma_y=240$ MPa, modulus of elasticity, $E=210$ GPa, Poisson's ratio, $\nu=0.3$, shear modulus, $G=84$ GPa. The corners of the cross-sections are assumed to have radius equals the radius of beams tested by Young and Hancock [20].

5.1. Results of beams with openings

The results of beams with openings are shown in table 3 and figs. 4 to 11. Table 3 shows the ultimate capacities of the analyzed beams, P_{open}, for different sizes and locations as ratios from those without openings, $P_{without}$. figs. 4 and 5 plot the failure modes of channels with stocky and slender webs, respectively, for beams without openings. Also, figs. 6 to 11 show the effect of the size and the location of openings on the ultimate capacities of each analyzed beam.

Figs. 6 to 8 show the variation of the ratio $P_{open}/P_{without}$ with different size ratios and different locations of openings. Theses figures represent the results of channels with stocky webs; for which the failure modes are lateral torsional buckling, as shown in fig. 4. From these figures, it can be noticed that the presence of opening in the webs gives a very significant reduction in the ultimate capacity of beams for different sizes and locations of openings. By increasing the size of opening and/or increasing the distance of opening from the edge of the beam, the ultimate capacity of the beam is decreased. For this category, channels of stocky webs, the reduction of the ultimate capacity of the beam is increased by increasing the web slenderness ratio, h/t.

For beams of channels of slender webs having web-crippling failure modes, as shown in fig. 5, the ultimate capacities decrease due to the presence of opening. The size and location of openings have insignificant effect compared to those of stocky webs in certain cases, as shown in figs 9 to 11. For the presence of openings in the mid-span, the failure modes are changed by varying the size ratios of openings. For these beams and for size ratio, a/h=0.25, the failure modes of the beam are web-crippling failure mode, so significant reduction in the capacities of beams are observed. By increasing the size ratio to be a/h=0.5, the failure modes are changed from web-crippling to upper flange yielding failure. Thus, the ultimate capacities of beams are increased compared to those of less size ratios. While, for size ratio, a/h=0.75, global failures are occurred due to the weakness of the webs. So, significant reductions in the ultimate capacities are encountered.

Table 2
Comparison between the results of crippling capacities of channels without openings with respect to experimental results

Channel No.	Crippling capacities (kN)					Comparison			
	P_{model}	P_{exp}	P_{thr}	P_{NAS}	$P_{AS/NZS}$	P_{model}/P_{exp}	P_{thr}/P_{exp}	P_{NAS}/P_{exp}	$P_{AS/NZS}/P_{exp}$
C-01	49.88	52.90	52.15	74.30	89.20	0.9428	0.9858	1.4045	1.6862
C-02	61.33	64.60	60.32	73.20	88.70	0.9378	0.9222	1.1193	1.3563
C-03	59.55	65.20	67.27	70.70	87.10	0.8581	0.9693	1.0187	1.2550
C-04	92.44	103.70	124.10	110.60	130.50	0.8914	1.1968	1.0665	1.2584
C-05	138.87	155.60	144.47	172.40	213.10	0.8925	0.9285	1.1080	1.3695
C-06	134.59	150.40	138.28	163.70	206.60	0.8949	0.9194	1.0884	1.3737
					Mean	0.9029	0.9870	1.1342	1.3832
					COV	0.0010	0.0113	0.0188	0.0250

Table 3
Comparison between the results of ultimate capacities of channels with openings as ratios from those without openings

C-No	Comparison $P_{open}/P_{without}$								
	X/L=0.25			X/L=0.33			X/L=0.50		
	a/h=0.25	a/h=0.50	a/h=0.75	a/h=0.25	a/h=0.50	a/h=0.75	a/h=0.25	a/h=0.50	a/h=0.75
C-01	0.5109	0.4634	0.4085	0.4098	0.4090	0.4085	0.4060	0.3659	0.2712
C-02	0.5206	0.4759	0.4407	0.4398	0.4194	0.4159	0.3923	0.3019	0.2491
C-03	0.9223	0.8834	0.8442	0.7940	0.7911	0.7864	0.7889	0.5945	0.3799
C-04	0.7730	0.7730	0.7870	0.7799	0.7580	0.7690	0.7817	1.0216	0.3892
C-05	0.8777	0.8722	0.8672	0.8755	0.8690	0.8671	0.8983	0.9826	0.8342
C-06	0.9989	0.9937	0.9796	0.9998	0.9938	0.9206	1.0048	1.0346	0.6477

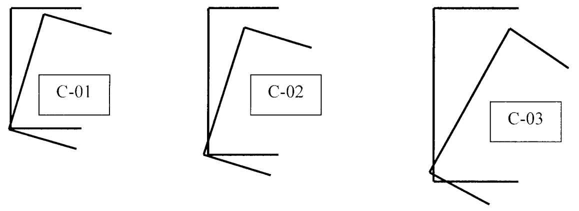


Fig. 4. Failure modes of channels of stocky webs.

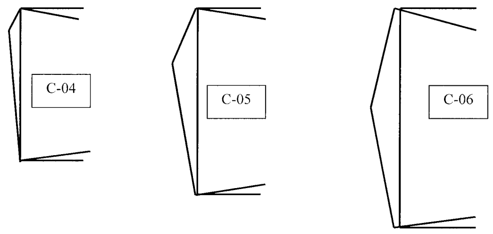


Fig. 5. Failure modes of channels of slender webs.

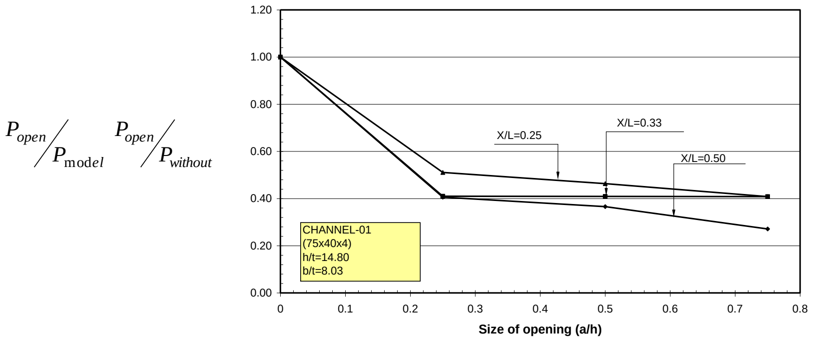


Fig. 6. Effect of opening position on the crippling capacity of channel (C-01) for different sizes of opening.

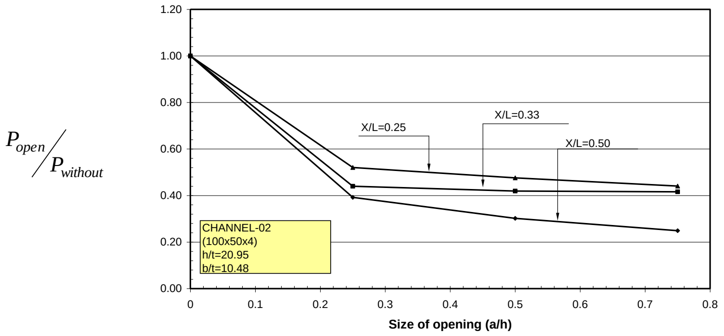


Fig. 7. Effect of opening position on the crippling capacity of channel (C-02) for different sizes of opening.

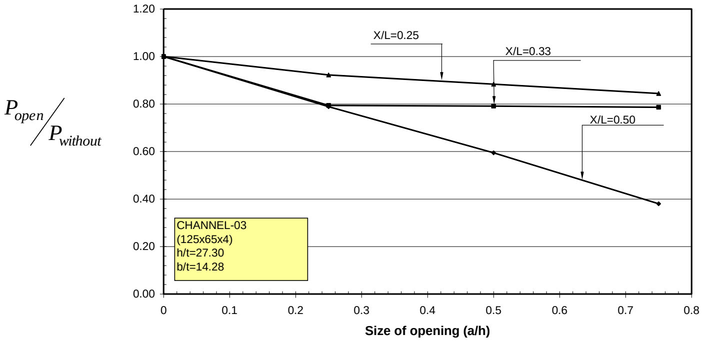


Fig. 8. Effect of opening position on the crippling capacity of channel (C-03) for different sizes of opening.

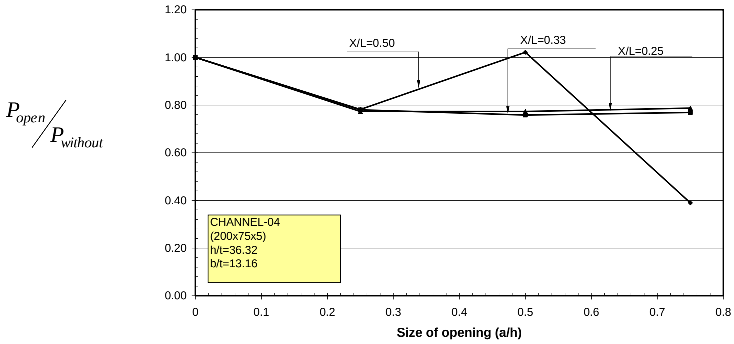


Fig. 9. Effect of opening position on the crippling capacity of channel (C-04) for different sizes of opening.

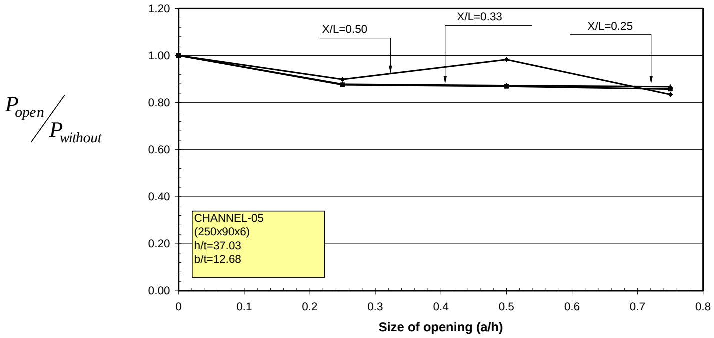


Fig. 10. Effect of opening position on the crippling capacity of channel (C-05) for different sizes of opening.

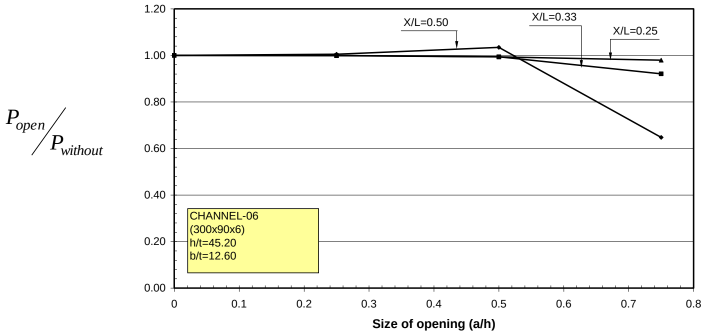


Fig. 11. Effect of opening position on the crippling capacity of channel (C-06) for different sizes of opening.

6. Conclusions

This paper presents a finite element model to calculate the ultimate capacities of cold-formed channel beams. Experimental and theoretical results conducted by several researchers in case of web-crippling failure mode were used to verify the finite element modelling techniques. A numerical parametric study was conducted to study the influence of the presence of openings in the webs on the ultimate capacity of the beams. The results obtained, show that the presence of opening affects the ultimate capacity and the mode of failure of the beam. The size and location of opening significantly affect the capacity degradation.

References

[1] Specification for the design of cold-formed steel structural members, with 1989 Addendum. American Iron and Steel Institute, Washington, D.C. (1986).

[2] Load and resistance factor design specification for cold-formed steel structural members. American Iron and Steel Institute, Washington, D.C. (1991).

[3] J. E. Langan, R. A. LaBoube, and W. W. Yu, Structural Behaviour of Perforated Web Elements of Cold-Formed Steel Flexural Members Subjected to Web Crippling and a Combination of Web Crippling and Bending. Final Rep., Civ. Engrg. Study 94-3, Cold-Formed Steel Series, Department of Civil Engineering, University of Missouri-Rolla, Rolla, Mo. (1994).

[4] M.Y. Shan, R.A. LaBoube, and W.W. Yu, Behavior of Web Elements with Openings Subjected to Bending, Shear and the Combination of Bending and Shear. Final Rep., Civ. Engrg. Study 94-2, Cold-Formed Steel Series, Department of Civil Engineering, University of Missouri-Rolla, Rolla, Mo. (1994).

[5] S. U.Deshmukh, Behavior of Cold-Formed Steel Web Elements with Circular Openings Subjected to Web Crippling and a Combination of Bending and Web Crippling For Interior-One-Flange Loading. MS thesis, University of Missouri-Rolla, Rolla, Mo. (1996).

[6] C.A. Uphoff, Structural Behavior of Circular Holes in Web Elements of Cold-Formed Steel Flexural Members Subjected to Web Crippling for End-One-Flange Loading. MS thesis, University of Missouri-Rolla, Rolla, Mo. (1996).

[7] R.A. LaBoube, W.W. Yu, J.E. Langan and M.Y. Shan, “Cold-formed steel webs with openings: Summary report.” Thin-walled structures, Vol. 27 (1), Elsevier Science, Great Britain. (1997).

[8] W.W. Yu, Cold-Formed Steel Design, 2nd Ed., Wiley, New York. (1991).

[9] B. Young, and G.J. Hancock, “Design of Cold-Formed Channels Subjected to Web crippling.” ASCE, Vol.127 (10), pp. 1137–1144 (2001).

[10] AS/NZS. Cold-Formed Steel Structures. Australian/New Zealand Standard, AS/NZS 4600, Sydney, Australia. (1996).

[11] X.L. Zhao, and G.J. Hancock, Square and Rectangular Hollow Sections Subject to Combined Actions. ASCE, Vol. 118 (3), pp. 648–668 (1992).

[12] X.L. Zhao, and G.J. Hancock, “Square and Rectangular Hollow Sections Under Transverse End-Bearing Force,” ASCE, 121(9), 1323–1329 (1995).

[13] North American Specification (NAS). “Commentary on the 2001 North American specification for the design of cold-formed steel structural members.” Commentary North American Cold-formed Steel Specification, American Iron and Steel Institute, Washington, D.C. (2001a).

[14] North American Specification (NAS). “Specification for the design of cold-formed steel structural members.” North American Cold-formed Steel Specification, American Iron and Steel Institute, Washington, D.C. (2001b).

[15] K. Prabakaran, and R.M. Schuster, “Web crippling of cold-formed steel members.” Proc., 14th Int. Specialty Conf. on Cold-Formed Steel Structures, Univ. of Missouri-Rolla, Rolla, Mo., pp. 151–164 (1998).

[16] B. Beshara, and R.M. Schuster, Web Crippling Data and Calibrations of Cold-Formed Steel Members, Final Rep., Univ. of Waterloo, Waterloo, Canada (2000).

[17] R.A. LaBoube, W.W. Yu, S.U. Deshmukh, and C.A. Uphoff, “Crippling Capacity of Web Elements with Openings.” ASCE, Vol. 125 (2), pp. 137-141 (1999).

[18] K.S. Sivakumaran, and K.M. Zielonka, “Web crippling strength of thin-walled steel members with web openings.” Thin-walled structures, Vol. 2, Elsevier Science, Great Britain (1989).

[19] COSMOS/M, A Computer Program for Nonlinear Static and Dynamic Analysis, Structural Research and Analysis Corporation, Santa Monica, California, USA (2000).

[20] B. Young, and G.J. Hancock, “Cold-Formed Steel Channels Subjected to Concentrated Bearing Load.” ASCE, Vol. 129 (8), pp. 1003-1010 (2003).

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