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ANALYSIS OF CONTACT BUCKLING IN BUILT-UP COLD-FORMED STEEL BEAMS ASSEMBLED BY LASER WELDING

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Abstract. *To investigate the effects of contact interactions on local buckling of a built-up cold-formed steel member assembled by laser welding a finite element model was developed. The numerical model was validated against the experimental results of a four point bending test on a full scale specimen. A good agreement with test data was observed both in terms of ultimate bending strength and deformed shape at collapse. The calibrated finite element model was used to estimate the effects on buckling resistance of contact forces between the parts of the beam by varying the connection spacing on the flanges. As a main result, it was shown that contact interactions influence remarkably the ultimate strength of the beam and that their effects decrease with decreasing spacing of connections.*

1 INTRODUCTION

The study presented in this paper is a part of the research activities carried at the University of Naples aimed at developing a special type of built-up cold-formed beam using laser welding as a connecting system.

The member is composed of double C-sections back-to-back, which form an I section beam with hollow flanges. The two C-profiles are connected with laser welds 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, in order to improve the load bearing capacity and to provide an additional connection system between the two C-profiles. The shape of the beam is also characterized by intermediate and edge flange stiffeners, circular web beads and web openings.

The prediction of the flexural and shear strength of developed beam depends on several parameters and involves material and geometric non-linearities as well as contact interactions. One of the most important parameters influencing the bending capacity of the beam is the connection spacing. The strength to local buckling which occurs between laser welds is strictly related to spacing. Connection arrangements should be determined in order to avoid early buckling phenomena and on the basis of technological and economical requirements.

It is clear that varying the spacing of connection the influence of contact interaction among the different parts of the developed beam changes. The analysis of buckling and post-buckling behavior of considered built-up cross section is quite difficult from the analytical point of view. Several studies can be found in the literature related to the assessment of contact buckling. In general, the results presented in these studies are relevant to unilaterally constrained plates and assume that the type of constraint is rigid

[1, 2]. On the contrary, the interactions in the beam which is considered in this work involve contacts between deformable surfaces with different boundary conditions.

To investigate the load bearing capacity of the members, four-point bending tests were carried out on full-scale prototypes. According to a specific testing program, the beams were manufactured with different spacing of connections along the flanges in order to evaluate the effects of weld configuration on the load bearing capacity. The results of this activity were described in [3].

In order to support experimental tests and to assess the effects of contact buckling on the selected beams, a numerical investigation was carried out.

The results of a preliminary numerical analysis carried out on a finite element model implemented in ANSYS have been presented in [4]. In this case only one half of the cross section of the selected beam was simulated since a symmetric behavior of the specimen under bending load was assumed along transversal direction and symmetric buckling modes were considered. The developed finite element models were relevant to the tested beams, with different spacing and arrangements of connections on the flanges.

In this paper, the results of a new model developed in ABAQUS are presented. The aim of the analysis was to assess the influence of interactions in contact buckling on the flexural strength of the beam for higher values of the spacing than previously considered by using a geometric model with full cross-section.

2 THE FINITE ELEMENT MODEL

The FE model of built-up beam assembled by laser welding was implemented in the ABAQUS finite element software package [5]. The details of the used modeling approach are given in the following.

2.1 Geometric model

A parametric generation of the model of the beam was carried out by using the scripting language.

To reduce computational time, only a part of the beam under uniform bending moment in the four point test was modeled. The length of the model is 900 mm. The cross-section depth H is 300 mm and the flange width B is 200 mm. The thickness t of the C-profiles obtained through cold forming process of steel sheets is equal to 2.0 mm. The nominal thickness of the reinforcing plates placed inside the hollow flanges is 6.0 mm and the width is 150.0mm. The depth of flange stiffeners is 38.0mm. The spacing of circular web beads is 600.0mm. The external and internal radius are 100.0 and 70.0 mm, respectively. The geometric dimensions of the web beads and flange stiffeners were assigned according to previous experimental studies carried out on MH MLC assembled with mechanical fasteners [6].

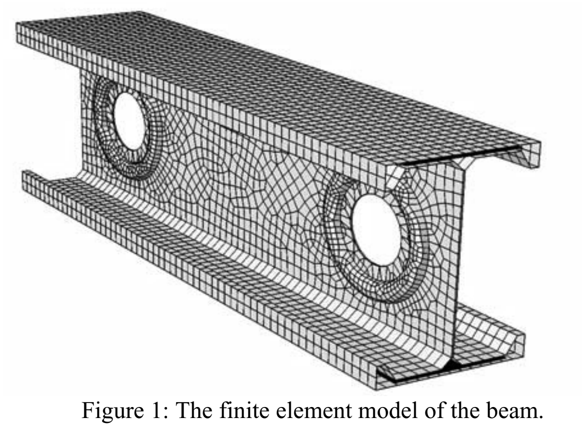

Figure 1: The finite element model of the beam.

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

2.2 Material modeling

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 320.0MPa. The effects of cold bending and rolling were neglected in the present study.

2.3 Modeling of laser welds

The profiles were connected by means of laser welds with nominal thickness t_w = 1.5 mm and with lengths l_w equal to 20.0 mm and 30.0 mm along the web and the flanges, respectively. The selected spacing of connections is 150.0mm and the arrangement on the flanges is in line.

The configuration of laser welds is illustrated in Fig. 2.

The connections were modeled using the mesh-independent fastener capability. Connector elements CONN3D2 were used to define fasteners. To implement the connections, two attachments points at each end of laser welds were considered with the exception of welds around the circular holes, which were modeled with a single attachment point.

Rigid behavior was assumed for connections and no rotational stiffness was considered in the analysis.

The motion of the fastening point was coupled to the motion of the 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.

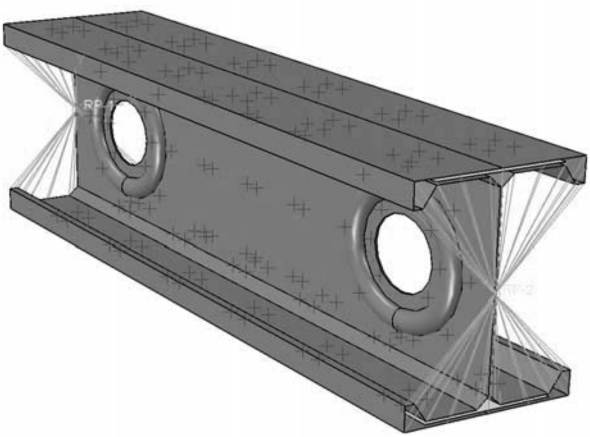

Figure 2: Boundary conditions and attachments points defined for the definition of laser welds.

2.4 Contact modeling

Surface-to-surface general contact capability in ABAQUS was selected as modeling 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 (Fig. 3).

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 behavior. The hard contact and separation algorithm was used as contact pressure-overclosure relationship to define the normal behavior. The augmented Lagrange method was used as constraint enforcement model.

All other parameters were set to default values.

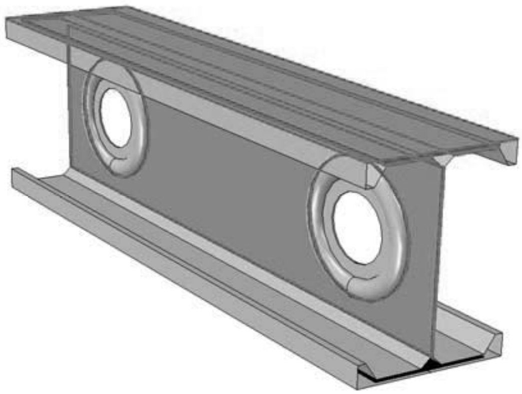

Figure 3: Detail of surfaces with contact interactions at the top flange and the web.

2.5 Loading and boundary conditions

The model was fixed at one end and loaded under displacement control applying a maximum rotation equal to 0.03 rad at the free end of the beam. The free-end cross section behavior 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.

2.6 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 constant over the duration of the analysis and were calculated from a dissipated energy fraction set equal to the default value of 2.0×10^{-4}.

3 RESULTS OF NON-LINEAR STATIC ANALYSIS

In this section, the moment-rotation curves obtained from numerical analysis are presented and the predicted buckling behavior is described.

The response of the beam determined by the implemented finite element model is given in Fig. 3.

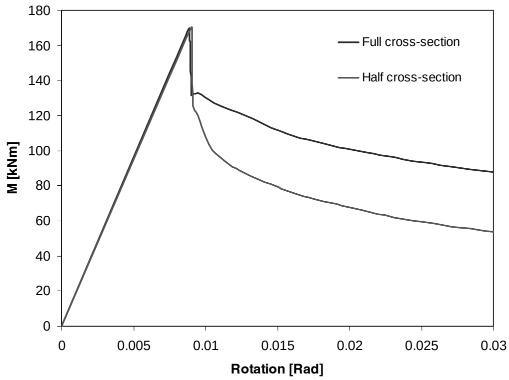

Figure 4: Moment-rotation curves.

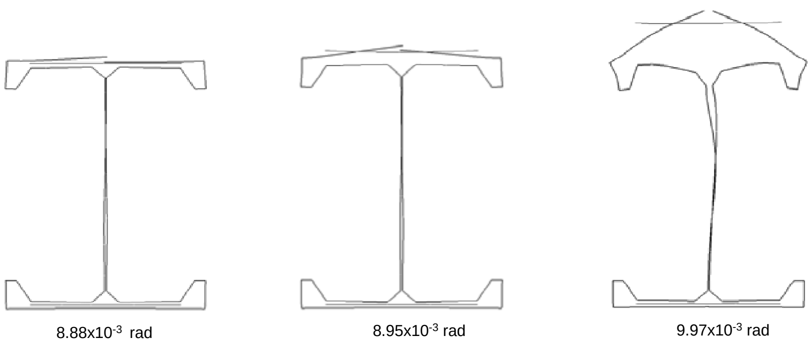

Figure 5: Local and distortional buckling at different rotation rates. Deformation scale factor 10.0.

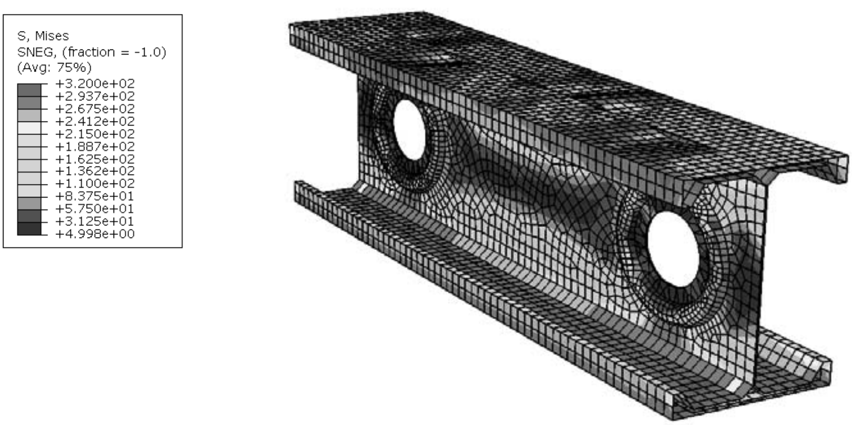

Figure 6: Stress distribution at collapse load. Deformation scale factor 2.0.

The maximum bending capacity is attained at the value of 169.8 kNm for a rotation of 8.90×10^{-3}rad. For higher values of rotation a sudden local buckling occurs.

According to implemented finite element model, the buckling behavior of the model can be divided in different phases, as reported in the following (Fig. 5).

The first phase corresponds to the buckling of the outer plates of the hollow flanges.

The second phase starts with the buckling of the reinforcing plate placed inside the hollow flange and with the attainment of flexural capacity.

In the third phase the buckling of the web develops till the maximum applied rotation is achieved.

In Fig. 6 the stress distribution at collapse load is shown, with local buckling in outer plates of hollow flange.

To evaluate the influence of symmetry on modeling results, a numerical analysis was carried out on a model with half cross-section. Boundary conditions at the reinforcing plates were assumed accordingly.

The comparison with previous results shows that in this case symmetry assumption does not influence the prediction of flexural strength (Fig. 3). This is due to the small thickness of the web. On the contrary, a remarkable difference can be noted for the post-buckling behavior.

4 COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS

The implemented finite element model was validated against the results of a four point bending test that was carried out on a full scale specimen.

Table 1: Comparison of numerical and experimental results.

Specimen ID	d_w [mm]	$M_{y,nom}$ [kNm]	$M_{pl,nom}$ [kNm]	$M_{u, Exp}$ [kNm]	$M_{u, Exp}/M_{y,nom}$	$M_{u, Exp}/M_{pl,nom}$	$M_{u,FE}$ [kNm]
MH MLC 1	150	174.3	191.6	168.1	0.96	0.88	169.8

The experimental bending strength and a comparison with nominal yield and plastic moments are reported in Table 1.

In particular, $M_{y,nom}$ and $M_{pl,nom}$ are the nominal yield and plastic moment calculated on the basis of yield strength f_y and considering the nominal gross cross-section properties. $M_{u,Exp}$ is the bending moment resistance determined by testing.

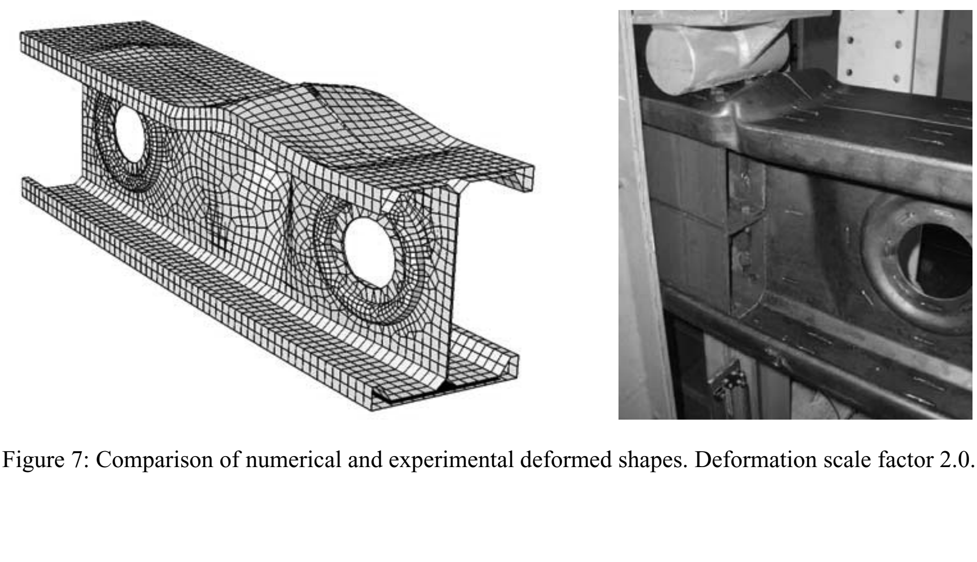

Figure 7: Comparison of numerical and experimental deformed shapes. Deformation scale factor 2.0.

It can be noted that the bending strength predicted by the numerical model is in a very good agreement with the flexural capacity measured from tests of 168.1 kNm.

The collapse mechanisms observed in the test is well fitted by deformed shape of the numerical model as well (Fig. 7).

5 APPLICATION TO THE ANALYSIS OF CONTACT BUCKLING

To evaluate the effects of contact interactions on the flexural strength of the beam, a numerical analysis of the model with no contact interactions was carried out for different spacing of connections.

The comparison of predicted buckling moments is reported in Table 2, where $M_{u,FE}$ and $M'_{u,FE}$ are the strengths with and without contact elements, respectively.

According to the results obtained from the implemented finite element model, the failure load is highly 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 of 39.8% for spacing of welds along the flanges equal to 600.0mm.

Table 2: Comparison of numerical results for different connection spacings, with and without contact elements.

Spacing of laser welds on the flanges d_w (mm)	$(M_{u,FE} - M'_{u,FE})/ M'_{u,FE}$ (%)
150.0	1.0
300.0	5.7
600.0	39.8

6 CONCLUSIONS

In this paper, a FE model of built-up cold formed steel beams assembled by laser welding has been presented. The model was implemented in ABAQUS and was validated against experimental investigation carried out on a full scale specimen.

The comparison with experimental tests showed a good agreement both in terms of ultimate bending moment and buckling mode shapes. The numerical model was used to analyze the influence on local buckling strength of contact forces between the cold-formed profile and the reinforcing plate assembled in the hollow flange of the beams. The analysis showed that contact forces increase remarkably the collapse load for considered welding configuration along the flanges and decrease with decreasing spacing of connections.

Further developments of the present study include sensitivity analysis to geometrical and material imperfections and the implementation of a full beam model of considered specimen under four point bending test.

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