CONTACT BUCKLING EFFECTS IN BUILT-UP COLD-FORMED STEEL BEAMS

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Abstract: The aim of this paper is to investigate the effects of contact interactions on local buckling of a built-up cold-formed steel member assembled by mechanical fasteners. To this end a finite element model was developed. The numerical model was validated against the experimental results of four point bending tests carried out on three specimens with different spacing of connections and configuration of web beads. The comparison with experimental results showed a good agreement with test data in terms of both the ultimate bending strength of the beam and the deformed shape at collapse. The calibrated finite element model was used to estimate the effects on buckling resistance of contact forces among the parts of the beam, varying the spacing of connections.

1. INTRODUCTION

The present paper presents the results of an experimental and numerical investigation on a riveted built-up cold-formed patented beam and it is aimed to assess contact buckling effects on the post-buckling response. The study was carried out within the activities of a research project aimed at comparing the effectiveness of different types of connection systems for the developed beams, including mechanical fasteners and laser welding [1, 2]. Other research activities were concerned with the effects of the rolling process and cold-work on the base material and with the evaluation of the shear strength of different connecting systems [3, 4].

The built-up cold-formed beam investigated in the present study is patented with the name of Modular Light-weight Cold-Formed Beam (MLC Beam).

The beam is made of two cold-formed C-shaped profiles assembled back to back, so that an I cross-section, with hollow flanges, is formed. The two profiles are jointed with mechanical fasteners, distributed on the web and on the flanges of the beam. Two reinforcing plates are placed inside the top and bottom hollow flanges of the I-section, providing a flange connection system between the two C-profiles (Fig. 1). To prevent early buckling phenomena, intermediate and edge flange stiffeners, web beads and web openings are used.

Due to web and flange stiffeners and to the configuration of the cross-section, the bending and post-buckling behaviour of the beams is strongly affected by different sources of nonlinearities. To design the beams, an assisted by testing approach was followed based on four-point bending tests and a finite element model was developed to support experimental investigation.

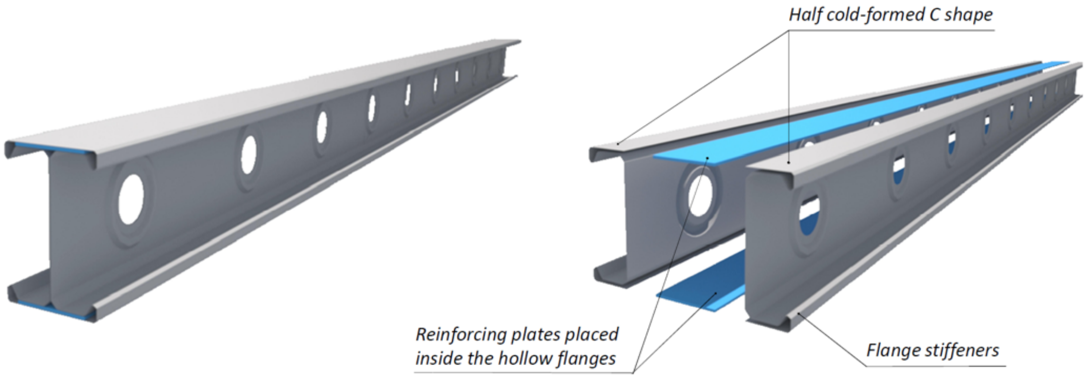


Fig. 1: MLC Beams.

The developed numerical model was then calibrated and validated on the basis of obtained test results and was applied to the analysis of the influence on the bearing capacity of the connection spacing and contact interactions.

In the following, a description of the test set-up and of the implemented numerical model is presented. The results of experimental tests and finite element analysis are compared and the effects of contact interactions on buckling response are discussed.

2. EXPERIMENTAL INVESTIGATION

In this section the performed four-point bending tests, carried out with the aim to investigate the load bearing capacity of the members, are presented.

The nominal cross-section depth (H) of MH MLC beams under investigation is 300.0 mm and the flange width (B) is 200.0 mm. The C-profiles are 2.0 mm thick and are obtained through cold forming process of S235JR steel sheet. The sheets are connected along the web and the flanges by means of different bi-component blind rivets (Avdelok type), with diameter 6.5mm and 10.0 mm respectively. Steel reinforcing plates of 6.0 mm thick are placed inside the hollow flanges in order to increase the load bearing capacity. The span (L_0) of the beams is 5800 mm.

The main geometric details of the MH MLC beams are shown in Figure 2.

The testing program included three prototypes manufactured with different configurations of rivet spacing (d_f) and web stiffeners (d_0) in order to evaluate the effects on the buckling and post-buckling behaviour (Table 1).

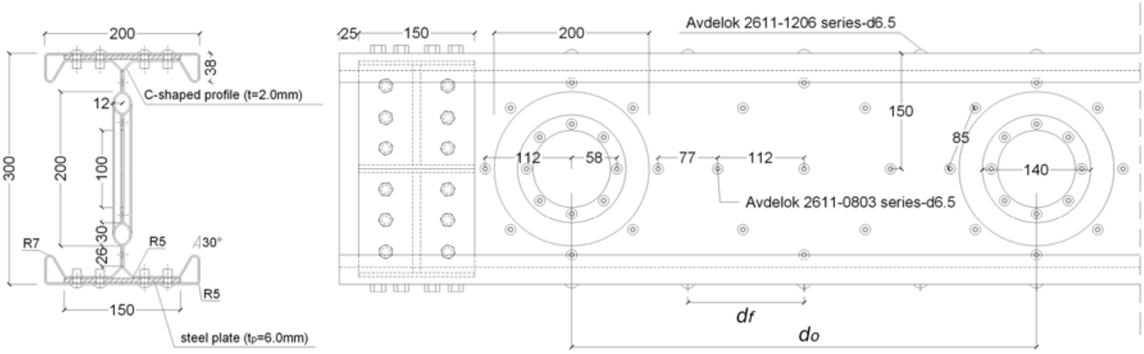


Fig. 2: Geometric dimensions and details of the MH MLC Beam.

a) b)

Fig. 3: Test set-up.

Table 1: Testing programme.

Specimen ID	d_o *(mm)*	d_f *(mm)*	t_p *(mm)*
MH MLC 1	-	150	6.0
MH MLC 2	600	150	6.0
MH MLC 3	600	300	6.0

d_o=spacing of web beads; d_f=spacing of connections; t_p=thickness of reinf. plates

The summary of the experimental results, both in terms of force-deflection curves (F - δ) and collapse modes, is shown in Figure 4. The identified experimental parameters are reported in Table 2. Those are: the elastic limit force F_{el}, calculated according to [12], the ultimate load F_u ,corresponding to the peak of the loading curve, the corresponding elastic and ultimate displacements δ_{el} and δ_u and the bending stiffness of the beams, $K_{0,}$ calculated as the initial tangent modulus of the loading curve.

The ultimate loads measured from the tests range from 123.3 kN for the MH MLC2 to 89.4 kN for the MH MLC 3. The ultimate deflections are included in the interval 32.6 ÷ 60.8 mm, corresponding to MH MLC 3 and the MH MLC 2 respectively.

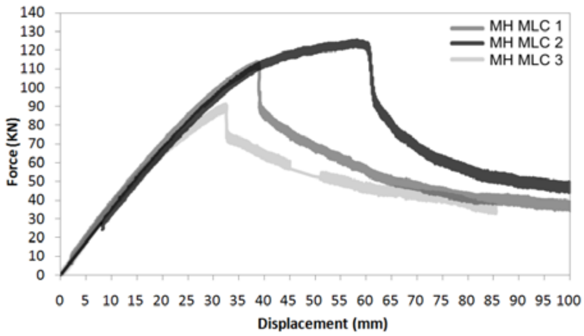
The beams collapsed with a local buckling mode between the fasteners of the reinforcing plate placed inside the hollow flanges.

The comparison between the tests carried out on the specimens MH MLC2 and MH MLC1 allow to evaluate the influence on the flexural response of the circular web beads. The web beads modified significantly the structural response, increasing the ultimate load of about 10% and even more the ultimate deflection δ_u. As for the bending stiffness $K_{0,}$ it can be observed that web openings and stiffeners slightly affect the response.

The influence of connection spacing on the flanges is assessed comparing the structural response of the MH MLC2 (fasteners spacing equal to 150 mm) with MH MLC3 (fasteners spacing equal to 300 mm). Due to interfastener buckling, the collapse load of the specimen MH MLC3 is 30% lower than the MH MLC2. In addition, in this case also the ultimate deflection is strongly reduced.

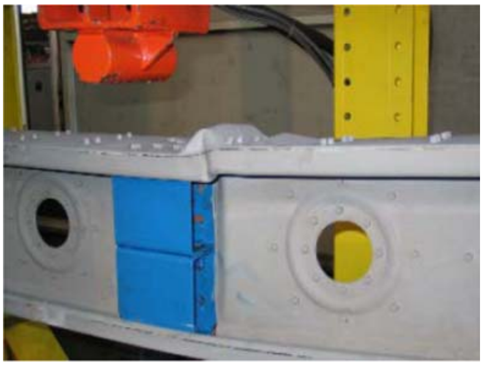
Table 2: Experimental results.

Specimen ID	K_0 (kN/mm)	F_{el} (kN)	F_u (kN)	δ_{el} (mm)	δ_u [mm]	M_u/M_y
MH MLC 1	3.57	72.8	112.2	20.2	38.9	0.87
MH MLC 2	3.25	90.5	123.3	27.6	60.8	0.95
MH MLC 3	3.50	56.4	89.4	15.9	32.6	0.69



a)

b) MHMLC1. Local buckling at 100.0 mm deflection



c) MHMLC2. Local buckling at 120.0 mm deflection

d) MHMLC3 – Local buckling at 85.0 mm deflection

Fig. 4: Experimental load deflection curves of the MLC Beams (a) and buckling modes (b-d).

The experimental ultimate bending moment M_u have been compared with the yield values M_y, which have been evaluated by considering the gross cross-section properties. The ratio M_u/M_y is lower than 1.0 for all the tested beams, showing that the failure modes which have to be ascribed to the buckling between the fasteners, do not allow all the plastic reserves to be achieved. As a consequence, according to Eurocode 3, the cross-section of the examined beams can be classified as class 4.

3. THE FINITE ELEMENT MODEL

The FE model of built-up beams was developed in ABAQUS. The details of the numerical model are given in the following.

3.1 Geometric model

A parametric generation of the models of the beams was carried out by using the scripting language. To reduce computational time, half part of the tested beams was modelled.

S4R elements were used to model cold-formed sheets and steel plates. The mesh size is 15.0 mm.

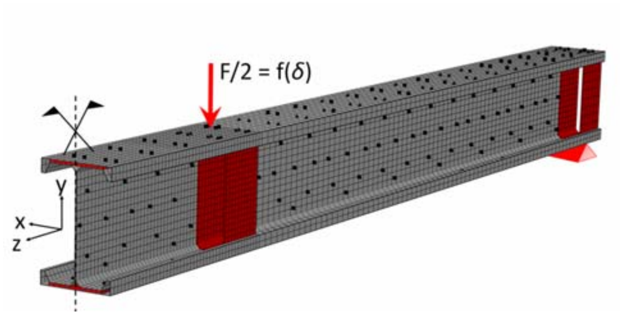


Fig 5: The finite element model of the MH MLC 1 beam [5].

3.2 Material modelling

The material model used for steel sheets and reinforcing plates was elastic-perfectly plastic. The selected plasticity model is based on von Mises yield surface with associated plastic flow. The assumed Young's modulus and Poisson's ratio were 210000 N/mm^2 and 0.3 respectively. The average yield strength was assumed equal to 270 N/mm^2.

3.3 Modelling of fasteners

For the assessment of the structural response of built-up members, a key aspect is represented by the modelling of mechanical fasteners. The approach proposed herein, for simulating the connection elements, is macro-modelling. In this case, a coarse discretization of the different parts of the built-up member is adopted and a beam element can be used for the FE model of the fasteners.

The connections were modelled using the mesh-independent fastener capability. Connector elements CONN3D2 were used to define fasteners. To implement the connections, a single attachment point was considered for each fastener .

Elastic behaviour was assumed for connections and no rotational stiffness was considered in the analysis.

The stiffness of the fastener elements was calibrated on the basis of the elastic response of the beams measured from tests.

The degrees of freedom of the fastening point were coupled to the adjacent nodes in a region of influence by a distributed coupling constraint. To assign the group of nodes on the surfaces near the fastening point a radius of influence of 10.0 was set. The default CONTINUUM coupling method was selected. The method couples the translation and rotation of each fastening point to the average translation of the group of coupling nodes on each of the fastened surfaces. The weighting method for the distributed coupling constraints created was UNIFORM.

3.4 Contact modelling

Surface-to-surface general contact capability in ABAQUS was selected as modelling approach to take into account the interactions at the flanges and at the web.

In particular, three surface interactions were defined, that is between the reinforcing plate and the upper and lower elements at the top flange and between the two sheets of the web.

The discretization method was node-to-surface and small sliding formulation was used. Shell element thicknesses were excluded in contact calculations. As for contact interaction properties, the frictionless formulation was selected for tangential behaviour. The HARD CONTACT and separation algorithm was used as contact pressure-overclosure relationship to define the normal behaviour. The augmented Lagrange method was used as constraint enforcement model.

All other parameters were set to default values.

3.5 Loading and boundary conditions

The model was loaded under displacement control applying a maximum displacement equal to 100.0mm at the load points. The free-end cross section behaviour was assumed to be rigid. With this aim, a kinematic coupling was applied at the relevant group of nodes, in order to constrain both translational and rotational degrees of freedom to the rigid body motion of a reference node placed at the center of cross-section.

3.6 Analysis type and nonlinear solution method

A non-linear static analysis including large-deflection effects was performed. The Newton Rapshon method was selected for solution control.

Automatic stabilization algorithm was used for the solution of non-linear problem. To stabilize the unstable quasi-static problem, an additional volume-proportional damping to the model was considered. The applied damping factors were calculated from a dissipated energy fraction set equal to the default value of 2.0×10^{-4}.

3.7 Geometric imperfection modelling

Geometric imperfections were introduced in the model with a sine-shape mode assigned to the inner plate of the flanges, with wavelength corresponding to the first buckling mode between the fasteners.

The amplitude of imperfections was calibrated on the basis of the load carrying capacity measured from the results of the four point bending test.

The value of the width to thickness ratio for the imperfection that was used to match the maximum load measured from tests of 112.2 kN was equal to 0.006 [5].

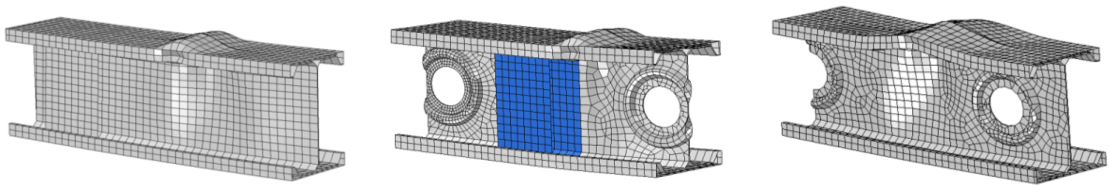
4. COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS

The results of the finite element analysis are reported in Table 3. Numerical load-deflection curves for MHMLC1 and MHMLC2 are shown in Figure 6. In the first case the response obtained with the full-length model is reported as well. The comparison with experimental results shows that the curves are well fitted by the numerical responses in the elastic range and up to the failure load, even if differences in the postbuckling branch can be noted.

The collapse behaviour observed in the test is well reproduced by the deformed shapes of the numerical models as well (see Fig.4, 6). Slight differences in the position and wavelength of buckling shapes in the web can be noted.

Table 3: Comparison of numerical and experimental results.

Specimen ID	$F_{u,Exp}$ (kN)	$F_{u,FE}$ (kN)	$F_{u,Exp} / F_{u,FE}$	$\delta_{u,Exp}$ (mm)	$\delta_{u,FE}$ (mm)	$\delta_{u,Exp} / \delta_{u,FE}$
MH MLC 1	112.2	109.2	1.03	38.9	39.5	0.98
MH MLC 2	123.3	124.7	0.99	60.8	59.6	1.02
MH MLC 3	89.4	94.3	0.95	32.6	35.4	0.92



(MH MLC 1) (MH MLC 2) (MH MLC 3)

Fig. 6: Comparison of numerical and experimental deformed shapes. Deformation scale factor 1.0.

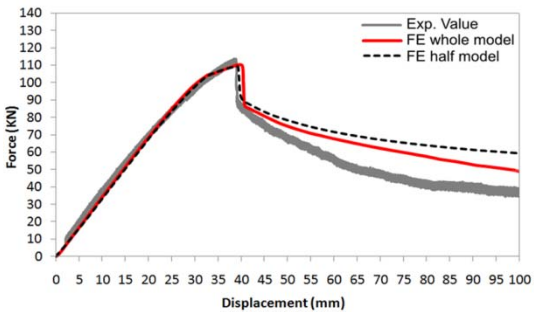


Fig. 7: (F - δ) curve of MH MLC 1.

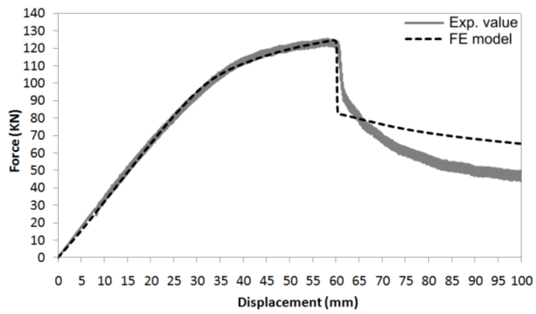


Fig. 8: (F - δ) curve of MH MLC 2.

5. ANALYSIS OF CONTACT BUCKLING

To evaluate the effects of contact interactions on the flexural strength of the beams, a numerical analysis of the models with and without contact interactions was carried out for different connection spacing.

The comparison of predicted response curves is shown in Fig. 9. According to the results obtained from the implemented finite element models, the failure load is slightly influenced by contact forces between the cold-formed section and the reinforcing plate in the hollow flange of the beams. In particular, contact effects increase the load bearing capacity up to 11% for spacing of fasteners along the flanges equal to 150.0mm.

More remarkable is the influence of contact interaction on ultimate displacements. The maximum increment obtained from numerical analysis is about 32% and is calculated for the spacing of 250.0mm.

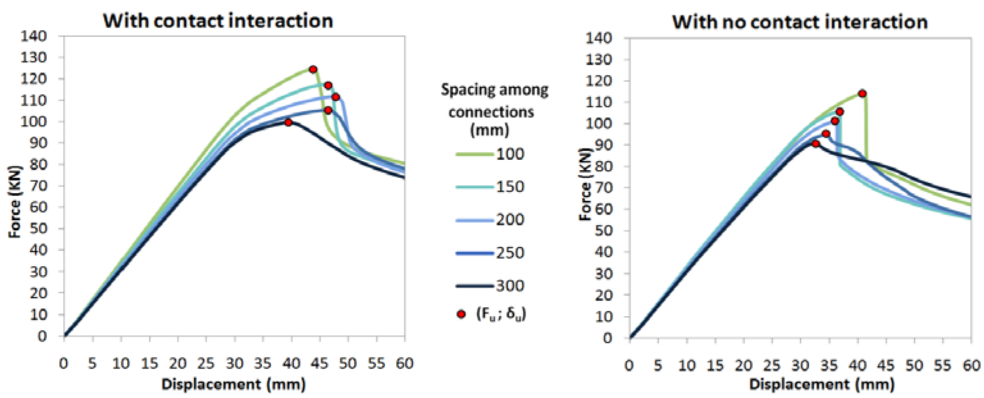


Fig. 9: Comparison of (F - δ) curves for different connection spacing.

6. CONCLUSIONS

In this paper, the results of experimental and numerical investigation on built-up cold formed steel beams assembled with mechanical fasteners were presented.

The aim of the study was to assess the influence of connection spacing, web beads and contact interactions on the load bearing capacity of the beams.

The results of experimental tests showed that the bending stiffness of the beams is just slightly influenced by web openings, web beads and spacing of connections along the flanges. In particular the use of web stiffeners decreases the bending stiffeners of 0.1% respect to the specimen with no beads. Also doubling the spacing of connections does not remarkably affect the bending stiffness of the investigated beams.

With regard to the effects on the load bearing capacity, it has been shown that the web beads increase the ultimate load of 10%, while spacing the connection from 150 mm to 300 mm produces a reduction of 30%.

The ultimate deflection is remarkably influenced both by spacing of connections and by the web beads. In particular it has been observed that reducing the spacing of connections on the flanges and introducing the beads on the web increase the inelastic deformation capacity by 85% and 60% respectively.

To support experimental investigation and to analyze the effect of contact interactions on the predicted response varying the spacing of connections, parametric analysis were carried out on a finite element model developed in ABAQUS. The analysis showed that for the investigated beams the ultimate load is slightly affected. Remarkable is the influence on the ultimate displacement at the buckling load, which is affected up to 30%.

References

[1] Landolfo R, Di Lorenzo G, Portioli F, Guerrieri M.R. "Performance of built-up cold-formed steel beams assembled with mechanical and laser welded connections", *Proc. of 5th European Conf. on Steel and Composite Structures (EUROSTEEL 2008)*, Graz, Austria, 3-5 Sept 2008. Vol A. (pp.699-704). ISBN: 92-0147-000-90. Ed. R. Ofner et. al. ECCS Brussels, Belgium, 2008

[2] Landolfo R, Mammana O, Portioli F, Di Lorenzo G, Guerrieri M.R. "Laser welded built-up cold-formed steel beams: Experimental investigations", *Journal of Thin-Walled Structures* 46, 781– 791. Elsevier, 2008.

[3] Di Lorenzo G, Landolfo R. "Shear experimental response of new connecting systems for cold-formed structures", *J. of Constructional Steel Research*, n.60, 561-579, 2004.

[4] Di Lorenzo G, Portioli F, Landolfo R. "On the characterization of the material properties for cold-formed steel members", *Proc. of the 4th Int. Conf. on Thin-Walled Structures (ICTWS 2004)*, Loughborough, England, 2004.

[5] Portioli, F., D'Amico, B., Di Lorenzo, G., Landolfo, R. "Modelling of geometric imperfections in numerical simulations of built-up cold-formed steel beams", *Proc. of the 6th Int. Conf. on Thin Walled Structures "Recent research advances and trends"-ICTWS2011*, Vol.1, pp. 345-352. Timisoara, Romania, 2011.