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Finite Element Analyses of Cold-formed Stainless Steel Beams Subject to Shear

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ABSTRACT

Stainless steel is a high-performance construction material that combines the strength and stiffness associated with ferrous alloys with the corrosion resistance derived principally from the high chromium content. Its unique combination of properties usually comes at a cost, which puts increased emphasis on ensuring that the material is utilized to the upmost in structural applications. Consequently, in the recent years, an increase in the use of stainless steel in the construction industry has been witnessed, more specifically in exposed architectural applications and where total life economics, durability, improved resistance to aggressive environment, etc. are prime deciding criteria. However, the shear behaviour and capacity of cold-formed stainless steel beams has not been investigated adequately in the past. Hence, detailed finite element analyses (FEA) were undertaken to investigate the shear behaviour and strength of stainless steel lipped channel beams (LCBs). The developed finite element models were first validated using the shear test results. They were then used in a detailed parametric study to investigate the effects of various influential parameters such as section thickness, depth and grade. Moreover, a parametric study was conducted to emphasize the beneficial effect of strain hardening of stainless steel on shear capacity of LCBs, in particularly for compact sections. FEA results showed that currently available design equations (EN1993-1-4) are inadequate to capture the available inelastic reserve capacity of compact stainless steel LCBs, thus suitable equations were proposed to enhance the predictions. This paper presents the details of finite element modelling and analyses of stainless steel LCBs and the development of these new shear design rules.

Keywords: Finite element modelling, Cold-formed stainless steel, Lipped channel beams, Shear tests and Shear design rules

1 INTRODUCTION

Stainless steel has multiple benefits unlike the conventional carbon steel in both structural and aesthetical aspects. It comes with significant appealing characteristics such as good corrosion resistance, higher strength-to-weight ratio, low maintenance cost, high ductility, impact resistance, greater durability, fire resistance, recyclability in addition to its aesthetically pleasing good finish. However, these benefits come along at a greater cost due to its alloying composition (i.e., chromium and nickel), thus, the material should be utilized to optimum possible level. In achieving this, more focus may be given to the design of stainless steel structural members. Therefore, it is vital to study the structural behaviour of stainless steel members in view of providing optimum and safe design guidelines. Stainless steel can be utilized in a wide range of applications, from structural members to non-structural components, such as cladding. Applications of stainless steel sections can be found in Gardner (1). However, a drawback is the lack of research into shear behaviour of stainless steel LCBs, which is limiting its application in construction.

Stainless steel has a non-linear stress-strain behaviour due to its strain hardening effect which is beneficial in the structural design viewpoint. However, currently available design codes are based on carbon steel design rules which ignore this beneficial material behaviour by incorporating an elastic, perfectly plastic material behaviour. In addition, element interactions present within the cross section; for instance at the web-flange junction for LCBs, tend to enhance the load carrying capacity of the beams (2). However, those design practices rely on the conventional effective width method which considers sections as just an assemblage of elements. Thus, the design codes develop more conservative cross section designs (2; 3).

Consequently, this paper investigates the shear behaviour of LCBs and their capacities, with aim to provide safe and efficient shear design rules to enhance their structural efficiency and range of application. In order to achieve these four different grades of stainless steel from austenitic and duplex stainless steel grades were incorporated in the parametric study. Used stainless steel grades include two austenitic grades of 1.4311 and 1.4318, and two duplex grades of 1.4462 and 1.4662. This paper further discusses, the development of finite element (FE) models of simply supported cold-formed stainless steel LCBs under a mid-span load, then a validation with available shear test results, and thereafter using a detailed parametric study assessing of existing shear design rules in EN1993-1-4 (4).

2 FINITE ELEMENT MODELLING

2.1 FE model development

This section elaborates the development of the FE models which were utilized to study the shear behaviour of LCBs by validation against the experimental results. Validation was done for both stainless steel and cold-formed sections while cold-formed experimental results used for the validation were found from the literature (3). For the development of the FE models, the commercially available FE software ABAQUS CAE 2017 was used. Geometric and material properties, loading and boundary conditions were conducted to suitably simulate the experimental conditions. In FEA, a bifurcation buckling analysis was initially performed to obtain the eigenvectors for the inclusion of geometric imperfections in the non-linear analysis. Then, non-linear static analysis were employed to study the shear behaviour of LCBs up to failure (5).

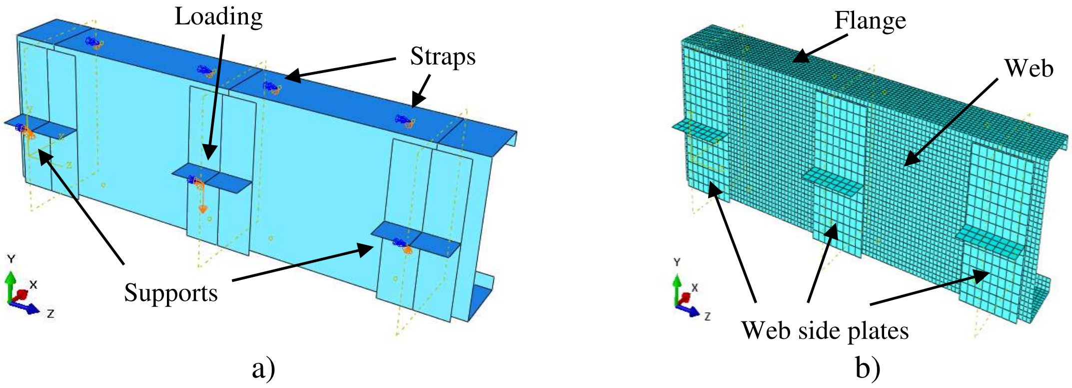


Fig. 1. a) Boundary conditions; b) FE mesh of LCB & web side plate

In the experiments, back-to-back beam setup was used to avoid any torsional effects present. Three full height web plates, each one 45 mm wide were used at the two ends and at the mid span. All considered sections have an aspect ratio (shear span (a) / clear web height (d_1)) of 1.0. More details on the experimental shear test setup of back-to-back LCBs can be found in the literature (3; 6). In the model, single beam sections with shear centre loading (see *Fig. 1.* a)) were used instead to avoid any torsional effect. FE models were developed using available S4R shell elements to simulate the thin section behaviour under shear which can also simulate any local buckling. 5 mm × 5 mm sized mesh (see *Fig. 1.* b)) was able to reach convergence with reasonably good accuracy.

Elastic-linear hardening material model was used to incorporate the strain hardening behaviour of stainless steel. Similar method was followed as proposed previously (1; 7) when developing the material model. Elastic modulus and Poisson's ratio of all the stainless steel grades were taken as 200,000 MPa and 0.3 respectively (4). To simulate the simply supported boundary conditions, pin and roller supports were assigned at the two supports. To simulate the effect of equal angle straps suitable boundary conditions were assigned at strap locations to the flange. Details of conditions used are elaborated below. The u_x, u_y and u_z are translations and θ_x, θ_y and θ_z are rotations in the x, y and z directions, respectively while 0 denotes free and 1 denotes restrained conditions.

- *Left support* : $u_x=1$ $u_y=1$ $u_z=1$ $\theta_x=0$ $\theta_y=0$ $\theta_z=1$
- *Right support* : $u_x=1$ $u_y=1$ $u_z=0$ $\theta_x=0$ $\theta_y=0$ $\theta_z=1$
- *Mid span loading point* : $u_x=1$ $u_y=0$ $u_z=1$ $\theta_x=0$ $\theta_y=0$ $\theta_z=1$
- *Strap locations* : $u_x=1$ $u_y=0$ $u_z=0$ $\theta_x=0$ $\theta_y=0$ $\theta_z=1$

The effect of geometric imperfections to the model was introduced through the *IMPERFECTION option which is available in ABAQUS. The imperfection coefficient was taken as the $0.006d_1$ for all the models. The manufacturing process of LCBs introduce residual stresses in thin stainless steel sections. However, the effect of these residual stresses was not taken into account, as according to Keerthan and Mahendran (8) the effect of residual stress on the shear capacity of channel sections is about 1%, thus it is negligible (9). More details of geometric imperfections and residual stresses can be found in the literature (10).

2.2 Validation

The validation process of developed FE models was performed for both stainless steel and cold-formed steel LCB sections. More details of cold-formed tests can be found in Keerthan and Mahendran (3). *Table 1* summarises the validation results for stainless steel sections while *Table 2* summarises the results for cold-formed steel sections. d_1 and t_w are the clear web height and web thickness of the section, respectively and f_{yw} and f_u are the yield stress and ultimate stress of the steel grade, respectively.

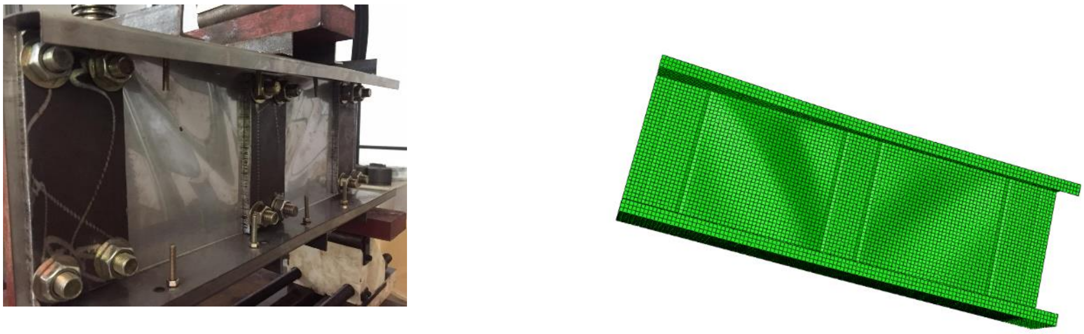
Table 1. Validation results for stainless steel sections

No.	LCB section	d_1 (mm)	t_w (mm)	f_{yw} (MPa)	f_u (MPa)	Shear Capacity (kN)		Test/ FEA
						Test	FEA	
1	200×75×15×1.2	197.0	1.18	240	540	23.0	22.3	1.03
2	150×65×15×1.2	147.0	1.18	240	540	21.6	19.6	1.10
3	150×65×15×1.5	147.0	1.5	240	540	26.3	27.1	0.97
4	150×65×15×2.0	146.5	1.99	240	540	43.6	40.7	1.07
5	100×50×15×2.0	95.5	1.99	240	540	36.0	34.2	1.05

Table 2. Validation results for cold-formed steel sections

No.	LCB section	d_1 (mm)	t_w (mm)	f_{yw} (MPa)	Shear Capacity (kN)		Test/ FEA
					Test	FEA	
1	120×50×18×1.5	116.8	1.49	537	43.3	47.8	0.91
2	120×50×18×1.95	118.6	1.95	271	38.1	34.9	1.09
3	160×65×15×1.5	157.5	1.51	537	54.5	55.2	0.99
4	160×65×15×1.9	156.8	1.92	515	73.8	77.6	0.95
5	200×75×15×1.5	197.0	1.51	537	57.0	61.9	0.92
6	200×75×15×1.95	198.0	1.93	271	55.1	50.1	1.10

From the results, it can be seen that the elaborated FE models were able to predict ultimate shear capacities of tests with good accuracy. The mean and coefficient of variance (COV) of the results are 1.04 and 0.047, respectively for the stainless steel sections and 0.99 and 0.084, respectively for the cold-formed steel sections. Furthermore, a comparison was conducted to show the ability of the FE models to capture the failure modes correctly. *Fig. 2* presents the shear failure mode of stainless steel 200×75×15×1.2 LCB section as captured during the experiment and from the FE model.



a) b)

Fig. 2. Shear failure mode of 200×75×15×1.2 stainless steel LCB: a) Experiment; b) FE model

In order to gather more data on the shear behaviour of stainless steel LCB sections, a comprehensive parametric study was carried out comprising of 65 different models following the validation process. Four different common LCB sections, LCB120×50×15, LCB145×62.5×20, LCB200×62.5×20 and LCB265×65×20 with an aspect ratio of 1.0 were employed in the parametric study. Seven different thicknesses (1 mm, 1.3 mm, 1.5 mm, 2 mm, 3 mm, 4 mm and 5 mm) were used to cover a wide range of slenderness values. Furthermore, austenitic stainless steel grades of 1.4311 and 1.4318, and duplex stainless steel grades of 1.4462 and 1.4662 were used in the analyses.

The parametric study was further extended in order to emphasize on the effect of strain hardening to the shear behaviour of LCBs. For that, the shear capacity of nine compact sections and four slender sections of stainless steel grade 1.4311 was compared with the results obtained without considering the strain hardening effect. Herein, the limiting stress was taken as the yield stress (f_y) of grade 1.4311. *Table 3* below summarises the shear capacity and percentage increment of strength for each section.

Table 3. Comparison of shear capacity of LCBs with & without strain hardening

LCB section	t_w (mm)	d_1/t_w	Shear capacity (kN)		% Increment
			With strain hardening	Without strain hardening	
120×50×15×5	5.0	22.0	142.9	89.2	60.20
120×50×15×4	4.0	28.0	110.5	71.7	54.11
120×50×15×3	3.0	38.0	73.9	53.4	38.39
145×62.5×20×5	5.0	27.0	167.1	108.2	54.44
145×62.5×20×4	4.0	34.3	119.3	86.4	38.08
145×62.5×20×3	3.0	46.3	79.3	64.4	23.14
145×62.5×20×2	2.0	70.5	44.8	42.0	6.67
200×65×20×3	3.0	64.7	94.0	81.8	14.91
265×65×20×3	3.0	86.3	108.5	99.4	9.15
145×62.5×20×1	1.0	143.0	18.1	17.9	1.12
200×65×20×1	1.0	198.0	20.3	20.0	1.50
265×65×20×1.3	1.3	201.8	33.0	32.4	1.85
265×65×20×1	1.0	263.0	21.7	21.3	1.88

Results highlight that strain hardening has a considerable effect on shear capacity of compact sections while that for slender sections can be neglected. This inelastic reserve capacity is more pronounced when $d_1/t_w < 28$ where more than 50 % increment for shear capacity can be achieved with the effect of strain hardening. Similar inelastic reserve capacity for compact sections were observed by Sonu and Singh (11) for stainless steel rectangular hollow sections. The FE results obtained from the parametric studies were then used to assess the applicability of the currently available EN1993-1-4 (4) shear capacity predictions, and based on the comparisons, new guidelines were also proposed.

3 EN1993-1-4 SHEAR DESIGN RULES

The ultimate shear capacities obtained from test results and parametric study results were compared with the current EN1993-1-4 (4) predictions for the stainless steel LCBs. *Fig. 3* compares the experimental and FE predictions with EN1993-1-4 (4). The mean and coefficient of variance (COV) of the FE (and experimental) predictions to code predictions are found to be 1.06 and 0.063, respectively. From *Fig. 3*, it can be seen that when web slenderness (λ_w) is smaller than 0.4, the current design rules tend to considerably underestimate the shear capacity of LCB sections. Following a regression analysis, new provisions for web shear buckling reduction factor (χ_w) were suggested and are presented in *Table 4* in a similar manner as in the literature (11).

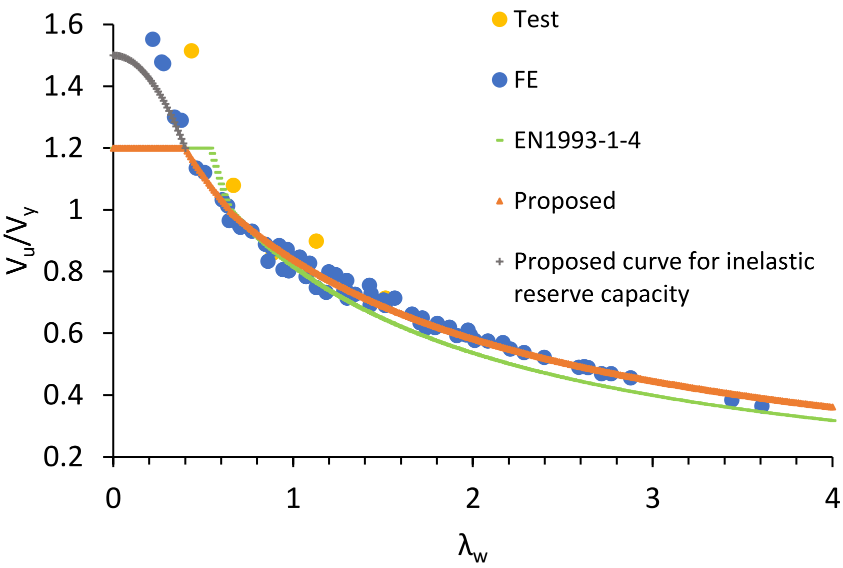


Fig. 3. Comparison of FE & EN1993-1-4 shear capacity predictions

FE (and experimental) predictions to proposed predictions have a mean and coefficient of variance (COV) of 1.01 and 0.061, respectively. Furthermore, to predict inelastic reserve capacity in shear for compact stainless steel LCB sections (when $\lambda_w < 0.4$) an expression of ($-1.875\lambda_w^2 + 1.5$) can be used as shown in *Fig. 3*.

Table 4. Current and proposed EN1993-1-4 expressions to calculate web buckling coefficients (χw)

Current EN1993-1-4 (4)		Proposed	
	χ_w		χ_w
$\lambda_w \leq 0.65/\eta$	η=1.2	$\lambda_w \leq 0.48/\eta$	η=1.2
$0.65/\eta < \lambda_w < 0.65$	$0.65/\lambda_w$	$0.48/\eta < \lambda_w < 0.65$	$1.5/(0.85+\lambda_w)$
$0.65 \leq \lambda_w$	$1.56/(0.91+\lambda_w)$	$0.65 \leq \lambda_w$	$1.901/(1.261+\lambda_w)$

According to *Fig. 3*, it can be clearly seen that proposed web shear buckling reduction factors (χ_w) were able to capture FE predictions well when web slenderness (λ_w) is greater than 0.4. In order to confirm the available inelastic reserve capacity in shear for stainless steel compact LCBs further shear tests are required.

4 CONCLUDING REMARKS

The paper discusses the detailed FE modelling of the shear behaviour of stainless steel and cold-formed steel LCBs. FE models were validated with available test results and highlighted the ability to predict the shear capacity and failure modes with good accuracy. From the parametric study, the beneficial effect of strain hardening of stainless steel on shear capacity, especially in compact LCB sections, was observed. It was found that more than 50 % strength increment can be achieved by taking strain hardening effect when $d_1/t_w < 28$. Further, parametric studies were conducted to assess the applicability of EN1993-1-4 (4) in predicting the shear capacity of LCBs while using linear regression analysis. Suitable expressions for web shear buckling coefficient (χw) were proposed to enhance the prediction accuracy. Results demonstrated that shear capacity predictions according to EN1993-1-4 (4) are too conservative for compact sections (when $\lambda_w < 0.4$). Thus, an alternative expression was derived to capture the considerable inelastic reserve capacity in compact sections.

5 ACKNOWLEDGEMENT

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