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Stiffening evaluation of flat elements towards stiffened elements under axial compression

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Abstract. Thin-walled cross-sections can be optimized to enhance their resistance and progress their behaviour, leading to more competent and inexpensive structural system. The aim of this study is to afford a methodology that would facilitate progress of optimized cold formed steel (CFS) column section with maximum ultimate strength for practical applications. The proposed sections are designed to comply with the geometrical standards of pre-qualified column standards for CFS structures as well as with the number of industrialized and practical constraints. The stiffening evaluation process of CFS lipped channel columns, a five different cross section are considered. The experimental strength and behaviour of the proposed sections are verified by using the finite element analysis (FEA). A series comprehensive parametric study is carried out covering a wide range of section slenderness and overall slenderness ratio of the CFS column with and without intermediate web stiffeners. The ultimate strength of the sections is determined based on the Direct Strength Specification and other design equation available from the literature for CFS structures. A modified design method is proposed for the DSM specification. The results indicate that the CFS column with complex edge and intermediate web stiffeners provides an ultimate strength which is up to 78% higher than standard optimized shapes with the same amount of cross sectional area.

Keywords: cold-formed steel; edge stiffener; intermediate web stiffener; finite element analysis; slenderness ratio

1. Introduction

In olden days, cold-formed steel (CFS) cross-sections are employed in the secondary load-carrying members such as roof purlins, wall panels and storage racks. Compared to hot-rolled members CFS members offers many advantages such as high strength to weight ratio, more structural efficiency, elevated strength for a light weight, simple manufacturing process and an ease of handling the process. Due to that, in recent years CFS cross-sections are employed as primary structural elements.

The flexibility of the manufacturing process, CFS section it can easily meet with the structural

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designer requirements. Due to their less thickness and large with-to-thickness ratio, CFS section is failing with local, distortional and global buckling modes. To meet the design requirements as well as to improve the buckling failure, in this study optimization of CFS cross-section is carried out.

2. Review of literature

Previous studies on the optimization of CFS elements have mainly limited and the results are scattered. Optimization standard cross section was discussed by lipped channel column by Anil Kumar and Kalyanaraman (2012), channel column with inclined edge stiffener by Young (2004), lipped channel column with intermediate web stiffener by Manikandan and Arun (2016), channel column with complex edge stiffener by Yan and Young (2002, 2004). Dinis and his research team (2011, 2011a, b) Yan and Young (2002) and Ungermann *et al.* (2014) were discussed the significance of local/distortional/global mode of interaction effects on the buckling behaviour and strength of lipped channel columns. Very recently, Wang *et al.* (2016) developed optimum CFS channel column with complex edge stiffener with various types of web stiffener. Direct strength methods (DSM) have been used conventionally to estimate the strength of the members fails by local/distortional/overall buckling. The conventional DSM specifications don't account for the interactive failure mode. The following researchers gave the solutions for interaction of the local/distortional/overall buckling failure modes by Yang and Hancock (2004) provided a suitable modified design equation for channel column with intermediate web stiffeners undergoing a local distortional buckling interaction. From the literature study, it is observed that the new innovative cold formed steel section is essential in the construction industry. Also, it is noted that the Direct Strength Method (DSM) for the cold formed steel structures is unconservatively predicting the interaction of the local/distortional/overall buckling modes.

Simple channel column sections are more familiar with the construction industry, because of simple manufacturing process and easy connection to other elements. Hence, in this study the basic overall geometry of all the sections is restricted to a simple channel section. However, an unstiffened element of the channel section is having low torsional rigidity. Therefore distortional buckling occurs at preliminary stage and it leads to reducing the strength of the column. To overcome similar kinds of problem with flexural members, Manikandan *et al.* (2014) were developed some efficient section as shown in Figs. 1(a)-1(d). In this research, the tested column section is similar to that tested by Manikandan *et al.* (2014). All the cross section dimensions are satisfied the pre qualified column limitations for cold-formed steel structures. Cross section dimensions are carefully arrived to meet with the interaction of the local/distortional/overall buckling modes. The buckling plot of the specimen is obtained from the finite strip buckling analysis by using the CUFSM software.

The aim of the current study is to investigate the buckling behaviour of new stiffened cold formed steel section with and without intermediate web stiffener under axial compression. An FE model is developed by using finite element analysis (FEA) software ANSYS. The performance of the developed model is verified against the test results. The validated finite element (FE) model is consequently used to carry out an extensive parametric study covering a wide range of varying depth and overall section slenderness of the section. Numerically gathered resistance is compared with the present strategy proposed in the Direct Strength Method (DSM) other design equation available from the literature for CFS structures. Design proposals for the interaction of buckling modes are given.

3. Experimental program

3.1 Detail of testing

In this study, five cross section geometries are selected as shown in Fig. 1, first is an unstiffened column (USC), second is stiffened column (SC), third is stiffened column with upright edge stiffener (SC-U), fourth is stiffened column with complex edge stiffener (SC-C) and fifth is stiffened column with complex edge and intermediate web stiffener (SC-C-I). Table 1 summarizes the measured dimensions of the test specimens.

As per the guidelines of Ye *et al.* (2016) , easy brake-pressed operation of folded elements and to avoid local buckling, size of stiffened element (A), size of edge stiffener (C), the size of the return lip (D) and size of intermediate web stiffener (E) is restricted to 15 mm. Angle of inclination of intermediate stiffener of SC-C-I is taken as 45^0. The actual nominal thickness of the section (t) is 2.0 mm. All the tested specimens are having an equal cross sectional area with an overall slenderness ratio of 50. Specimen labeling are discussed in the subsequent section 3.2.

Table 1 Dimensions of the selected cross section

Specimen ID	Section dimensions (mm)							Slenderness ratio (λ)
	Flange width (W)				E	H	t	
	A	B	C	D				
USC-150	65				-	150	2.0	50
USC-200	65				-	200	2.0	50
SC-150	15	50	-	-	-	150	2.0	50
SC-U-150	15	35	15	-	-	150	2.0	50
SC-C-150	15	35	15	15	-	135	2.0	50
SC-C-I-150	15	35	15	15	15	150	2.0	50
USC	65				-	H^*	1.6,2.0,3	50
SC	15	50	-	-	-	H^*	1.6,2.0,3	50
SC-U	15	35	15	-	-	H^*	1.6,2.0,3	50
SC-C	15	35	15	15	-	H^*	1.6,2.0,3	50
SC-C-I	15	40	15	15	15	130	1.6	λ^*

H^*: 50,100,150,200,250,300 ; λ^*:20,30,40,50,60,70,80,90,100,110,120.

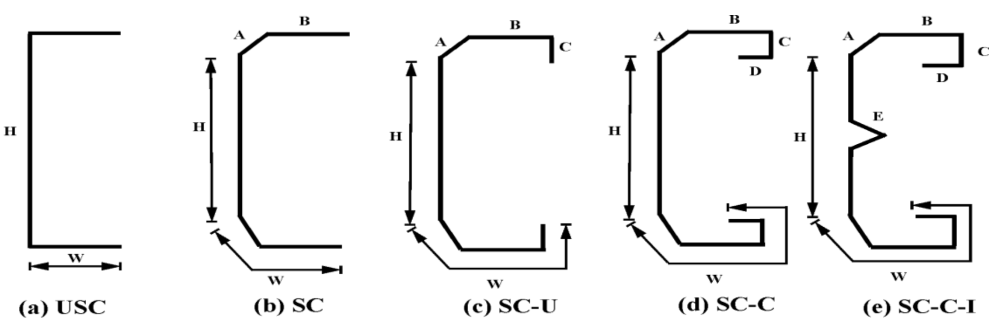


Fig. 1 Cross section profiles with acronym

The material properties of the specimens are obtained through the coupon test as per the Indian standard (IS 1608-R2006). The magnitude of yield stress, Poisson's ratio, Young's modulus and tangent modulus are 270 N/mm^2, 0.3, 2.03X10^5 N/mm^{2}and 2.03X10^4 N/mm^2 respectively. The specimens are tested under pinned and conditions with axial compressive loading. The loading application is prepared through the centroid of the section after arrangement of geometrical and physical alignment of an LVDT. A 100 T capacity loading frame with 400 kN hydraulic rams are used to test the specimen. A computerized data acquisition system with load cell and LVDT are used to measure the applied load and deformation of all the elements respectively.

3.1 Specimen labelling

The test specimens are labeled such that the category of specimen, thickness and depth of the section is expressed by the label. For example, the label "USC-1.6-50" defines the following specimen:
• "USC" indicates that the section is an unstiffened column;
• "1.6" indicates the nominal thickness of the column is 1.6 mm; and
• "50" indicates the nominal depth of the column is 50 mm.

4. Finite element modeling and parameters

The structural behaviour of USC, SC, SC-U, SC-C and SC-C-I of cold-formed steel sections have been performed numerically by using FEA software ANSYS. Finally, the FEA approach has been validated with the test results and verification are shown in Figs. 3 and 4. The FE models are developed using the SHELL 181 element with an appropriate mesh size of 10 X 10 mm. The master nodes at the ends (Fig. 2) are generated using the structural 3D mass element. As per the guidelines of Yan and Young (2004c) and Technical code of cold-formed thin-walled steel structure (1) the effects of residual stress and cold-forming process are not considered in the FE model. All the sections are analyzed under pinned end conditions with subjected to axial loading. The master nodes (RP1 and RP2) are generated at the CG of the section and that are interconnected to the column ends as shown in Fig. 2.To ensure the axial compression, boundary conditions (RP1 and RP2) and load are applied (RP2) at the master nodes. The end conditions of the column are pinned end with loaded end prevented rotation about the X and Z axis and translation in both X and Y directions. Similarly, the unloaded end is prevented from translation in three directions X, Y and Z and from rotation along the X and Z axis. Similarly, the axial load is applied at the top master node (RP1) using modified Newton-Raphson iteration with displacement-controlling technique.

In this study two types of analysis are performed. Initially, a linear buckling analysis is performed to determine the buckling modes for superposition of imperfection. Finally, non-linear analysis is performed to determine the behaviour and the load deflection response of pre buckling ranges. In this study, material and geometric nonlinearity are considered. For material non-linearity, a bilinear stress strain curve is used to consider the plasticity of the material. Geometric nonlinearity is implemented through a superposition of a known lowest deformed configuration which derived from the Eigen buckling analysis, because it is unfavorable. As per the recommendation of Schafer and Pekoz (1998), in this study the magnitude of geometric imperfection is 25% of plate thickness for local/distortional buckling and the magnitude of geometric imperfection is L/500 for overall buckling are included to investigate the effects of such imperfections.

5. Results and discussions

Local, distortional, flexural buckling and interaction between these buckling modes are analyzed experimentally and are those compared numerically as illustrated in Fig. 3. The comparison of results between experimental and finite element analysis is presented in Table 2.The basic failure mode of the unstiffened channel column (USC-150) is pure local buckling as shown in Fig. 3. The specimen USC-200 have largest depth, shows the lowest strength when compared to specimen USC-150. The larger width-to-thickness ratio decreases the local buckling strength. However, flanges without edge stiffener are highly fails to local buckling. Therefore, adding the edge stiffener in the flanges, failure modes are changed from local buckling to mixed local and flexural buckling mode. Adding intermediate web stiffener in SC-C-150 increased the ultimate strength of the about 73.78% compared to USC-150. Similarly, failure modes are changed from mixed local and distortional buckling to the interaction of distortional and flexural buckling due to provisions of intermediate web stiffener on the specimen SC-C-150 (Fig. 3(a)). From the observation of results, it can be concluded that CFS column section, intermediate stiffeners is much more efficient in increasing the section capacity than edge stiffeners.

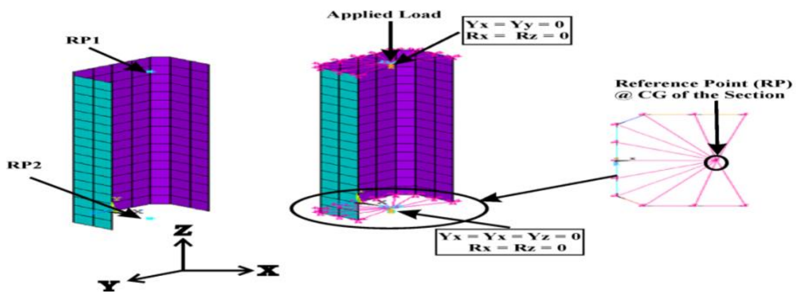


Fig. 2 Details of finite element model

Table 2 Comparisons of test and ANSYS results

Specimen ID	Ultimate strength (kN)		P_{ANSYS} / P_{EXP}	% of increase in load	Failure mode
	P_{EXP}	P_{ANSYS}			
USC-150	53.32	55.15	0.97	-	L*
USC-200	49.34	52.22	0.94	-8.07	L*
SC-150	67.70	63.63	1.06	14.38	L*
SCU-150	74.86	78.60	0.95	21.54	L +D*
SCC-150	53.23	49.73	1.07	-0.09	L+FB*
SC-C-I-150	127.10	130.90	0.97	73.78	D+FB*
	Mean		0.99		
	Standard Deviation		0.06		

* L- Local Buckling; D- Distortional Buckling; FB- Flexural Buckling

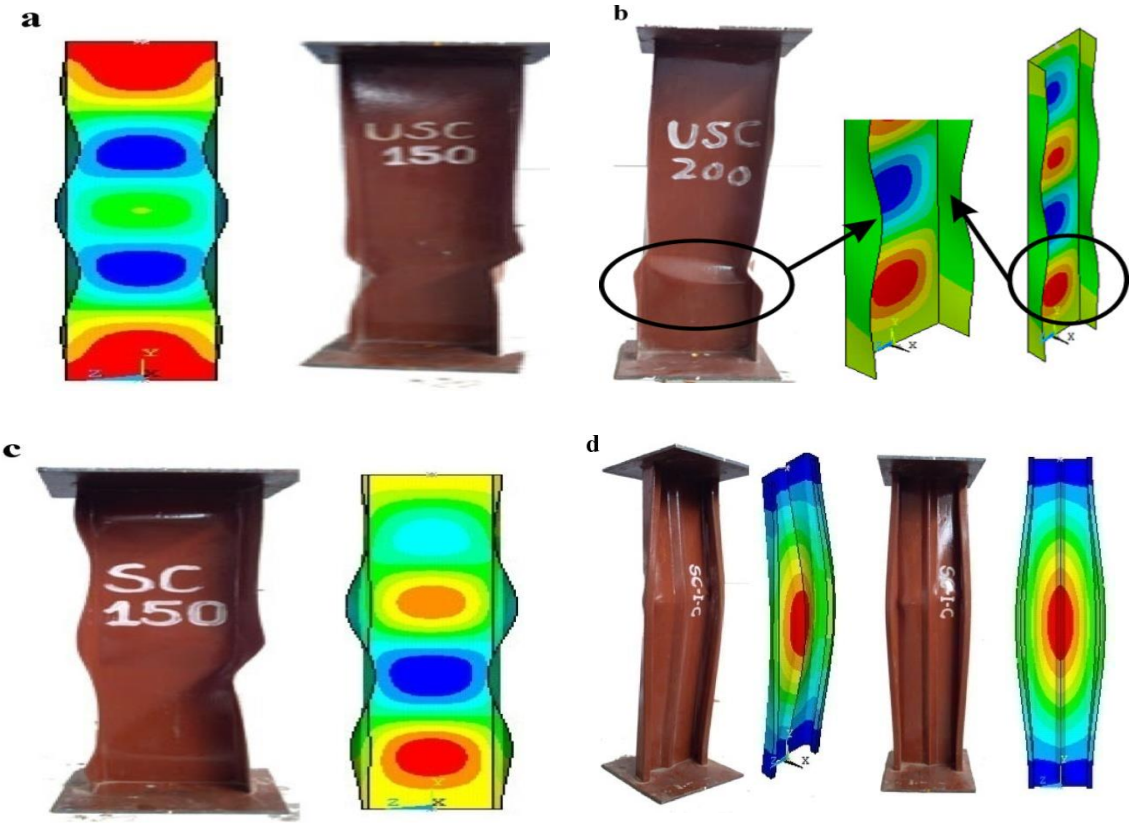
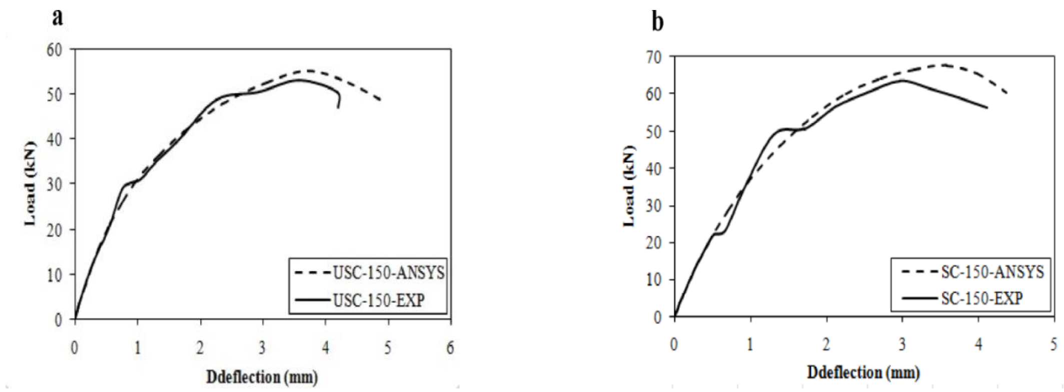


Fig. 3 Comparison of test and FEA results (a) USC-150, (b) USC-200, (c) SC-150 and (d) SC-C-I-150



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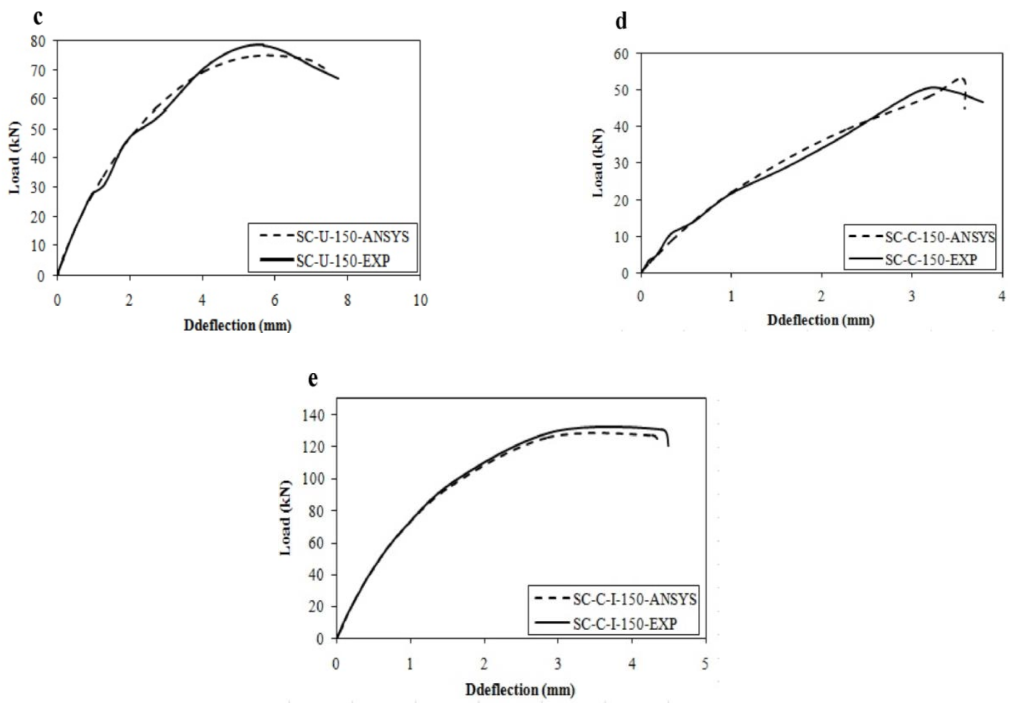


Fig. 4 Comparison of load- deformation curve between experiment and FEA

6. Parametric studies

A total of 83 FE models, which include both the web slenderness and overall slenderness ratio are analyzed using the verified FE modeling. The effects of section and overall slenderness are discussed in the subsequent section.

6.1 Effect of section slenderness for specimens without intermediate web stiffener

To study the effect of web slenderness USC, SC, SC-U, SC-C series of specimen are considered as illustrated Figs. 1(a)-1(d). Three plate thickness and six depth of the web (50, 100, 150, 200, 250 and 300 mm) with constant column length of 1000 mm gave the eighteen cross section slenderness for each series of column, in a total of 72 cross section slenderness for all the series. Graphical representation of the effect of section slenderness for USC, SC, SC-U, SC-C series of specimens and the consequent results are displayed in Fig. 7 and results are also presented in Table 3 to Table 6. From the results, observation are USC and SC series of specimens fails by local buckling where as SC-U series of specimens fails by interaction of local and distortional buckling and SC-C series of specimens fails by distortional and flexural buckling modes. In all the series, for a particular depth of the section, strength of the column increases with increases in the thickness of the section. Whereas for a particular thickness of the section, strength of the column increases with increases in the depth of the section and is also reduced by increasing the depth of the section. It is concluded that, depth and thickness of the section having a significant role in the behaviour of the section.

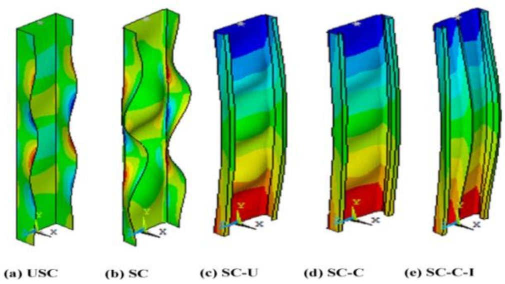


Fig. 5 Comparison of failure modes

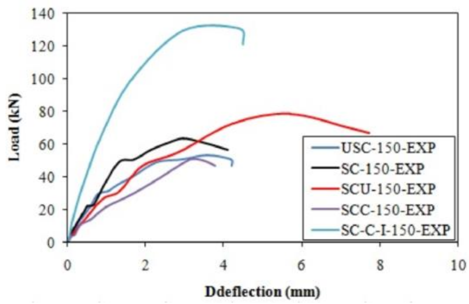


Fig. 6 Comparison of load deflection curves

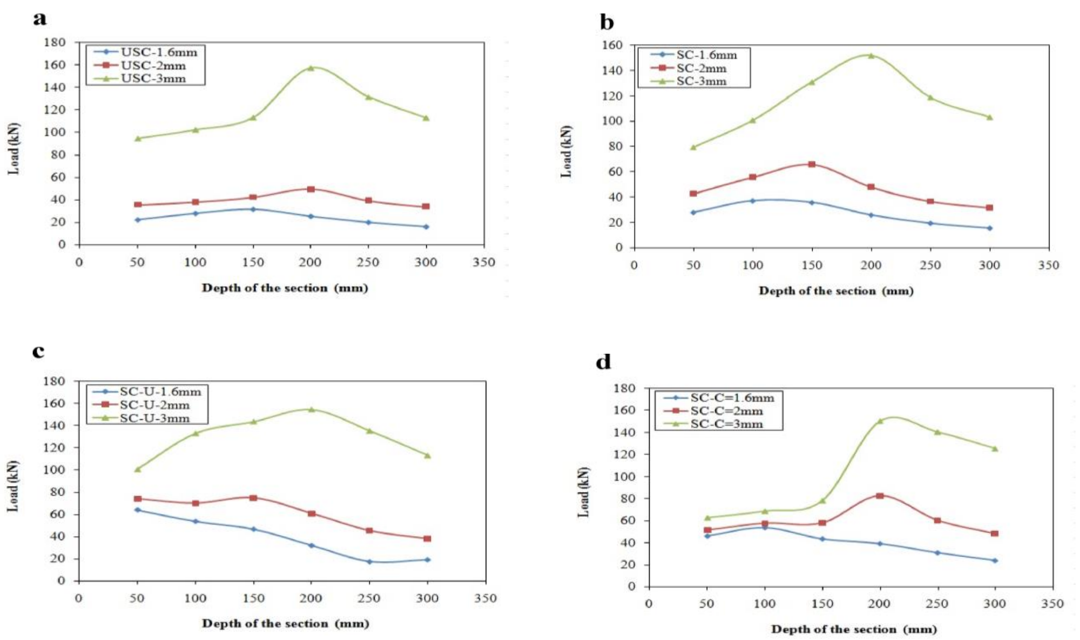


Fig. 7 Relationship between load and depth of the section (a) USC series, (b) SC series, (c) SC-U series and (d) SC-C series

6.2 Effect of overall slenderness for specimens with intermediate web stiffener

From the experimental investigation, it is observed that the specimen SC-C-I provides the maximum ultimate strength compared to all other sections. A total of 11 FE models is analysed. The slenderness ratios of the section are varying from 20 to 120 with a thickness of 1.6 mm. In this particular FEA, a separate specimen labeling is used. For an example “SC-C-I-20”, the first three letters are stiffened column with complex edge and intermediate web stiffener (SC-C-I) and the last letter is the overall slenderness ratio equal to 20.

As an illustration, the deformed shape and load versus deflection curves for SC-C-I series is shown in Figs. 8 and 9 respectively. The comparison of FEA with various design predications is presented in Table 7. The slenderness ratio is less than 30, all the specimens failed by combined local and distortional buckling whereas the slenderness ratio is greater than 30, the specimens failed by combined distortional and flexural buckling.

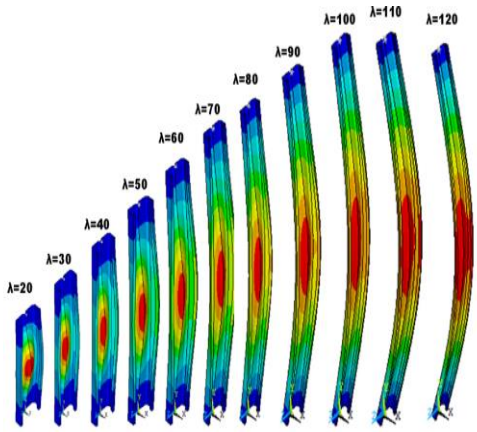


Fig. 8 Failure modes - SC-C-I series

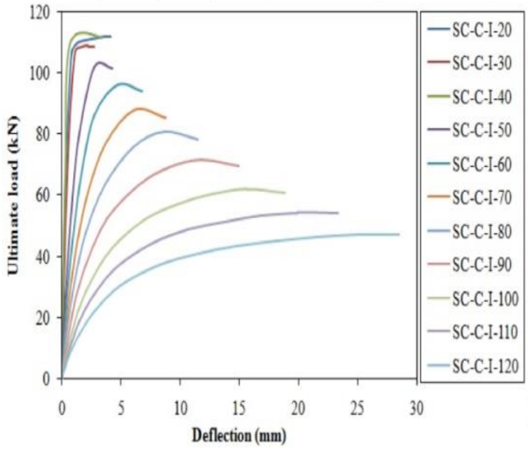


Fig. 9 Load deflection curve - SC-C-I serie

Table 3 Comparison of results - USC series

Specimen ID	Ultimate strength (kN)		P_{ANSYS} / $P_{n,DSM}$	P_{ANSYS} / $P_{d,DSM}$	P_{ANSYS} / $P_{Prop.1}$	Failure mode
	P_{ANSYS}	$P_{n,DSM}$				
USC-1.6-50	22.24	23.57	0.94	1.11	0.91	L*
USC-1.6-100	27.95	24.04	1.16	1.37	1.13	L*
USC-1.6-150	31.64	27.84	1.14	1.34	1.12	L*
USC-1.6-200	25.35	22.06	1.15	1.35	1.11	L*
USC-1.6-250	19.97	16.78	1.19	1.40	1.10	L*
USC-1.6-300	16.05	13.00	1.23	1.45	1.10	L*
USC-2.0-50	35.39	31.50	1.12	1.32	1.12	L*
USC-2.0-100	37.92	33.37	1.14	1.34	1.14	L*
USC-2.0-150	42.13	37.07	1.14	1.34	1.15	L*
USC-2.0-200	49.53	44.08	1.12	1.32	1.15	L*
USC-2.0-250	39.01	35.50	1.10	1.29	1.11	L*
USC-2.0-300	33.50	36.52	0.92	1.08	0.93	L*
USC-3.0-50	94.39	103.83	0.91	1.07	0.96	L*
USC-3.0-100	102.13	118.47	0.86	1.01	0.92	L*
USC-3.0-150	113.19	135.83	0.83	0.98	0.89	L*
USC-3.0-200	157.34	187.23	0.84	0.99	0.90	L*
USC-3.0-250	131.29	149.67	0.88	1.03	0.94	L*
USC-3.0-300	112.80	115.06	0.98	1.15	1.04	L*
Mean			1.04	1.22	1.04	
Standard Deviation			0.14	0.16	0.10	

*L- Local Buckling

As an illustration, the deformed shape and load versus deflection curves for SC-C-I series is shown in Figs. 8 and 9 respectively. The comparison of FEA with various design predications is presented in Table 7. The slenderness ratio is less than 30, all the specimens failed by combined local and distortional buckling whereas the slenderness ratio is greater than 30, the specimens failed by combined distortional and flexural buckling.

7. Comparison of the FEA results with design predictions

7.1 General

The Direct Strength Method has recently emerged as a widely adopted and very promising approach for the design of cold formed steel members. The nominal capacity of members in axial compression ($P_{n,, DSM}$) shall be minimum of local buckling (P_{nl}), distortional buckling (P_{nd}) and flexural torsional buckling (P_{ne}). The comparison of P_{ANSYS} / $P_{n, DSM}$ and P_{ANSYS} / $P_{d, DSM}$ for all the series of column are presented in Table 3-7. The $P_{n, DSM}$ and $P_{d, DSM}$ provides unconservative and speckled results for all the series of columns where as the $P_{n, DSM}$ provides conservative results for the SC-U series of columns. Since the DSM specifications are not accurately predicts the ultimate strength of the new innovative cold formed steel sections with various types of edge and intermediate stiffener.

Table 4 Comparison of results - SC series

Specimen ID	Ultimate strength (kN)		$\frac{P_{ANSYS}}{P_{n,DSM}}$	$\frac{P_{ANSYS}}{P_{d,DSM}}$	$\frac{P_{ANSYS}}{P_{Prop.1}}$	Failure mode
	P_{ANSYS}	P_{DSM}				
SC-1.6-50	27.81	29.48	0.94	1.11	0.93	L*
SC-1.6-100	37.01	38.86	0.95	1.12	0.96	L*
SC-1.6-150	35.70	37.49	0.95	1.12	0.96	L*
SC-1.6-200	25.80	27.34	0.94	1.11	0.93	L*
SC-1.6-250	19.32	19.90	0.97	1.14	0.92	L*
SC-1.6-300	15.45	17.00	0.91	1.07	0.85	L*
SC-2.0-50	42.67	47.79	0.89	1.05	0.92	L*
SC-2.0-100	55.50	61.05	0.91	1.07	0.94	L*
SC-2.0-150	65.66	69.60	0.94	1.11	0.99	L*
SC-2.0-200	47.82	49.73	0.96	1.13	0.99	L*
SC-2.0-250	36.57	38.39	0.95	1.12	0.96	L*
SC-2.0-300	31.50	33.39	0.94	1.11	0.94	L*
SC-3.0-50	79.28	81.66	0.97	1.14	1.02	L*
SC-3.0-100	100.67	107.72	0.93	1.10	0.99	L*
SC-3.0-150	130.79	139.95	0.93	1.10	1.00	L*
SC-3.0-200	151.78	188.21	0.81	0.95	0.86	L*
SC-3.0-250	118.75	118.75	1.00	1.18	1.06	L*
SC-3.0-300	103.10	103.10	1.00	1.18	1.06	L*
Mean			0.94	1.11	0.96	
Standard Deviation			0.04	0.05	0.06	

*L- Local Buckling

$$P_{n,DSM} = \mathrm{Minimum}(P_{nl}, P_{nd}, P_{ne}) \tag{1}$$

$$P_{d,DSM} = 0.85 X P_{n,DSM} \tag{2}$$

7.2 Design equation

The current DSM specification does not accurately predict, the members affected by interactive failure. Hence, the following approaches are used to estimate the strength of the sections by interactive failure. The comparison of results of all the options with FEA for all the series of column is presented in Table 3-7.

7.3 Option 1

Manikandan and Arun (2016) proposed an approach to calculate the strength of lipped channel columns with intermediate web stiffener ($P_{MAN, DSM}$) by

$$P_{MAN,DSM} = 0.85 X P_{n,DSM} \tag{3}$$

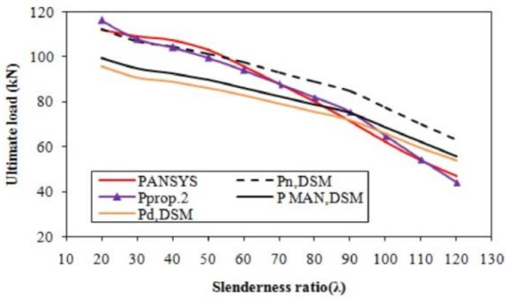


Fig. 10 Comparison of results- SC-C-I series

Table 5 Comparison of results - SC-U series

Specimen ID	Ultimate strength (kN)		$P_{ANSYS}/P_{n,DSM}$	$P_{ANSYS}/P_{d,DSM}$	$P_{ANSYS}/P_{Prop.1}$	Failure mode
	P_{ANSYS}	P_{DSM}				
SC-U-1.6-50	64.07	65.35	0.98	1.15	1.02	L+D*
SC-U-1.6-100	53.72	52.65	1.02	1.20	1.05	L+D*
SC-U-1.6-150	46.65	44.78	1.04	1.23	1.06	L+D*
SC-U-1.6-200	31.86	33.13	0.96	1.13	0.96	L+D*
SC-U-1.6-250	17.23	17.40	0.99	1.16	0.92	L+D*
SC-U-1.6-300	18.97	20.49	0.93	1.09	0.88	L+D*
SC-U-2.0-50	74.07	83.70	0.88	1.04	0.93	L+D*
SC-U-2.0-100	70.04	83.35	0.84	0.99	0.88	L+D*
SC-U-2.0-150	74.86	87.59	0.85	1.01	0.90	L+D*
SC-U-2.0-200	60.75	58.93	1.03	1.21	1.07	L+D*
SC-U-2.0-250	45.12	44.67	1.01	1.19	1.03	L+D*
SC-U-2.0-300	37.73	36.98	1.02	1.20	1.03	L+D*
SC-U-3.0-50	100.56	95.53	1.05	1.24	1.11	L+D*
SC-U-3.0-100	132.92	122.29	1.09	1.28	1.16	L+D*
SC-U-3.0-150	143.54	127.75	1.12	1.32	1.20	L+D*
SC-U-3.0-200	154.51	135.97	1.14	1.34	1.21	L+D*
SC-U-3.0-250	135.29	119.05	1.14	1.34	1.21	L+D*
SC-U-3.0-300	113.10	100.66	1.12	1.32	1.19	L+D*
Mean			1.01	1.19	1.05	
Standard Deviation			0.09	0.11	0.11	

*L- Local Buckling; D- Distortional Buckling

Where,

$P_{MAN,\ DSM}$ = Design strength calculated by design rules in Manikandan and Arun (2016)

The observation of results presented in Table 7 and Fig. 10. The mean and standard deviation of $P_{ANSYS}/\ P_{MAN,\ DSM}$ are 1.09 and 0.13 respectively. From the results it is concluded that, $P_{MAN,\ DSM}$ produces conservative results only for the slenderness ratio between 80 and above.

Table 6 Comparison of results -SC-C series

Specimen ID	Ultimate strength (kN)		$\frac{P_{ANSYS}}{P_{n,DSM}}$	$\frac{P_{ANSYS}}{P_{d,DSM}}$	$\frac{P_{ANSYS}}{P_{Prop.1}}$	Failure mode
	P_{ANSYS}	P_{DSM}				
SC-C-1.6-50	46.15	42.00	1.10	1.29	1.12	D+FB*
SC-C-1.6-100	53.77	58.61	0.92	1.08	0.95	D+FB*
SC-C-1.6-150	43.48	47.83	0.91	1.07	0.93	D+FB*
SC-C-1.6-200	39.16	45.43	0.86	1.01	0.88	D+FB*
SC-C-1.6-250	30.83	37.00	0.83	0.98	0.84	D+FB*
SC-C-1.6-300	23.66	28.16	0.84	0.99	0.83	D+FB*
SC-C-2.0-50	51.47	58.68	0.88	1.03	0.91	D+FB*
SC-C-2.0-100	57.68	58.83	0.98	1.15	1.02	D+FB*
SC-C-2.0-150	58.01	61.49	0.94	1.11	0.98	D+FB*
SC-C-2.0-200	82.33	86.45	0.95	1.12	1.00	D+FB*
SC-C-2.0-250	60.14	63.14	0.95	1.12	0.99	D+FB*
SC-C-2.0-300	48.23	51.12	0.94	1.11	0.97	D+FB*
SC-C-3.0-50	62.52	64.40	0.97	1.14	1.01	D+FB*
SC-C-3.0-100	68.54	75.39	0.91	1.07	0.95	D+FB*
SC-C-3.0-150	78.13	87.51	0.89	1.05	0.94	D+FB*
SC-C-3.0-200	150.20	165.22	0.91	1.07	0.97	D+FB*
SC-C-3.0-250	140.20	148.61	0.94	1.11	1.01	D+FB*
SC-C-3.0-300	125.30	130.31	0.96	1.13	1.02	D+FB*
	Mean		0.93	1.09	0.96	
Standard Deviation			0.06	0.07	0.07	

*D- Distortional Buckling; FB- Flexural Buckling

7.4 Proposed design expression

From the comparison of results, it is observed that the mean values of all the approaches are greater than unity and scattered results for all the series of columns. To predict the exact solution of interactive failure, a linear regression analysis is conducted between the P_{ANSYS} and $P_{n,\ DSM}$ as shown in Fig. 11.

The new design equation for lipped channel columns without intermediate stiffener is

$$P_{\mathrm{Pr}op,1} = 0.921XP_{n,\ DSM} + 3.386 \tag{4}$$

The new design equation for lipped channel columns with intermediate stiffener is

$$P_{\mathrm{Pr}op,2} = 1.458XP_{n,\ DSM} - 47.59 \tag{5}$$

Results obtained from the FEA (P_{ANSYS}) are compared with the proposed design equation (P_{Prop}) for all the series of column as discussed from Table 3-7. From these results it is observed that, the mean value for lipped channel columns without intermediate stiffener (P_{ANSYS}/ P_{Prop}) for all the series of column is almost equal to unity, the maximum and minimum mean value are 1.05 and 0.96 respectively.

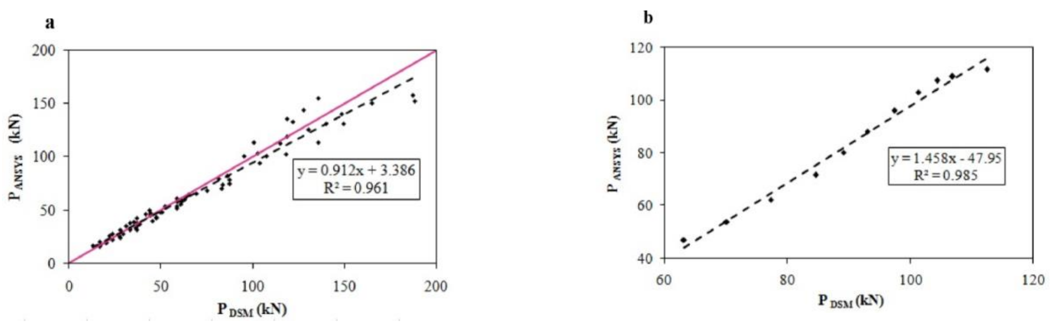
Table 7 Comparison of results -SC-C-I series

Specimen Labels	Ultimate load (kN)		$\frac{P_{ANSYS}}{P_{n,DSM}}$	$\frac{P_{ANSYS}}{P_{d,DSM}}$	$\frac{P_{ANSYS}}{P_{MAN,DSM}}$	$\frac{P_{ANSYS}}{P_{Prop.2}}$	Failure mode
	P_{ANSYS}	$P_{n,DSM}$					
SC-C-I-20	111.65	112.49	0.99	1.17	1.19	0.96	L+D*
SC-C-I-30	108.95	106.84	1.02	1.20	1.22	1.01	L+D*
SC-C-I-40	107.42	104.35	1.03	1.21	1.23	1.03	D+FB*
SC-C-I-50	102.91	101.24	1.02	1.20	1.22	1.03	D+F*B
SC-C-I-60	95.95	97.41	0.99	1.16	1.18	1.02	D+FB*
SC-C-I-70	88.17	93.05	0.95	1.11	1.13	1.01	D+FB*
SC-C-I-80	80.28	89.09	0.90	1.06	1.08	0.98	D+FT*
SC-C-I-90	71.55	84.60	0.85	0.99	1.01	0.95	D+FT*
SC-C-I-100	62.26	77.31	0.81	0.95	0.96	0.96	D+FT*
SC-C-I-110	53.91	70.10	0.77	0.90	0.92	0.99	D+FT*
SC-C-I-120	47.00	63.12	0.74	0.88	0.89	1.07	D+FT*
Mean			0.91	1.08	1.09	1.00	
Standard Deviation			0.11	0.13	0.13	0.04	

*L- Local Buckling; D- Distortional Buckling; FB- Flexural Buckling; FT- Flexural Torsional Buckling

Table 8 Verification of design equation

Specimen ID as per Literature (Young 2004)	Ultimate load (kN)			$\frac{P_{EXP}}{P_{Prop}}$
	P_{EXP}	P_{DSM}	P_{Prop}	
T1.5F120L1500	145.70	157.00	146.94	0.99
T1.5F120L2000	139.50	150.40	140.87	0.99
T1.5F120L3000	131.30	133.30	125.16	1.05
T1.9F120L1000	231.20	230.8	214.76	1.08
T1.9F120L1500	227.30	225.1	209.52	1.08
Mean				1.04
Standard Deviation				0.05



(a) Specimens without intermediate web stiffener (b) Specimens with intermediate web stiffener

Fig. 11 Correlation between P_{ANSYS} and P_{DSM}

Similarly, the mean value for lipped channel columns with intermediate stiffener (P_{ANSYS}/ P_{Prop}) is almost equal to unity, the mean and standard deviation 1.00 and 0.04 respectively. The mean and standard deviation of the test results P_{EXp} (Young 2004) to the new design proposals P_{Prop} are 1.04 and 0.05 respectively. The new design proposals are well agreed with the test results (2). It can be clearly observed that the proposed design equation rationally predicts the strength of lipped channel columns without intermediate stiffener.

8. Conclusions

A total of 6 intermediate new innovative cold-formed steel channel columns are tested. A nonlinear finite element modeling is developed and verified with the test results. The effect of section slenderness and overall slenderness are further evaluated by using the verified FE model. Obtained section strength is compared with the Direct Strength Method (DSM) for cold formed steel sections as well as the modified DSM proposed by Manikandan and Arun (2016) for lipped channel sections with intermediate stiffeners. Based on the experimental, numerical and theoretical studies some crucial conclusions are drawn as follows:

- Numerical simulation for ultimate section strength of the proposed section is reliable and accurate.
- The local buckling capacity of the sections adequately improved by intermediate web stiffener.
- The distortional buckling strength of the section is also improved to some degree as the flanges are restrained/stiffened at the flange/web junction.
- Edge and intermediate web stiffener increase the torsional and flexural stiffness of the section respectively.
- Section slenderness and overall slenderness can significantly affect the behaviour and strength of the member.
- Nominal and allowable design strength based on DSM specifications is providing scattered and slightly unconservative results for interactive failure.
- For the section with intermediate web stiffeners, nominal design prediction overestimated the strength of the section for slenderness ratio is greater than 50 whereas allowable design predictions and the modified DSM specification from literatures (option 1) is underestimating the strength of the section for slenderness ratio is less than 90. Design equation is proposed for interactive failure and the proposed design prediction provides more accurate results.

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