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Research Paper

Parametric study with FE model of cold-formed plain lipped C-section in shear, and combined bending and shear

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ABSTRACT

The study focuses on the finite element (FE) modelling of cold formed plain lipped C-section in shear, and combined bending and shear, which was developed using ANSYS. Hence, a parametric study on plain C-section was conducted to investigate the applicability of the direct strength method (DSM). In addition, DSM capacity curves were constructed to find out the limitations of DSM. It is found that the DSM equations for nominal shear capacity with tension field action (TFA) gives the capacity that is acceptable when full tension field action is developed while the nominal DSM moment capacity at local buckling outlines conservative results. However, the study also reveals that the DSM nominal shear capacity without tension field action provides lower capacity than the real peak capacity and therefore, it concludes that this method is more conservative.

1 Introduction

The cold formed sections are widely being used in different types of structures for various reasons such as the light weight of the structure, easier manufacturing process, strength, easier handling process etc. Research on these sections has been of great importance in modern times. There are design methods for the cold formed sections such as the traditional effective width method, also known as the unified method or the main Specification method and direct strength method. The North American Specification for the Design of Cold-Formed Steel Structural Members (AISI 2001) is the document, referred to as the Specification, or main Specification, forms the basis for design of cold-formed steel and the Direct Strength Method was added to the Specification in 2004[1]. 2004 Supplement to the North American Specification for the Design of Cold-Formed Steel Structural Members (AISI 2004) is the document which is a supplement to the Specification [2]. Direct Strength Method (DSM) was developed by Schafer and Peköz [3]. The DSM was formally adopted in the North American Design

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Specification in 2004 and in Australian/New Zealand Standard AS/NZS 4600:2005 in 2005 as an alternative to the traditional effective width method (EWM) [1, 2, 4]. There is no need to calculate cumbersome effective sections, especially with intermediate stiffeners. The development of the DSM for columns and beams, including the reliability of the method, is well researched. DSM provides a design method for complex shapes that requires no more effort than for normal shapes. There are some practical advantages of DSM such as no requirement of effective width calculations, no iterations required, and taking into account of gross cross-sectional properties [5]. There are some theoretical advantages of the DSM approach such as explicit design method for distortional buckling, includes interaction of elements (i.e., equilibrium and compatibility between the flange and web is maintained in the elastic buckling prediction), and explores and includes all stability limit states [5]. There are some philosophical advantages to the DSM approach such as encourages cross-section optimization, provides a solid basis for rational analysis extensions, potential for much wider applicability and scope, and engineering focus is on correct determination of elastic buckling behavior, instead of on correct determination of empirical effective widths [5]. Elastic buckling analysis performed on the computer (e.g., by CUFSM) is directly integrated into DSM [5, 6]. This provides a general method of designing cold-formed steel members and creates the potential for much broader extensions [5]. Actually, Australian and American standard/specification for the design of cold-formed steel structures, which include direct strength method (DSM) of design, are limited to pure compression and pure bending [7]. There are no presented rules in this standard for shear and combined bending and shear [7]. Therefore it became necessary to extend this method to shear and combined bending and shear [8,9,10]. For the application of the DSM to the purlin systems for shear and for combined bending and shear, an extensive study was conducted to calibrate the DSM design for shear and for combined shear and bending, and this design technique was recommended by Pham [11] to apply in the design of C-sections for shear and for combined bending and shear. DSM of design of cold-formed C-sections for shear and for combined bending and shear was proposed by Pham [7]. In this investigation program the validity of these proposed design rules had been checked by numerical analysis process using the ANSYS. This paper mainly focuses on the applicability and limitations of nominal shear capacity based on AISI in DSM format in shear without tension field action (TFA), nominal shear capacity based on AISI in the DSM format in shear with tension field action, direct strength method (DSM) of design for bending in finding capacity. For this research, the structural behaviour of cold-formed C-section was evaluated by an extensive numerical study. Therefore, a FE model was constructed by the ANSYS which is a numerical model of simply supported beam of cold formed C section. A detailed parametric study was conducted to observe the relation between the ratios of ultimate shear strength to nominal shear capacity using the DSM against depth. In addition, the relation between the ratios of ultimate flexural strength to nominal moment capacity at local buckling using DSM against depth was also evaluated. The DSM capacity curves were constructed to observe the influence of the TFA. The data that were found from the ANSYS were analyzed thoroughly to see the behaviour of this model.

From this numerical study, it is found that the DSM equations for nominal shear capacity with tension field action give the shear capacity that is acceptable well whenever full tension field action is developed. Whereas, The DSM equations for nominal shear capacity without tension field action provides more conservative shear capacity. The DSM capacity of nominal moment capacity at local buckling always gives conservative results.

2 Methods of estimating strength

2.1 Nominal shear capacity based on AISI in DSM format in shear without tension field action

The equations in Section C3.2.1 of the North American Specification [12] are expressed in terms of a nominal shear stress that is changed to DSM format by replacing stresses by loads as follows:

For $\lambda_v \leq 0.815$:

$$V_v = V_y \tag{1}$$

For $0.815 < \lambda_v \leq 1.227$:

$$V_v = 0.815\sqrt{V_{cr} \times V_y} \tag{2}$$

For $\lambda_v > 1.277$:

$$V_v = V_{cr} \tag{3}$$

Where,

$$\lambda_v = \sqrt{\frac{V_y}{Vcr}} \tag{4}$$

$$V_y \text{ (yield load of web)} = 0.6 A_w f_y \tag{5}$$

$$V_{cr} \text{ (elastic shear buckling force of the web)} = \frac{k_v \pi^2 A_w E}{12\left(1-\nu^2\right)\left(\frac{d_1}{t_w}\right)^2} \tag{6}$$

d_1 is depth of the flat portion of the web measured along the plane of the web, t_w is thickness of web, A_w is area of web $A_w = d_1 \times t_w$, *and* k_v is the shear buckling coefficient.

2.2 Nominal shear capacity based on AISI in DSM format in shear with tension field action

The DSM nominal shear capacity (V_v) is proposed based on the local buckling as follows [12]:

$$V_v = \left[1-0.15\left(\frac{V_{cr}}{V_y}\right)^{0.4}\right]\left(\frac{V_{cr}}{V_y}\right)^{0.4} V_y \tag{7}$$

Where,

k_v = shear buckling coefficient for the whole channel sections

2.3 Direct strength method (DSM) of design for bending

The nominal section moment capacity at local buckling (M_{sl}) is determined from Section 7.2.2.3 of AS/NZS 4600 [4] as illustrated in the following Equations:

For $\lambda_l \leq 0.776$: $$M_{sl} = M_y \tag{8}$$

For $\lambda_l \leq 0.776$: $$M_{sl} = \left[1-0.15\left(\frac{M_{ol}}{M_y}\right)^{0.4}\right]\left(\frac{M_{ol}}{M_y}\right)^{0.4} M_y \tag{9}$$

Where:

λ_l is non-dimensional slenderness used to determine M_{sl}, $$\lambda_l = \sqrt{\frac{M_y}{M_{ol}}} \tag{10}$$

$$M_y = Z_f f_y, \tag{11}$$

M_{ol} is elastic local buckling moment of the section, $$M_{ol} = Z_f f_{ol} \tag{12}$$

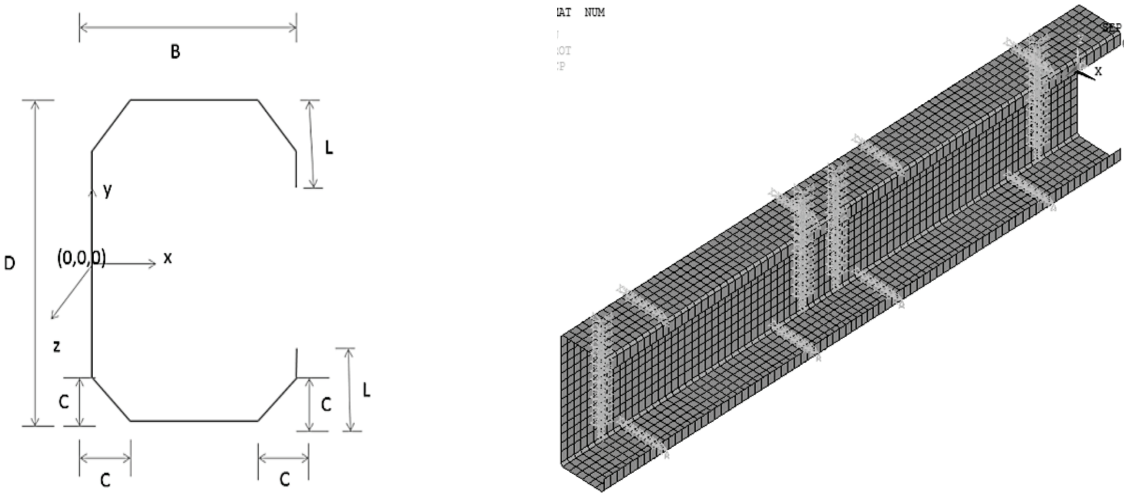
Z_f: section modulus about a horizontal axis of the full section

f_{ol}: elastic local buckling stress of the section in bending

3 Illustrations FE Modelling and verification

A finite element model of cold-formed plain C- lipped sections was developed using ANSYS with the reference to the past experimental program conducted by Pham and Hancock [13]. This numerical model was developed to study the structural behaviour of high strength cold-formed section in shear (V), combined bending and shear (MV), and bending only (M). In addition, the model was developed by considering both material and geometric non-linearities in which SHELL181 element was applied for the model generation [14]. The material behaviour is described by a bilinear total stress-total strain curve starting at the origin and with positive stress and strain values [14]. Optimum element meshing was done in this FE model generation. Fig.1 shows the detailed FE model for only shear series (V- series) and combined bending and shear series (MV-series) with straps.

The developed finite element model was verified by comparing the load deflection curve and by the deformed shapes obtained from the numerical analysis done by the ANSYS [14]. And the corresponding information was obtained from the experimental results and analysis reported by Pham [13, 15]. This FE model can be used to study the buckling phenomena associated with these thin cold-formed members in shear, combined bending moment and shear and only bending. Fig. 2 shows the comparison of the load vs. displacement plots found from the ANSYS simulation with the experimental results executed by Pham [13]. From the Fig. 2, it is found that load-displacement plot shows strain softening behaviour compared to the simulation conducted by Pham [15] and this might be happened due to the limitation of the ANSYS model in which the nodes along the depth excluding two lips were selected at the supports and the loading locations to apply the boundary conditions [16]. The ultimate load found from the ANSYS simulation differs approximately 0.5 to 8% compared to the experimental results [16].



(a) Cross section of the C-section used for the FE model

(b) FE Model

Fig. 1 – (a) Cross section of the C-section and (b) FE model for shear series (V-series) and combined bending and shear series (MV-series) with straps

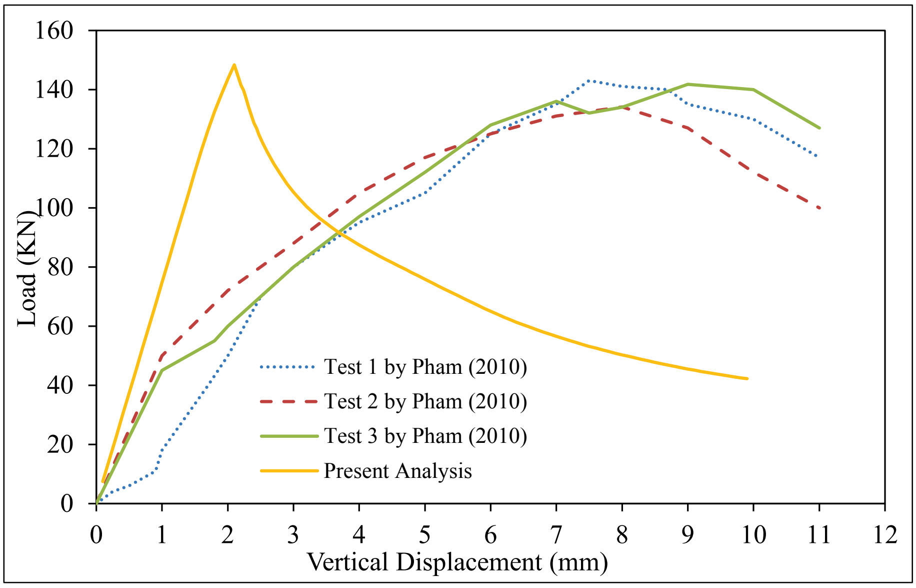


Fig. 2 – Load and Vertical Displacement Relations of MV-C15015 with straps

4 Specimen dimensions for parametric study

Table.1 summarizes the specimen dimensions for the parametric study. These sections are used for shear (*V*), and combined bending and shear (*MV*) series. For the *V* series, the ratio of shear span to depth was 1:1 whereas that of *MV* series was 2:1. The sections with 1.5 mm thickness were used for only bending series. In the case of bending series, the shear span was 800mm and the distance between the loading points were 1000mm.

Table 1 - Specimen dimension for parametric study (D/B = 2.5)

Section	D (mm)	B (mm)	L (mm)	Thickness (mm)	f_y (MPa)
C10015	100	40	16	1.5	500
C12515	125	50	16	1.5	500
C17515	175	70	16	1.5	500
C20015	200	80	16	1.5	500
C25015	250	100	16	1.5	500
C10024	100	40	16	2.4	500
C12524	125	50	16	2.4	500
C17524	175	70	16	2.4	500
C20024	200	80	16	2.4	500
C25024	250	100	16	2.4	500

5 Analysis results of plain C- sections

For the nominal shear capacities (V_v), DSM format without tension field action (e.g., Equations 1–6) with k_v (shear buckling co-efficient) for whole channel sections was applied and DSM pro-posed shear curve, with tension field action (TFA), Equation (7) was utilized. For the nominal moment capacities M_{sl} at local buck-ling (Equations 8– 12) were utilized. Full ultimate load (P_T) was found from analysis from ANSYS. In this analysis, V_T is the shear at the support and M_T is the bending moment at loading position.

Fig.3 shows all data for shear (V-series), combined bending and shear series (MV-series) and nominal shear capacity curves, which includes the tension field action (TFA) curve [17]. In addition, the existing effective width method (EWM) shear curve without TFA (based on AISI), elastic buckling curve V_{cr} (Equations 1– 6) and new DSM proposed curve for shear V_v including TFA are also illustrated in the Fig. 3. Four types of analysis were done with one section and they are only shear with straps, only shear without straps, combined bending and shear with straps and combined bending and shear without straps.

Fig. 3 outlines that V_T/V_y ratio moves right ward with the increment of the depth for the certain thickness. This may be resulted from the buckling effects and the presence of tension field action. However, for the specific depth, the V_T/V_y ratios move leftward and the ratio tends to lie below the DSM proposed nominal shear curve with TFA with the increment of the thickness. This may be resulted from the buckling effects and the absence of full tension field action. For one section the only shear with straps results lies higher, then lies only shear without straps, and then combined bending and shear with straps and finally the combined bending and shear without straps result is the most lower value. Which indicates that in case of only shear with straps the ratio tends to lie above the DSM proposed nominal shear curve with TFA than in case of only shear without straps. In case of only shear without straps the ratio tends to lie above the DSM proposed nominal shear curve with TFA than in case of combined bending and shear. In case of combined bending and shear, the ratios lie below the DSM proposed nominal shear curve with TFA. In only shear analysis, the chances of the development of tension field action is higher especially in case of with straps because of the shorter span. In combined bending and shear analysis, the chances of the development of tension field action is lower because of the longer span. From this thorough investigation, it can be concluded that with the development of tension field action the ratio gets close or above the DSM proposed nominal shear curve with TFA.

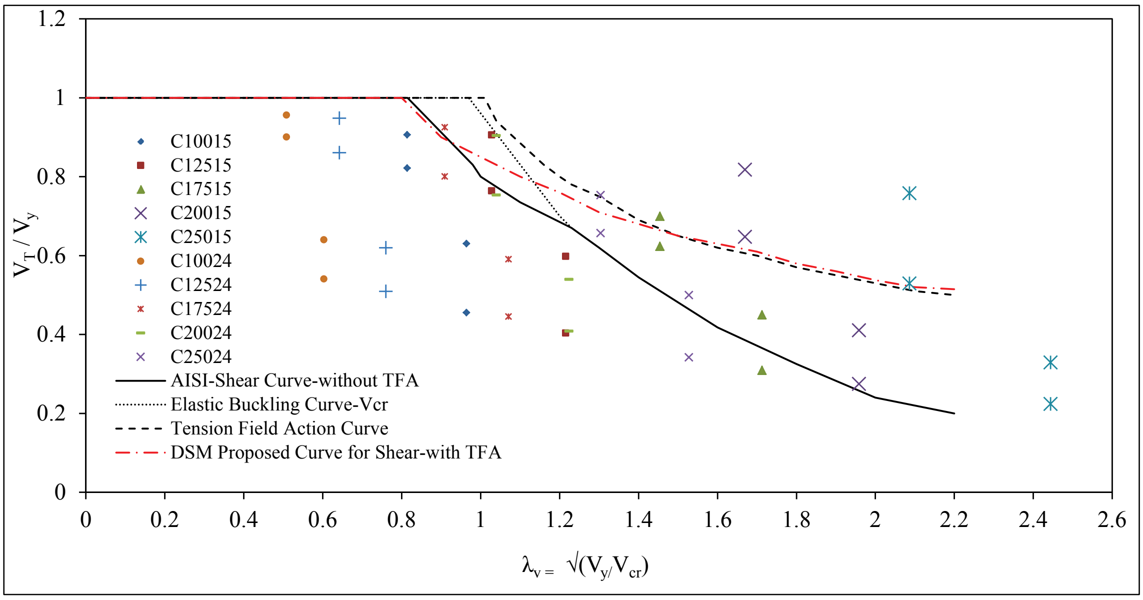
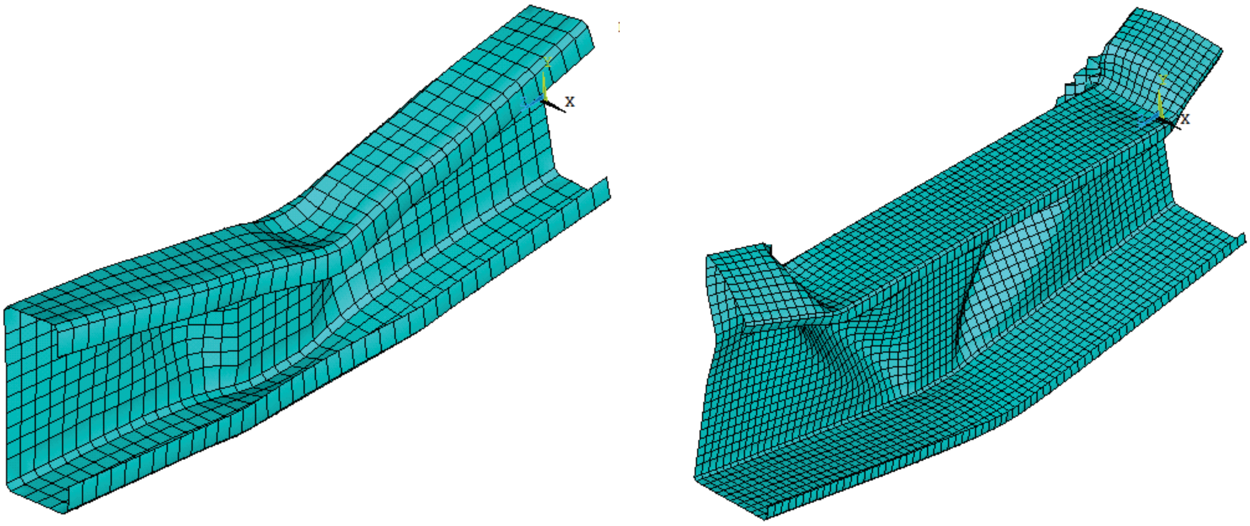


Fig. 3 – DSM Proposed nominal shear curve and shear data (from ANSYS) for V- series and MV- series.

In the Fig. 4, the buckling mode of V-C10024 with straps (Fig.4a) is compared with the buckling mode of V-C25024 with straps (Fig.4b) obtained from ANSYS. Diagonal tension field action has been more developed in case of V-C25024 with straps. For MV series, the ratio of shear span to depth is 2:1 and that's why for long span full tension field action cannot be developed. These results therefore are below the DSM proposed nominal shear curve with TFA. With increasing depth and of lower thickness the points get closer and lie higher above the DSM proposed nominal shear curve with TFA .This might happen due to development of tension field action. When the points are above the DSM curve with TFA it means that the capacity is less than the ultimate strength which is obtained from FE model. It is conservative but still it indicates the safe side. In the case of lower depth and higher thickness, the results are well below the DSM curve with TFA and this might be happened because of not developing full tension field action.



(a) V-C10024-with straps (b) V-C25024-with straps

Fig. 4 – Buckling mode shape.

Local direct strength curve for braced beam (M_{sl}) is demonstrated in Fig. 5, which is based on the Equations 8– 12. Fig. 5 also illustrates all the data for shear (*V*-series), combined bending and shear (*MV*-series) and only bending moment (*M*-series) series and local direct strength curve for braced beam (M_{sl}). Local direct strength curve for Braced Beam (M_{sl})

evaluates conservative results as shown in Fig. 5. Six types of analysis were done with one section and they are only shear with straps, only shear without straps, combined bending and shear with straps, combined bending and shear without straps, only bending with straps and only bending without straps.

The ratio M_T/M_Y which is found from the analysis in shear series, combined bending and shear and only bending series are always above the curve of the DSM proposed nominal moment at local buckling for every sections. Whereas, the moment ratio (M_T/M_Y) for different depths and for a thickness of 1.5 mm are well above the DSM proposed nominal moment curve at local buckling. The ultimate capacity found from FE model is higher than DSM capacity for braced beam at local buckling. So it can be said that the DSM capacity for braced beam at local buckling is conservative.

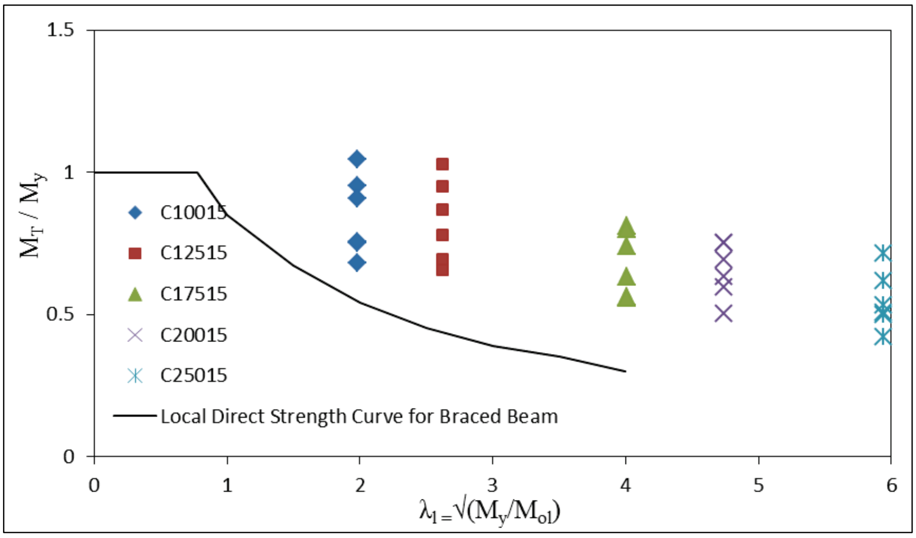


Fig. 5 – DSM proposed nominal moment curve at local buckling and moment data (from ANSYS) of V-series, MV-series and M-series.

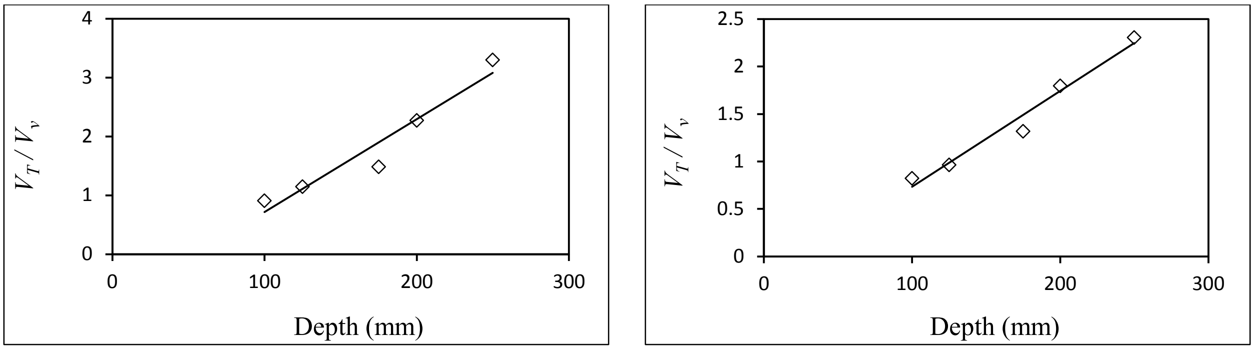
6 Relation between V_T / V_v and depth

Figs. 6 to 7 illustrate the ratio of V_T/V_v versus depth plots for V-series and MV-series. Fig. 6 shows the ratio V_T/V_v vs. depth for thickness of 1.5 mm without TFA. From the Fig. 6a, it is seen that for only shear series with straps with thickness of 1.5 mm and V_v without considering tension field action, the ratio V_T / V_v increases with depth which is shown from regression line. In addition, Fig. 6b outlines the similar behavior without TFA as found for with TFA condition.

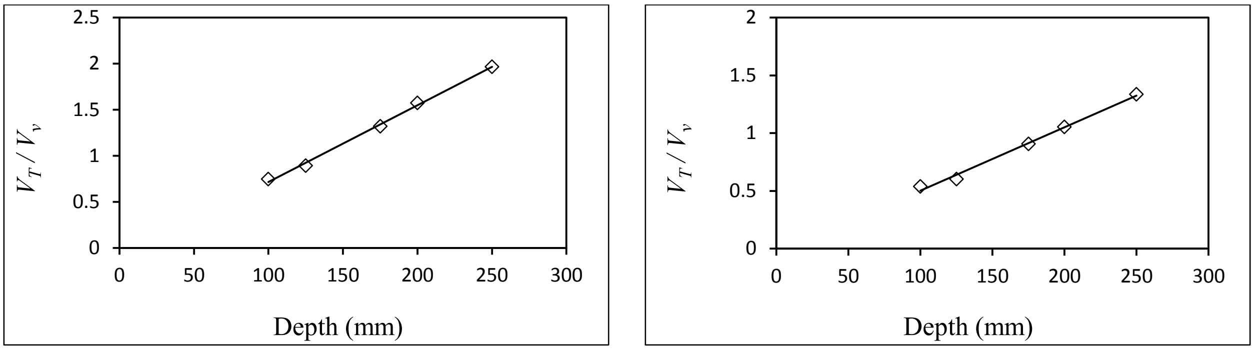
In the case of combined shear and bending moment series, the ratio of V_T/V_v increases linearly against the depth of the section for a specified thickness of 1.5 mm (Figs. 6c and 6d). However, it is seen that straps have significant effects over the ratio and for the straps the ratio is higher than that of without straps condition. This might be happened due to increased stiffness for the presence of straps in the model.

Fig. 7 demonstrates the ratio of V_T / V_v vs depth for thickness of 1.5 mm with TFA. In Figs.7a and 7b for only shear series with tension field action, the ratio of V_T / V_v increases with the depth, however, the slope of regression is mild compared to the slope of regression line for the shear series without considering tension field action. This outlines the ultimate capacity is higher than the nominal capacity when depth increases. With increasing depth, with more buckling potential, the DSM gives reduced capacity than the ultimate capacity and thus, the DSM is more conservative when tension field action is not considered. However, the DSM capacity can be considered whenever tension field action is developed. Conversely, in the case of lower buckling potential for sections, lower depths, the DSM capacity cannot be used since the DSM gives higher capacity than the ultimate capacity.

Fig. 7c illustrates the combined shear and bending moment series with straps for the specified thickness of 1.5 mm in which V_v is considered for tension field action, the ratio V_T/V_v decreases gradually against depth. In addition, Fig. 7d illustrates the similar behavior as observed in Fig. 7c.

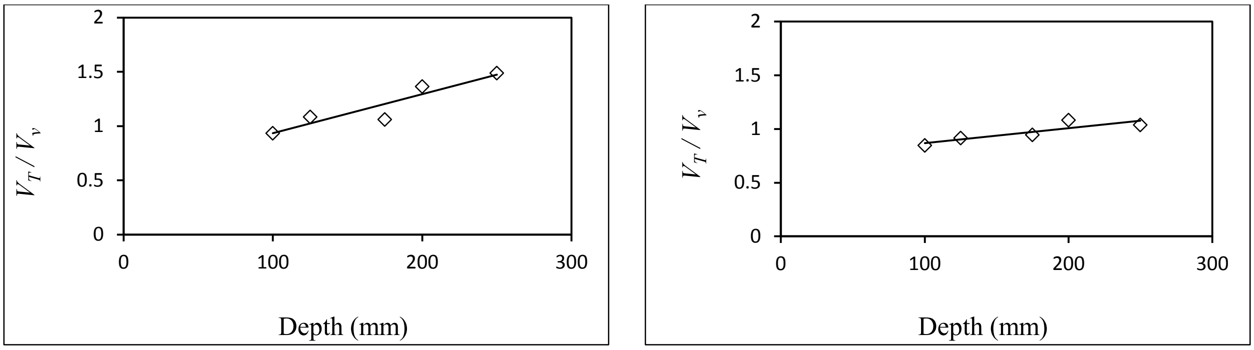


(a) V-C with straps (b) V-C without straps

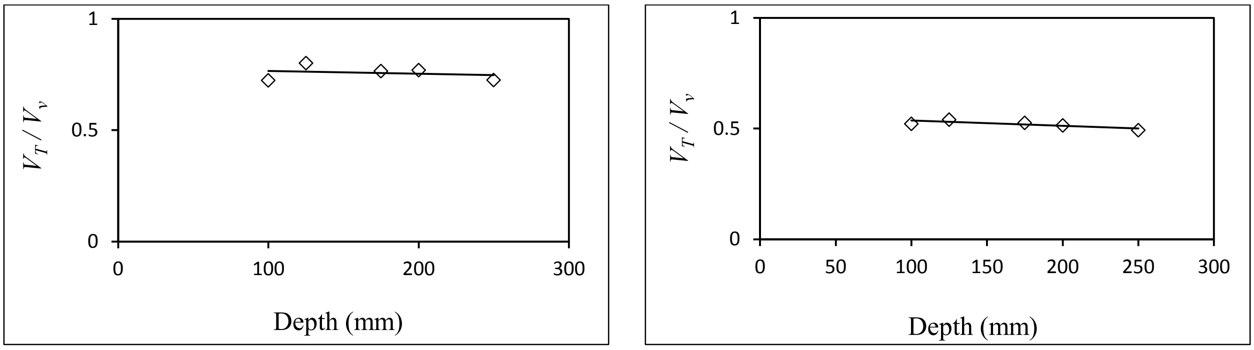


(c) MV-C with straps (d) MV-C without straps

Fig. 6 – V_T / V_v vs depth for thickness of 1.5 mm without TFA



(a) V-C with straps (b) V-C without straps

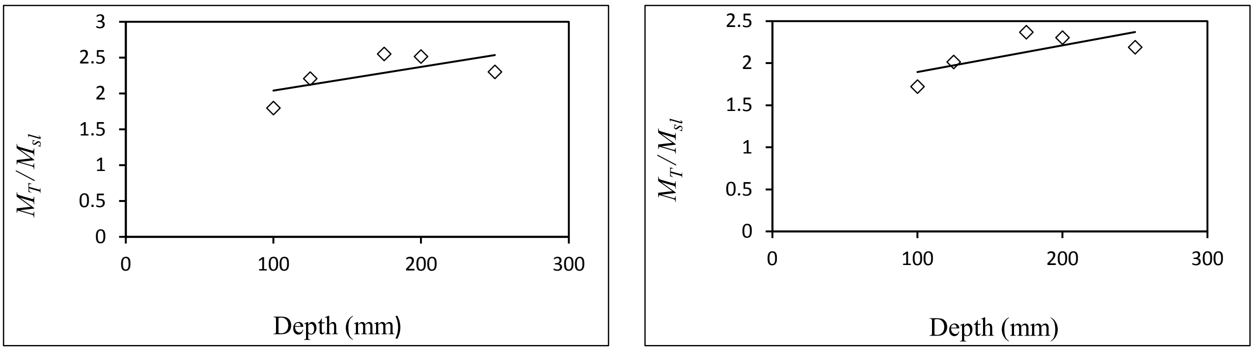


(c) MV-C with straps (d) MV-C without straps

Fig. 7 – V_T / V_v vs. depth for thickness of 1.5 mm with TFA

7 M_T / M_{sl} and depth

For the case of bending series, the distance between the loading points was selected 1000 mm, which is the region of pure bending -there is no shear along that span. The results of only bending series are shown in Fig. 8. Fig. 8a illustrates the ratio of M_T / M_{sl} only bending series with straps, varying from 1.79 to 2.55 for the depth of 100 mm to 250 mm. whereas, the ratio of M_T / M_{sl} for only bending series without straps is shown in Fig. 8b. By comparing the Figs. 8a and 8b, it is found that the ratio is always higher than 1 in both cases. This indicates that the ultimate capacity is higher than the nominal capacity.



(a) M-C with straps (b) M-C without straps

Fig. 8 – M_T / M_{sl} vs depth for thickness of 1.5 mm

8 Conclusion

The study focuses on the finite element (FE) modelling of cold formed plain lipped C-section in shear, and combined bending and shear, which was developed using ANSYS. Hence, a parametric study on plain C-section was conducted to investigate the applicability of the direct strength method (DSM).

The DSM nominal shear capacity equation with TFA (tension field action) cannot be used for lower depth and higher thickness as it gives higher capacity than the capacity found from the FE model. The DSM nominal shear capacity with TFA gives conservative results where buckling potential is prominent. In the case of longer span in combined bending and shear (MV series), the DSM nominal shear capacity equation with TFA might not be used since it gives higher capacity than the simulated capacity. So, it can be concluded that the DSM nominal shear capacity equation with TFA can be used where tension field action is developing in the actual phenomenon of the structure. The range of sizes of the section and structure need to be investigated for design purposes using the DSM. Otherwise, miscalculation of capacity can lead to faulty construction process and structural mishap.

The ultimate moment capacity found from FE model is higher than DSM capacity for braced beam at local buckling. DSM proposed nominal moment at local buckling gives conservative results in shear, combined bending and shear as well as in only bending series (M-series). Therefore, it seems safer to use this rule in the design process.

When tension field action develops, the DSM nominal shear capacity without considering tension field action remains in more conservative side than DSM nominal shear capacity with considering tension field action. On the other hand, when tension field action does not develop, DSM nominal shear capacity without considering tension field action and DSM nominal shear capacity with considering tension field action could not be used. Therefore, it is found from the study that there is a fault in the design rule of DSM nominal shear capacity without considering tension field action.

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