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NUMERICAL STUDIES OF STEEL CHANNELS WITH STAGGERED SLOTTED PERFORATIONS SUBJECT TO COMBINED BENDING AND SHEAR ACTIONS

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Keywords: Cold-formed Steel, Channels with Staggered Slotted Perforation, Combined Bending and Shear, Finite Element Analyses.

Abstract. *Cold-formed steel studs and purlins with staggered slotted perforations in webs are used in construction to improve thermal performance of the profiles and energy efficiency of structures. On the other hand, the web perforations adversely affect structural performance of the members, especially their shear, bending and combined bending and shear strengths. Relatively little research has been reported on this subject despite its importance. Many research studies have been carried out to evaluate the combined bending and shear behaviour of conventional cold-formed channel beams. To date, however, no investigation has been conducted into the strength of cold-formed steel channels with staggered slotted perforations under combined bending and shear actions. Finite element models of cold-formed steel channels with staggered slotted perforations were developed to simulate their combined bending and shear behaviour and strength. They were then validated by comparing the results with available experimental test results and used in a detailed parametric study. This paper presents the details of the numerical studies of cold-formed steel channels with staggered slotted perforations and the results.*

1 INTRODUCTION

In recent times, the use of advanced manufacturing technologies and high strength steels has led to increased levels of cold-formed steel construction using a range of thin-walled steel sections. Cold-formed steel (CFS) channels with slotted webs (see Figure 1) have been used in residential and commercial construction to enhance the thermal performance of the profiles and energy efficiency of buildings [1–3]. Figure 2 shows the application of cold-formed steel (CFS) channels with slotted webs. Slotted steel profiles have over the past years become a widely used section in building construction due to moisture resistance, light weight, faster assembly and good sound performance. The main difference for slotted steel profiles compared to non-slotted steel profiles is the reduced thermal conductivity, which is beneficial in terms of heat transfer (see Figure 3). On the other hand the slotted steel profiles reduce the load bearing capacity in bending and shear and add to deflections.

The flexural and shear strength and behavior of CFS channels with slotted webs were investigated in [4–6]. Many experimental studies have been conducted on the combined bending and shear behaviour of different cold-formed sections including C-sections, Z-sections, SupaCee sections, hollow flange channel beams [7-12]. However, the research on the combined bending and shear behavior and strength of channels with slotted webs is unavailable. Therefore, numerical study was undertaken to investigate the combined bending and shear behaviour of channels with slotted webs. This paper presents the details of the numerical studies of cold-formed steel channels with slotted web subject to combined bending and shear action and the results.

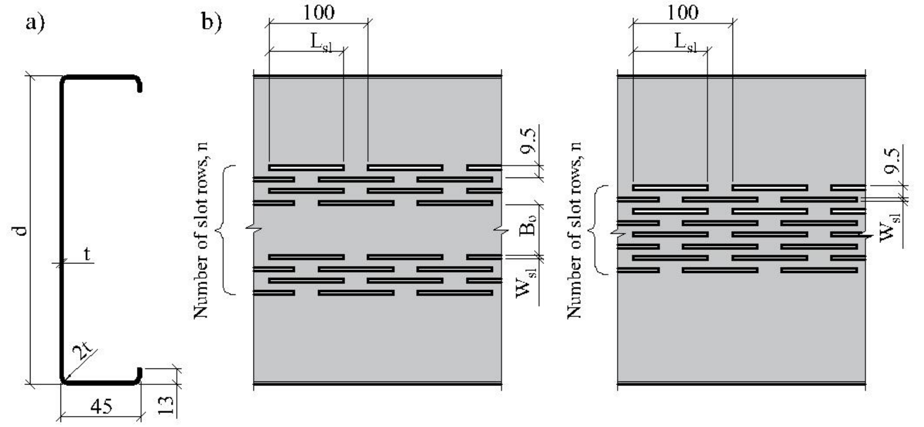


Figure 1: Channels with slotted webs (a) Cross-section (b) Perforation patterns and sizes

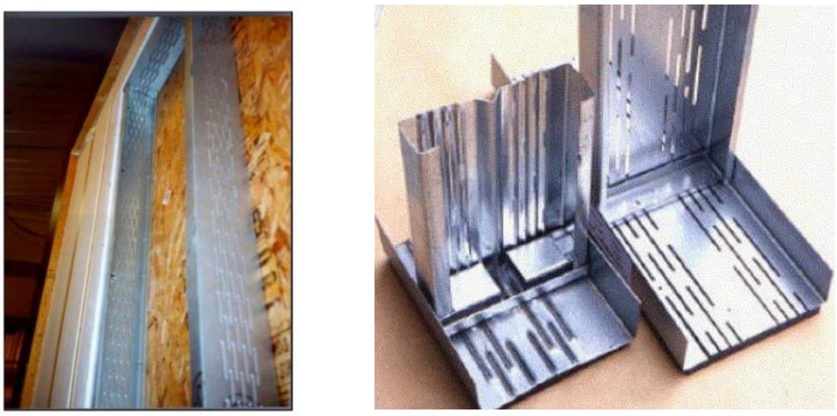


Figure 2: Application of cold-formed steel (CFS) channels with slotted webs [2]

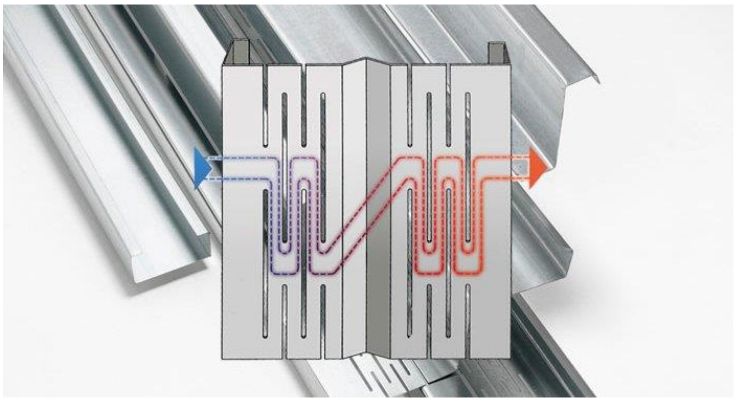


Figure 3: Thermal transmittance in wall sections with slotted steel sections

2 NUMERICAL STUDIES

2.1. Element types and material properties

Channels and web side plates (WSPs) were modeled with the four-node shell elements with six degrees of freedom at each node, type SHELL181. The channels were modeled as elastic-perfectly plastic materials using the bilinear isotropic hardening material model (BISO). The web side plates were assumed to be elastic. The elastic modulus and Poisson's ratio of the channels and web side plates were taken as 200,000 MPa and 0.3, respectively. Figure 4 shows FE models of solid and slotted channels.

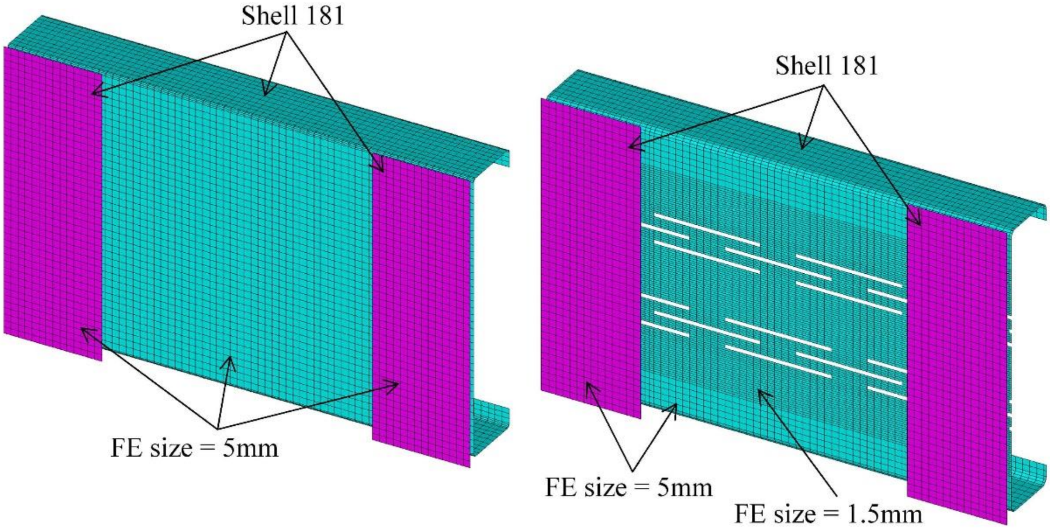


Figure 4: FE models of solid and slotted channels

2.2. Finite element discretization

The channels and web side plates were discretized with quadrilateral element meshes. Solid channels were modeled using the maximum element size of 5 mm. The non-perforated regions of the slotted channels and their perforated regions in the longitudinal direction were also meshed using the maximum element size of 5 mm. The maximum element size in the vertical direction was 1.5 mm for perforated regions. The same mesh density of the slotted channels was used in the study [6].

2.3. Load and Boundary Conditions

Figures 5 and 6 show the boundary conditions applied to channels without and with slotted webs sections subject to combined bending and shear actions. One-half of the test set-up was modelled using symmetry boundary conditions.

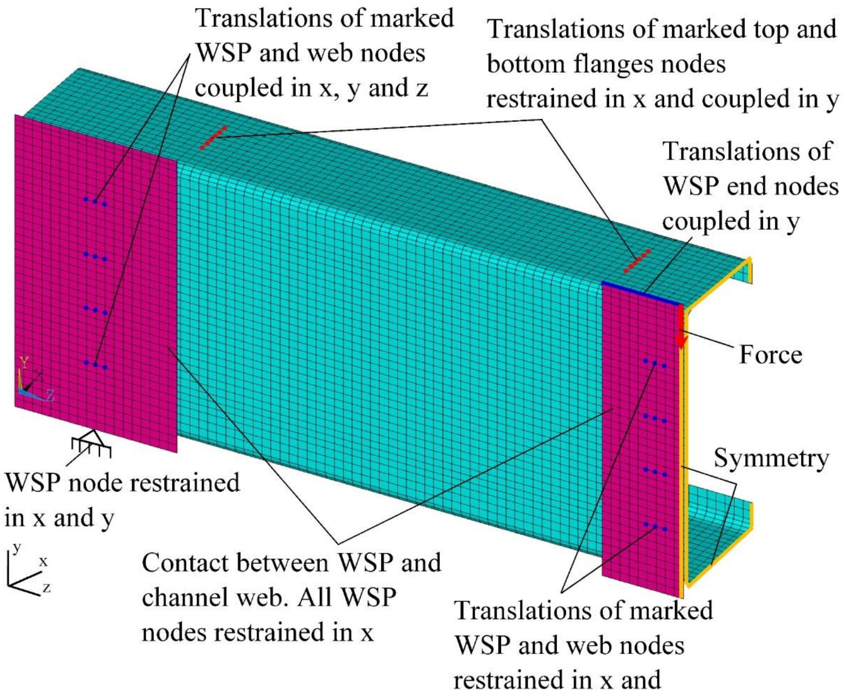


Figure 5: Finite element model and boundary conditions of soild channels for validation

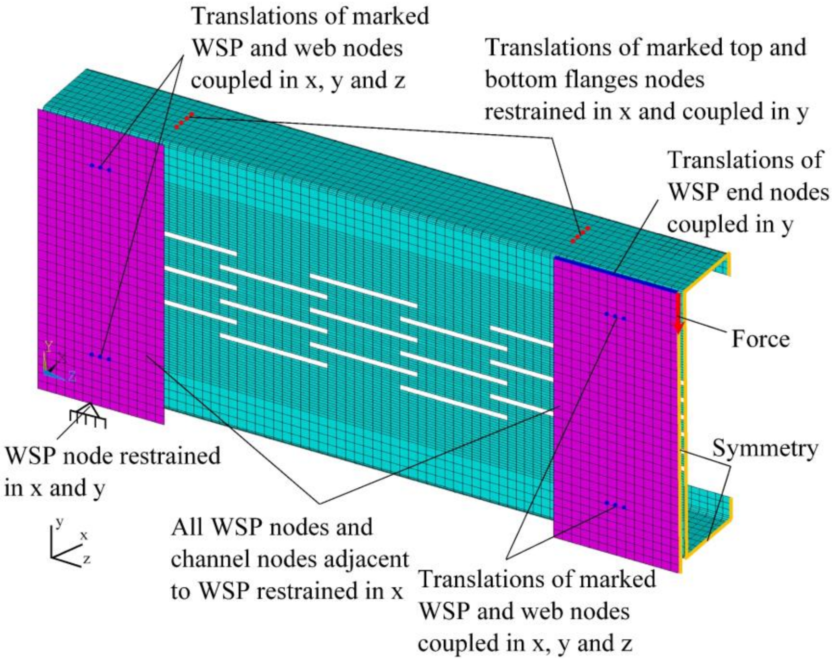


Figure 6: Finite element model and boundary conditions of channels with slotted web for parametric study

2.4. Initial geometric imperfections

The initial geometric imperfections were added to the finite element models using eigenvalue buckling analysis. The initial geometric imperfections were incorporated by modifying the geometry of the model from the lowest elastic buckling mode obtained in previous linear buckling analysis. Scaling factor of 0.15t was used to introduce imperfections for all models where t is thickness.

2.5. Analysis methods

Linear buckling analysis was conducted to obtain elastic buckling modes for models of slotted channels. The first elastic buckling mode was used to simulate the initial geometric imperfections for nonlinear analysis. The nonlinear static analysis was performed to obtain the combined bending and shear capacity and the failure mode of the model. The effects of large deformations and material yielding were taken into consideration in the nonlinear analysis. The sparse direct equation solver was selected for the nonlinear analysis.

2.6. FE Model Validation

Combined bending and shear capacities obtained from FE analyses (FEA) and experiments for solid channels are compared in Table 1. The mean value of combined bending and shear capacities of solid channels from experiment and FEA is 1.00 while its associated COV is 0.059. These comparisons confirm that FEA results agree well with corresponding experimental results of solid channels subject to combined bending and shear action.

Load-deflection plots obtained from experiments [10] and FEA are compared in Figure 7. As illustrated in Figure 7 FE model predicts the ultimate capacity accurately. However it can be noticed that when load approaching to peak load the vertical displacement of the model is less than that of test results. This is due to the slip and elongation of the holes caused by the bearing capacity of channel ply in test. Therefore, this won’t affect the prediction of ultimate capacity and failure types. Figure 8 illustrates the failure mode of channel with solid web from experiment and FEA.

Table 1: Comparison of FEA and experimental combined bending and shear capacities of solid channels

Sections	Test (kN) [10]	FEM (kN)	Test/FEM
C15015-MV1	34.91	35.55	0.98
C15015-MVw	26.80	28.44	0.94
C15019-MV1	48.37	50.94	0.95
C15019-MVw	38.41	38.51	1.00
C15024-MV1	63.99	57.69	1.11
C15024-MVw	54.18	47.84	1.13
C20015-MV1	34.22	35.00	0.98
C20015-MVw	24.25	24.55	0.99
C20019-MV1	54.51	56.07	0.97
C20019-MVw	39.80	40.92	0.97
C20024-MV1	72.47	72.85	0.99
C20024-MVw	55.30	54.57	1.01
		MEAN	**1.00**
		COV	**0.059**

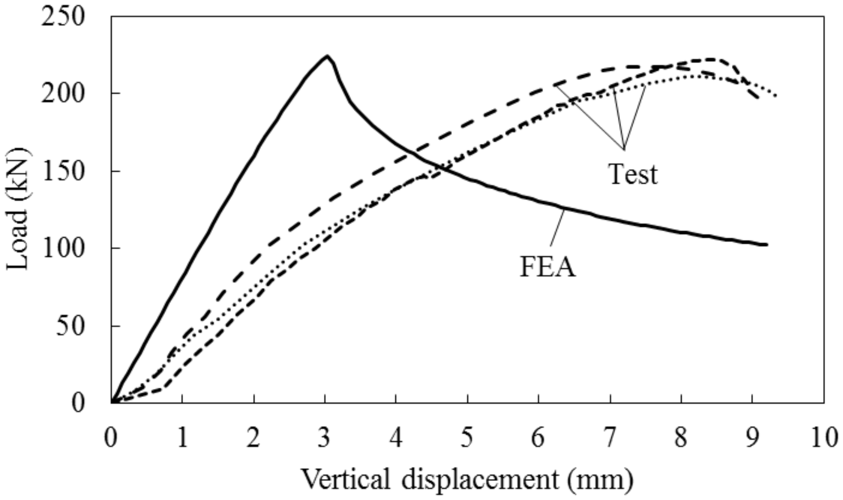
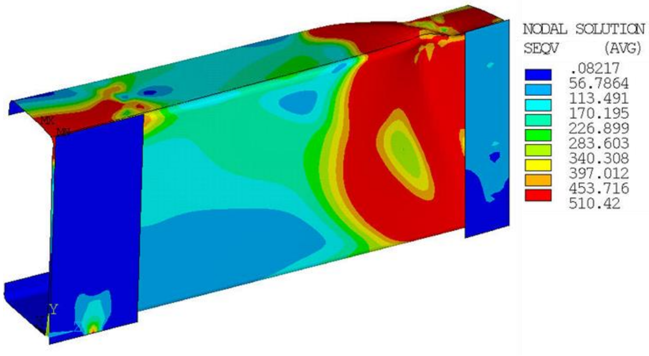


Figure 7: Load-deflection plot for 200 mm deep channel with thickness of 1.9 mm with straps (C20019-MV1)

(a) Test



(b) FEA

Figure 8: Failure mode shapes of tested specimen and FE model of 200 mm deep channel with thickness of 1.9 mm with straps (C20019-MV1)

3 PARAMETRIC STUDIES

This section presents the details of a parametric study into the combined bending and shear behaviour of channels with slotted webs. The objectives of the parametric study are to investigate the combined bending and shear behaviour of channels with slotted webs and develop new and/or improved design rules for them in order to use their combined bending and shear capacities effectively and increase their range of applications in the construction industry.

Following the validation of the developed finite element models as described in the earlier sections, a detailed parametric study was undertaken based on the validated model to develop an extensive combined bending and shear capacity data base and then to use them to develop improved design equations for channels with slotted webs subjected to combined bending and shear action. In order to investigate the effect of section depth (d), thickness (t), inside bent radius (r_i), slot length (L_{sl}), slot width (W_{sl}), number of rows (n), yield strength (f_y) and aspect ratio (a/d) on the combined bending and shear capacity, different section depths (d =150 and 200 mm), thicknesses (t = 1 and 2 mm), slot lengths (L_{sl} = 60 and 75 mm), slot widths (W_{sl} = 3 and 5 mm), inside bent radius (r_i = 2 and 4 mm), number of rows (n = 6 for 150 mm section and n = 6 and 8 for 200 mm section) yield strengths (f_y = 300 and 500 MPa) and aspect ratios (a/d = 1.0, 1.5, 2.0, 3.0, 4.0) were considered in the parametric study. Total of 384 FEM were considered in the parametric study. Figure 9 shows the dimensions of finite element model of channels for parametric study while Figures 10 and 11 show the Von Mises stresses in solid and slotted channels at the maximum applied load. Table 2 shows the part of parametric study results (Aspect ratio = 3.0).

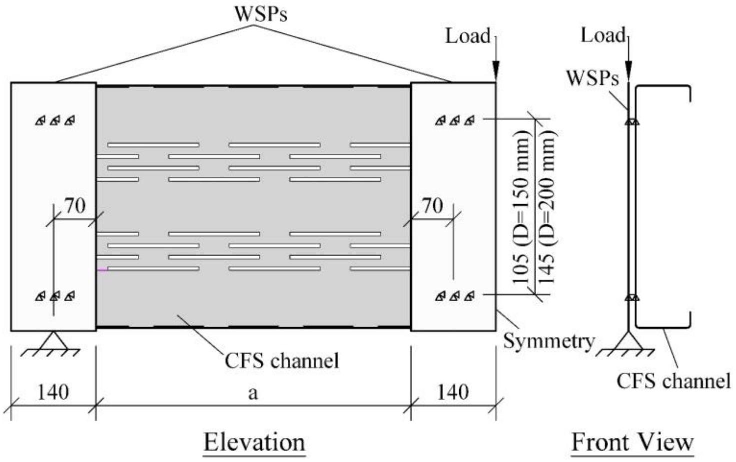


Figure 9: Dimensions of finite element model of channels for parametric study

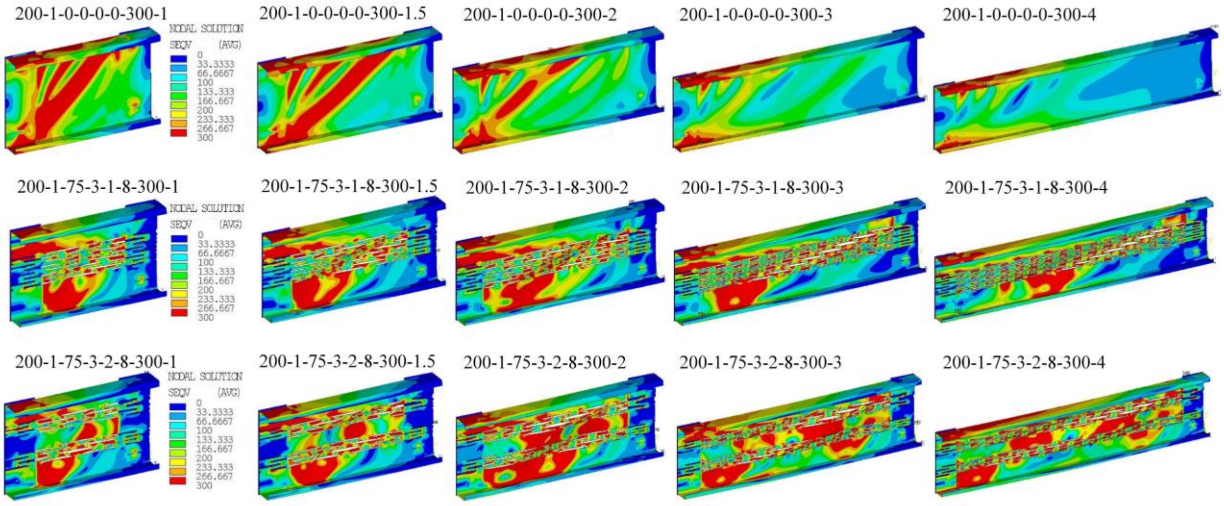


Figure 10: Von Mises stresses in solid and slotted channels at maximum applied load

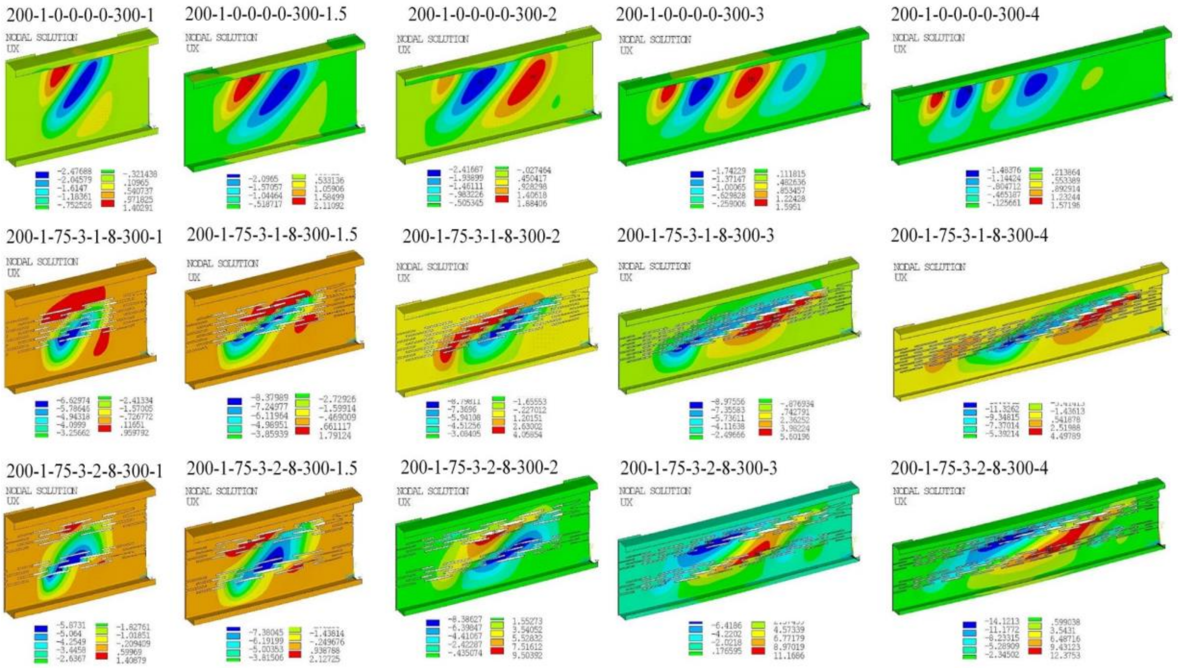


Figure 11: Failure modes in solid and slotted channels at maximum applied load

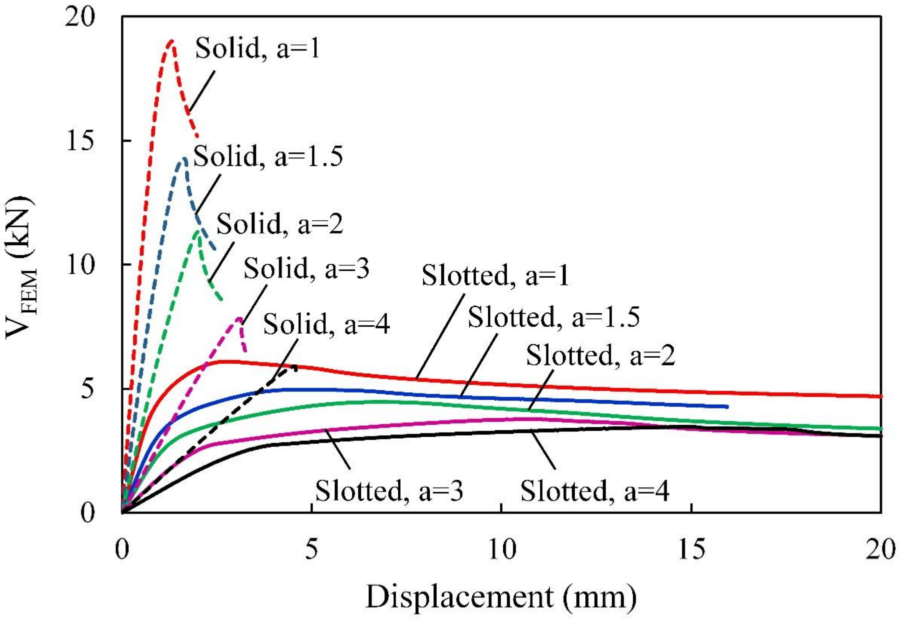


Figure 12: Load-deflection plots of solid (200-1-0-0-0-0-300) and slotted (200-1-75-3-1-8-300) channels with different aspect ratios

Table 2: Part of Parametric study results (Aspect ratio = 3.0)

Channels with Slotted Webs	d (mm)	t (mm)	L_{sl} (mm)	W_{sl} (mm)	f_y (MPa)	r_i (mm)	MV_{nl}	MV_u	MV_{nl}/ MV_u
150-45-13-1-60-3-1-6-300-3	150	1	60	3	300	2	4.08	7.51	0.54
150-45-13-1-60-5-1-6-300-3	150	1	60	5	300	2	3.20	7.51	0.43
150-45-13-1-75-3-1-6-300-3	150	1	75	3	300	2	3.22	7.51	0.43
150-45-13-1-75-5-1-6-300-3	150	1	75	5	300	2	2.57	7.51	0.34
150-45-13-1-60-3-2-6-300-3	150	1	60	3	300	2	4.39	7.51	0.58
150-45-13-1-60-5-2-6-300-3	150	1	60	5	300	2	3.36	7.51	0.45
150-45-13-1-75-3-2-6-300-3	150	1	75	3	300	2	3.00	7.51	0.40
150-45-13-1-75-5-2-6-300-3	150	1	75	5	300	2	2.27	7.51	0.30
150-45-13-2-60-3-1-6-300-3	150	2	60	3	300	4	11.10	19.54	0.57
150-45-13-2-60-5-1-6-300-3	150	2	60	5	300	4	9.04	19.54	0.46
150-45-13-2-75-3-1-6-300-3	150	2	75	3	300	4	8.09	19.54	0.41
150-45-13-2-75-5-1-6-300-3	150	2	75	5	300	4	6.61	19.54	0.34
150-45-13-2-60-3-2-6-300-3	150	2	60	3	300	4	10.48	19.54	0.54
150-45-13-2-60-5-2-6-300-3	150	2	60	5	300	4	8.42	19.54	0.43
150-45-13-2-75-3-2-6-300-3	150	2	75	3	300	4	7.79	19.54	0.40
150-45-13-2-75-5-2-6-300-3	150	2	75	5	300	4	6.31	19.54	0.32
150-45-13-1-60-3-1-6-500-3	150	1	60	3	500	2	6.09	10.56	0.58
150-45-13-1-60-5-1-6-500-3	150	1	60	5	500	2	4.71	10.56	0.45
150-45-13-1-75-3-1-6-500-3	150	1	75	3	500	2	4.96	10.56	0.47
150-45-13-1-75-5-1-6-500-3	150	1	75	5	500	2	4.01	10.56	0.38
150-45-13-1-60-3-2-6-500-3	150	1	60	3	500	2	6.28	10.56	0.59
150-45-13-1-60-5-2-6-500-3	150	1	60	5	500	2	4.97	10.56	0.47
150-45-13-1-75-3-2-6-500-3	150	1	75	3	500	2	4.64	10.56	0.44
150-45-13-1-75-5-2-6-500-3	150	1	75	5	500	2	3.47	10.56	0.33
150-45-13-2-60-3-1-6-500-3	150	2	60	3	500	4	15.24	31.67	0.48
150-45-13-2-60-5-1-6-500-3	150	2	60	5	500	4	13.49	31.67	0.43
150-45-13-2-75-3-1-6-500-3	150	2	75	3	500	4	12.76	31.67	0.40
150-45-13-2-75-5-1-6-500-3	150	2	75	5	500	4	10.25	31.67	0.32
150-45-13-2-60-3-2-6-500-3	150	2	60	3	500	4	14.58	31.67	0.46
150-45-13-2-60-5-2-6-500-3	150	2	60	5	500	4	11.90	31.67	0.38
150-45-13-2-75-3-2-6-500-3	150	2	75	3	500	4	11.89	31.67	0.38
150-45-13-2-75-5-2-6-500-3	150	2	75	5	500	4	9.73	31.67	0.31

Figure 12 shows the load-deflection plots of solid (200-1-0-0-0-0-300) and slotted (200-1-75-3-1-8-300) channels with different aspect ratios while Figure 13 shows the plot of reduction factor ($q_s = MV_{nl}/MV_u$) versus aspect ratio (a/d). Figure 13 showed that the staggered slotted perforations in the channel webs significantly reduced combined bending and shear capacities of the channels (67%, 65%, 62%, 52%, 43% capacity reductions for aspect raios 1.0, 1.5, 2.0, 3.0 and 4.0, repectively).

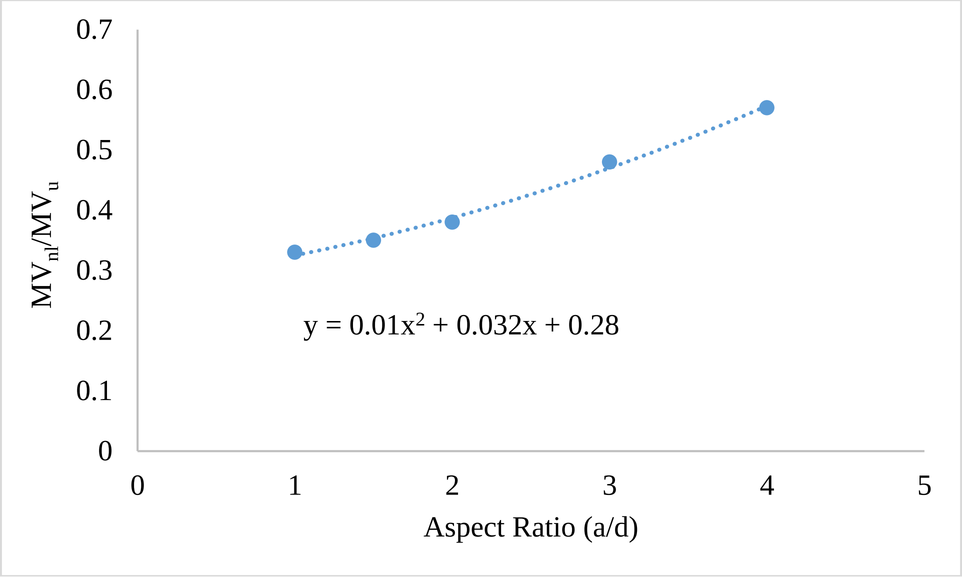


Figure 13: Plot of reduction factor (MV_{nl}/MV_u) versus aspect ratio (a/d)

4 DESIGN RULES

The equation (Equation 1) for combined bending and shear capacities of solid channel is given in AS/NZS 4600 [13] and AISI [14].

$$0.6\left[\frac{M^*}{M_S}\right]+\left[\frac{V^*}{V_V}\right]=1.3 \tag{1}$$

where

M^* is bending action,
M_s is the bending section capacity in pure bending,
V^* is the shear action, and
V_v is the shear capacity in pure shear.

FEA combined bending and shear capacities of the perforated and solid channels were directly compared. The comparison showed that the staggered slotted perforations in the channel webs reduced combined bending and shear capacities of the channels. Current shear design rules for cold-formed steel beams with web openings are based on a reduction factor (q_s) defined as the ratio of the nominal shear capacity of cold-formed steel beams with web openings (V_{nl}) to the nominal shear capacity of cold-formed steel beams without web openings (V_u). Hence suitable design rules are also needed to predict combined bending and shear capacities of channels with slotted webs (MV_{nl} – applied load capacity when openings present (kN)) based on reduction factor (q_s) and combined bending and shear capacity of cold-formed steel beams without web openings (MV_u – load capacity in solid sections (kN)). New equation (Equation 2) was also proposed for reduction factor based on FEA results. Combined bending and shear capacities of channels with slotted webs can be determined using Equations 1 and 2.

$$q_s=\frac{MV_{nl}}{MV_u}=0.01\left[\frac{a}{d}\right]^2+0.032\left[\frac{a}{d}\right]+0.28 \tag{2}$$

where

q_s is reduction factor for combined bending and shear capacity

a is the shear span
d is the depth of channel

This reduction factor q_s would lead to predicting the maximum load that can be applied to a staggered perforated slotted section subject to combined bending and shear behavior from its corresponding solid section.

5 CONCLUSIONS

This paper presents the details of the numerical studies of cold-formed steel channels with slotted webs subject to combined bending and shear action and the results of these analyses. Numerical combined bending and shear capacities of the perforated and solid channels were directly compared. The comparison showed that the staggered slotted perforations in the channel webs significantly reduced combined bending and shear capacities of the channels (67%, 65%, 62%, 52%, 43% capacity reductions for aspect radios 1.0, 1.5, 2.0, 3.0 and 4.0, respectively). Numerical results were used to develop new design equations to predict the combined bending and shear capacities channels with slotted webs.

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REFERENCES

[1] Höglund, T. and Burstrand, H., “Slotted steel studs to reduce thermal bridges in insulated walls”, *Thin-Walled Structures*, 32, 81–109, 1998.

[2] Development of cost-effective, energy efficient steel framing: thermal performance of slit-web steel wall studs. *Research rep. AISI/Steel Framing Alliance*, RP02-9; 2002 (Revision2006).

[3] Liptak-Varadi, J., “Equivalent thermal conductivity of steel girders with slotted webs”, *Period, Polytech*. 54 (2), 163-170, 2010.

[4] Kesti, J., Local and Distortional Buckling of Perforated Steel Wall Stud, D.Sc. Dissertation, Helsinki University of Technology, Espoo, Finland, 2000.

[5] Degtyareva, N.V and Degtyarev, V.V., “Experimental investigation of cold-formed steel channels with slotted webs in shear”, *Thin-walled Structures*, Vol. 102, 30-42, 2016.

[6] Degtyarev, V.V and Degtyareva, N.V., “Finite element modeling of cold-formed steel channels with solid and slotted webs in shear”, *Thin-walled Structures*, 103, 183-198, 2016.

[7] Keerthan, P., Hughes, D. and Mahendran, M. (2014) Experimental Studies of Hollow Flange Channel Beams Subject to Combined Bending and Shear Actions, *Thin-Walled Structures*, Vol.77, pp.129-140.

[8] Keerthan, P. and Mahendran, M. Hughes, D 2014) Numerical Studies and Design of Hollow Flange Channel Beams Subject to Combined Bending and Shear Actions, *Engineering Structures*, pp. 197-212.

[9] Keerthan, P. and Mahendran, M. (2015) Experimental Investigation and Design of Lipped Channel Beams in Shear, *Thin-Walled Structures*, pp. 174-184.

[10] Pham, C.H., Hancock, G.J. (2012), Direct Strength Design of Cold-formed C-Sections for Shear and Combined actions, *Journal of Structural Engineering* Vol. 138, pp. 759-768.

[11] Keerthan, P., Hughes, D. and Mahendran, M. (2012), Behaviour of LiteSteel Beams Subject to Combined Shear and Bending Actions, *Proc. of the 21st International Specialty Conference on Cold-formed steel Structures*, St. Louis, Missouri, USA, pp. 265-279.

[12] Keerthan, P., Hughes, D. and Mahendran, M. (2012), Tests of LiteSteel Beams Subject to Combined Shear & Bending Actions, *Proc. of the Australian Struct. Eng*., Perth, pp. 81-87.

[13] Standards Australia/Standards New Zealand, "*Australia/New Zealand Standard AS/NZS 4600 Cold-formed steel structures*", Sydney, Australia, 2005.

[14] American Iron and Steel Institute (AISI), "*Specifications for the cold-formed steel structural members, cold-formed steel design manual*", AISI S100, Washington DC, USA, 2012.