Ninth International Conference on Advances in Steel Structures (ICASS'2018)
5-7 December 2018 - Hong Kong, China

WELDING TECHNOLOGIES FOR BUILT-UP COLD-FORMED STEEL BEAMS: EXPERIMENTAL INVESTIGATIONS

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Abstract: *Structural efficient elements are very attractive due to their economical savings but also for their ease of construction. Cold formed elements are among the solutions for rational use of material as trusses and, lately, corrugated web beams. The connection between the built-up beam parts can be easily obtained by screws but the developments in the welding process also led to other solutions as spot weld. The WELLFORMED research project, ongoing at the CEMSIG Research Center of the Politehnica University of Timisoara, proposes to study a new technological solution for built-up beams made of corrugated steel sheets for the web and thin-walled cold-formed steel profiles for the flanges, connected by spot welding or cold-metal transfer (CMT) welding. Within the research project, the experimental work includes tensile-shear tests on the lap joint welded specimens, were different combinations of steel sheets with various thicknesses were tested and, tests on five full-scale beams in bending. The paper presents the experimental results of the tests performed on lap joint specimens and on the full-scale beams. A numerical model that replicates both the beam instabilities and the force-displacement response of the beam is presented.*

Keywords: Built-up beams; cold-formed steel members; corrugated web; resistance spot welding; experimental tests; galvanized steel

DOI: 10.18057/ICASS2018.xxx

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1 INTRODUCTION

Built-up steel beams, with sinusoidal or trapezoidal corrugated webs, represent a relatively new structural system that has been developed in the last two decades, especially in Germany and Austria. An increased interest for this solution was observed for the mainframe of single storey buildings and steel bridges, respectively. The main advantage of this type of element is the effect of the corrugation in stability problems, leading to increased buckling resistance, with a more economical design. The use of thinner materials leads to lower costs for materials, saving 10-30% compared to conventional welded beams and over 30% compared to hot-rolled ones. The height of a common sinusoidal corrugated steel sheet used as web is comparable to a 12 mm thick flat sheet or more. In the solutions developed so far, the flanges are made of flat sheets, welded to the sinusoidal sheet for the web, involving a specific welding technology. For these elements, the flanges provide the main bending resistance, with a small contribution of the sinusoidal corrugated web that offers shearing capacity. The design of corrugated web beams is included in Annex D of EN 1993-1-5 [1] together with the specific aspects covered by EN 1993-1-1 [2] and EN 1993-1- 3 [3].

A fully cold-formed built-up beam, consisting of trapezoidal corrugated web and parallel flanges made of thin-walled cold-formed steel lipped channel sections, was developed within the CEMSIG Research Center (http://www.ct.upt.ro/en/centre/cemsig) of the Politehnica University of Timisoara [4,5] in which the connections between the flanges and the web were done by self-drilling screws.

The technical solution presented above [4] was also extended for trapezoidal steel beams [6]. In the latter case, experimental tests were carried out on two beams with a 12 m span, with different connection arrangements between the flanges and the web. A detailed state-of-the-art regarding built-up beams using cold-formed steel elements, was presented in [4].

The paper presents the results of the experimental program performed on small specimens, tensile-shear tests on the lap joint spot-welded specimens, and on full scale built-up beams of corrugated web beams and cold-formed steel profiles as flanges, connected by resistance spot welding.

2 EXPERIMENTAL TESTS

The WELLFORMED research project involves a large experimental program on tensile-shear tests on the lap joint spot-welded specimens, were different combinations of steel sheets with various thicknesses were tested, and tests on full scale beams, to demonstrate the feasibility of the proposed solutions, to assess their performance and to enlarge the knowledge by using numerical simulations for the optimization of the current solution and to define the limits of applicability of the solution by parametric studies.

The proposed new solution is based on an experimental program previously developed within the CEMSIG Research Center, in which five corrugated web beams with flanges of back-to-back cold-formed lipped channel steel profiles were tested, having a span of 5157 mm and a height of 600 mm, with different arrangements/configurations for the self-drilling screws position and for the additional shear panels as shown in [4,5].

In order to fully investigate the response of full scale built-up beams connected by spot welding, the experimental tests comprised: a) tensile-shear tests on lap joint spot-welded specimens with various thickness combinations, b) tensile tests on base material and c) full scale tests on built-up beams in bending.

2.1 Tensile-shear tests on lap joint spot-welded specimens

To understand the behaviour of the built-up beams made of corrugated web beams and cold-formed steel profiles as flanges, connected by using spot welding, and for the characterization of the behaviour of all types of connections, tensile-shear tests on lap joint spot-welded specimens have been performed.

The combinations between different sheet thicknesses, experimentally tested, are shown in Table 1. The notations t_1 and t_2 represent the thicknesses of the steel sheets in the connection and ds is the diameter of the spot welding. The diameter of the spot welding, ds, was determined according to EN 1993-1-3 [3] for the case of resistance welding, i.e. $d_s = 5\sqrt{t}$, where t is the smallest thickness of the connected steel sheets. A total number of 140 specimens were tested. The dimensions of the specimens, generically represented in Figure 1, were chosen in accordance with the specifications given in Chapter 8.4 of EN 1993-1-3 [3]. According to EN 1993-1-3 [3], all specimens were connected using one spot of welding. The specimens have been produced using Inverspotter 14000 Smart Aqua equipment from Telwin company, able to control the variables of a spot welding as: welding current, welding time and force between the electrodes in Smart Auto Mode

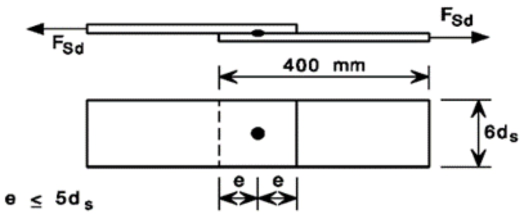


Figure 1: The dimensions of the specimens according to EN 1993-1-3 [3].

It should be mentioned that a similar experimental program, but focused on 0.7 and 0.8 mm thicknesses only, was performed by Benzar et al. [7] at the CEMSIG Research Center. The above sheet thickness combinations only concerned the connection of corrugated steel sheets of the web, to ensure the continuity of the web.

Table 1: Types of spot welding specimens (one spot of welding per specimen).

Name	t_1 [mm]	t_2 [mm]	d_s [mm]	No. of tests
SW-0.8-0.8	0.80	0.80	4.5	7
SW-0.8-1.0	0.80	1.00	4.5	7
SW-0.8-1.2	0.80	1.20	4.5	7
SW-0.8-1.5	0.80	1.50	4.5	7
SW-0.8-2.0	0.80	2.00	4.5	7
SW-0.8-2.5	0.80	2.50	4.5	7
SW-1.0-1.0	1.00	1.00	5.0	7
SW-1.0-1.2	1.00	1.20	5.0	7
SW-1.0-1.5	1.00	1.50	5.0	7
SW-1.0-2.0	1.00	2.00	5.0	7
SW-1.0-2.0	1.00	2.50	5.0	7
SW-1.2-1.2	1.20	1.20	5.5	7
SW-1.2-1.5	1.20	1.50	5.5	7
SW-1.2-2.0	1.20	2.00	5.5	7
SW-1.2-2.5	1.20	2.50	5.5	7
SW-1.5-1.5	1.50	1.50	6.1	7
SW-1.5-2.0	1.50	2.00	6.1	7
SW-1.5-2.5	1.50	2.50	6.1	7
SW-2.0-2.0	2.00	2.00	7.1	7
SW-2.0-2.5	2.00	2.50	7.1	7

Experimental tests were conducted using the UTS universal testing machine. The distance between the sensors of the extensometer was 80 mm. Figure 2 shows a tested specimen with one spot welding of the SW-1.2-1.5 set, developing the full button pull-out failure.

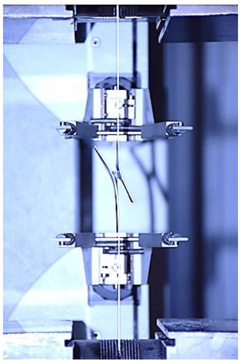


Figure 2: Full button pull-out failure mode.

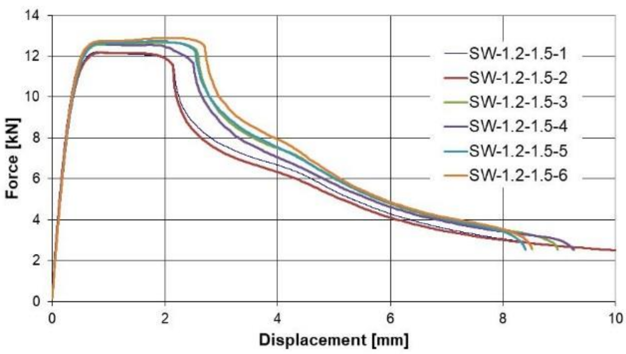


Figure 3: Force-displacement curves for SW-1.2-1.5 specimens (one spot of welding).

Figure 3 depicts the comparison of the force-displacement curves for the specimen set presented above, using different welding regimes. It can be seen that the specimens have a very good capacity and ductility, the maximum recorded force exceeding 12 kN.

Performing the tests on all the specimens presented in Table 1, the general conclusion that can be drawn is that both the capacity and the ductility of the tested specimens are very good. Moreover, compared to the same specimens tested using self-drilling screws [4,5], the capacity of the tested specimens is double, but the ductility is decreased.

The tests revealed two types of failure modes, i.e. full button pull-out (nugget pull-out) and interfacial fracture (see Figure 4). For the investigated combinations of thicknesses, most of them failed by full button pull-out.

In the full button pull-out, the fracture occurs in the base metal or in the perimeter of the weld. In this failure mode, the material is completely torn from one of the sheets with the weld remaining intact. This is the most common failure mode for the tested specimens.

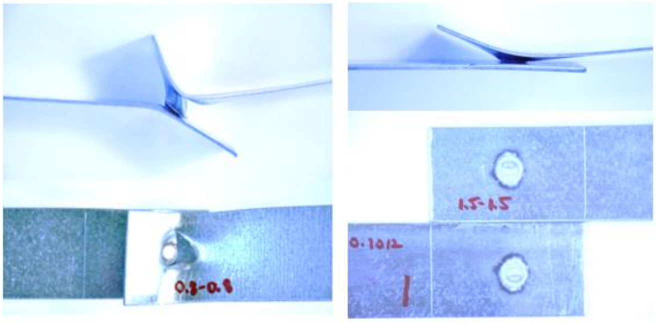


Figure 4: Failure modes of the spot welding specimens: a) full button pull-out, b) interfacial fracture.

Another type of failure mode is the interfacial fracture in which the weld fails at the interface of the two sheets, leaving half of the weld nugget in one sheet and half in the other.

As a conclusion, in the case of full button pull-out, the strain in the base material outside the weld nugget is greater than the strain developed at the weld interface and the opposite is true for the case of the weld interfacial failure. In addition, from the experimental results, it is noticed that the load-bearing capacity of the weld is not affected by the fracture mode.

The quantitative results, in terms of force – displacement curves are presented in Figure 5.

It may be observed that for each combination the maximum force is not limited by the minimum thickness, as the force increases if a smaller thickness is connected to a thicker sheet, but it exists an upper limit of the bearing capacity of the welded connection which is the equivalent of a plastic force of the smaller thickness.

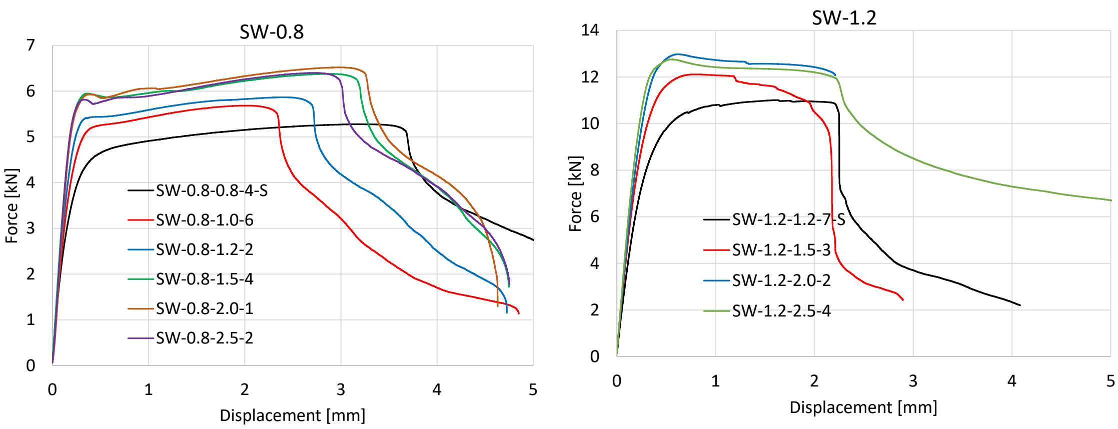


Figure 5: Response of simple SW specimens.

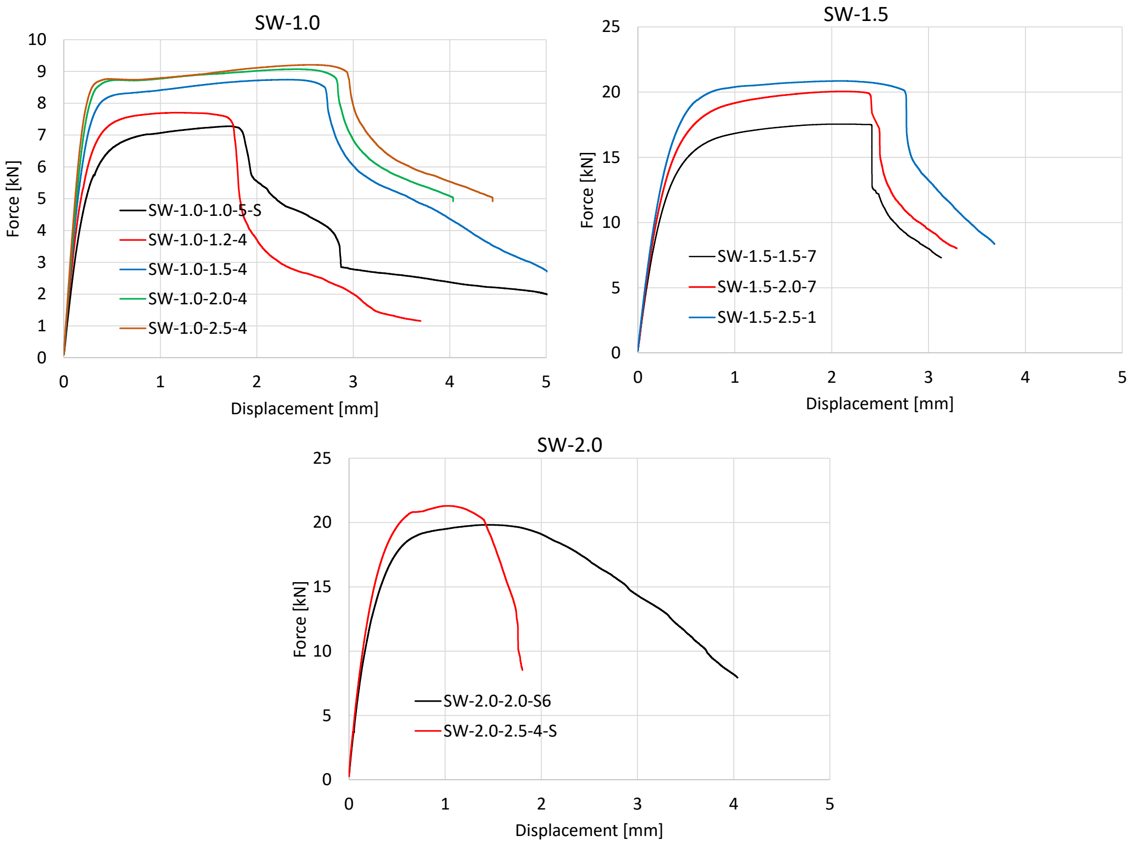


Figure 5: Response of simple SW specimens (continue).

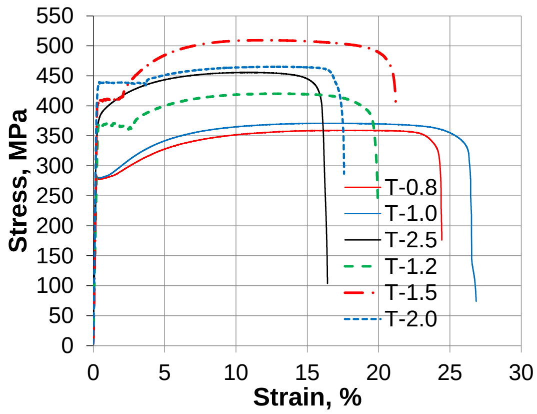


Figure 6: Stress-strain relationships.

Table 2: Material properties.

t [mm]	$R_{p0.2}$ [MPa]	R_{eH} [MPa]	R_m [MPa]	A_{gt} [%]	A_t [%]
0.8	279.64	282.67	361.76	18.41	26.60
1.0	281.33	-	373.50	16.70	26.14
1.2	366.82	367.81	420.68	13.15	19.83
1.5	407.70	409.00	497.12	13.06	20.38
2.0	431.78	430.43	464.46	11.79	19.70
2.5	374.68	-	452.98	11.40	16.76

where:

$R_{p0.2}$ - stress at 0.2% strain

R_{eH} - maximum value of stress prior to the first decrease in force

R_m - stress corresponding to the maximum force

A_g - plastic extension at maximum force

A_t - total extension at the moment of fracture

A_{gt} - total extension at maximum force

2.3 Full scale beam specimen tests

For the full-scale specimen tests, two beams were built-up, i.e. CWB SW-1 and CWB SW-2, having a span of 5157 mm and a height of 600 mm. The process for the manufacturing consists of 4 steps: a) connecting the corrugated steel sheets for the web, b) connecting the shear panels at the ends of the beam, c) connecting the top and bottom flanges and e) connecting the end parts of the beam for the rigid connection to the experimental stand, as presented in Figure 7. The first step in only necessary if the corrugated web is not available in one piece. For the current case, the corrugated steel sheets had a maximum length of 1.05 m.

The components of the built-up beams are shown in Figure 8 and detailed below:

- two back-to-back lipped channel sections for flanges - 2 × C120/2.0
- corrugated steel sheets (panels of 1.05 m length with 0.8 mm and 1.2 mm thicknesses);
- additional shear panels - flat plates of 1.0 or 1.2 mm;
- reinforcing profiles U150/2.0 used under the load application points;
- bolts M12 grade 8.8 for flange to endplate connection.

Except the differences between the shear panel’s thicknesses of the two beams, as shown in Figure 8 and Table 3, another aspect of interest was the connection between the corrugated steel sheets of the web. By using the same number of spot welds, the corrugated sheets of beam CWB SW-1 were connected on two rows (Figure 9(a)), while the corrugated sheets of beam CWB SW-2 were connected on one row only as shown in (Figure 9(b)).

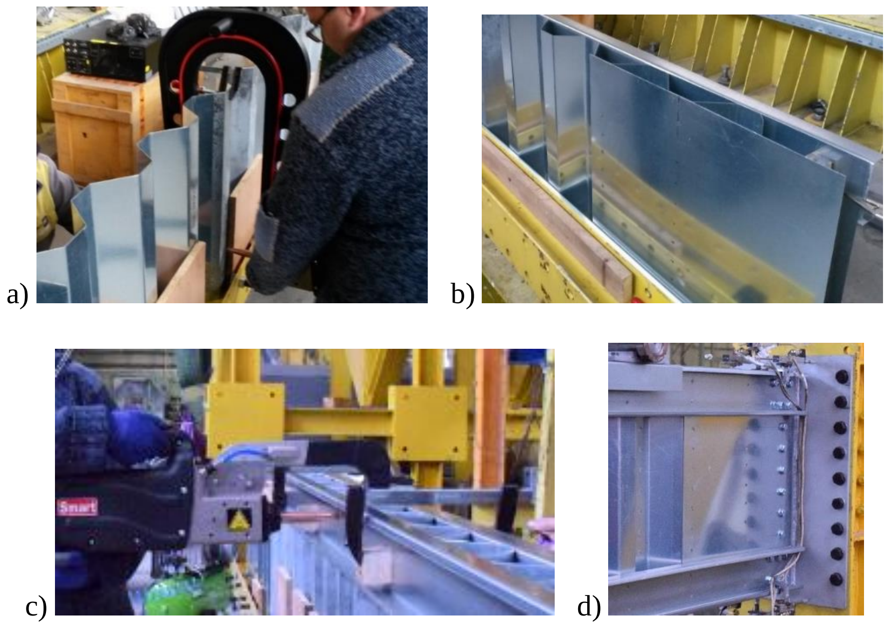


Figure 7: Stages of beam built-up.

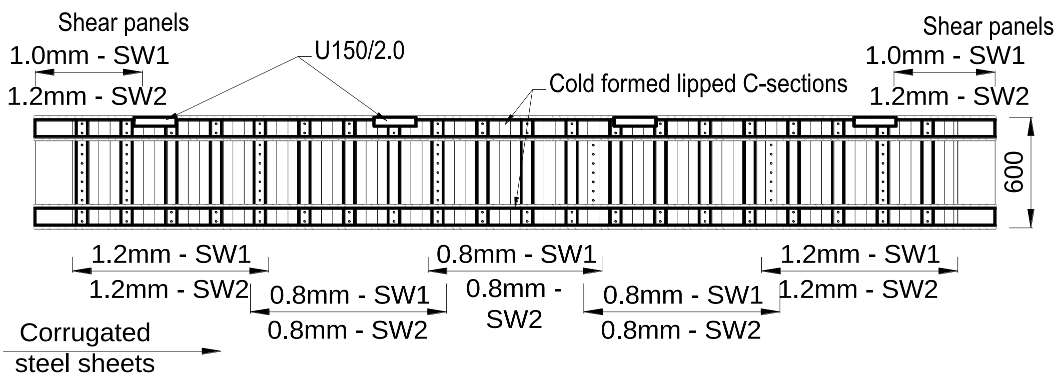


Figure 8: Components of the built-up beams.

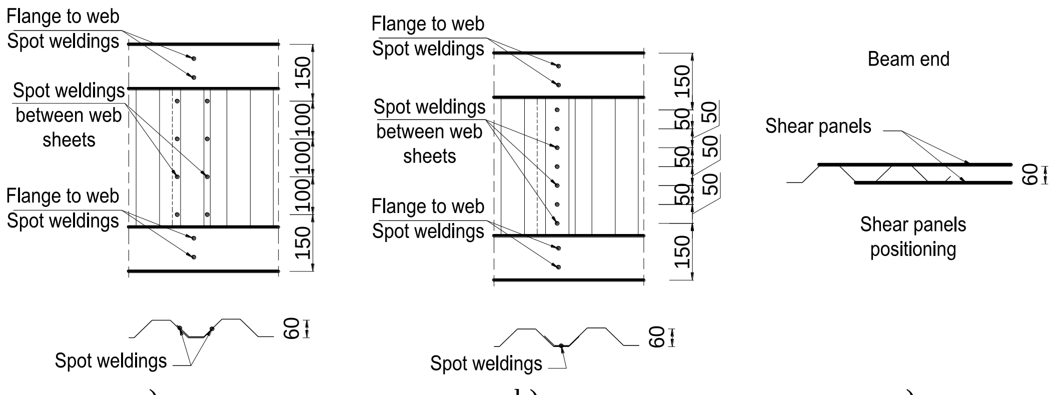


Figure 9: a) Connection between corrugated sheets of beam CWB SW-1, b) Connection between corrugated sheets of beam CWB SW-2, c) position of the shear panels.

Table 3: Distribution of the steel sheets used for the web of the spot-welded beams.

Name	Thickness			Length of shear panels
	Outter corrugated sheets	Inner corrugated sheets	Shear panels	
CWB SW-1	1.2 mm	0.8 mm	1.0 mm	470 mm; 570 mm
CWB SW-2	1.2 mm	0.8 mm	1.2 mm	510 mm; 630 mm

Finally, the beams were loaded in a 2D loading frame, with the test set-up depicted in Figure 10. The beams were loaded by an actuator of 500 kN which transmitted the force to the beam by a system able to distribute the load in 4 points. An out-of-plane independent frame was used to avoid stability problems during loading.

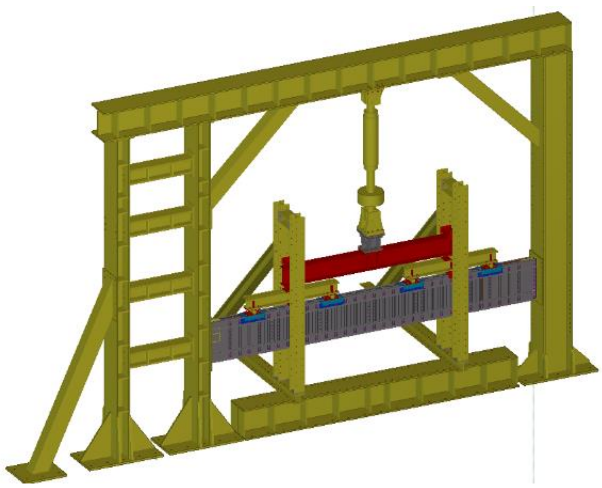


Figure 10: Test setup

The recordings aimed to monitor the displacements at each end of the top or bottom flange, between the flange and the end plate as well as between the end plate and the rigid frame. The vertical deflection of the beam was monitored at each quarter of the span by 2 wire displacement transducers connected to each of the bottom flange part. The force was recorded through the actuators load cell.

3 RESULTS AND DISCUSSIONS

In the following, the remarks during the experiments are presented and discussed. Since similar failure mechanism was exhibited by both beams, the same remarks are valid for both tests.

For the first tested specimen, CWB SW-1 (see Figure 11), the failure mode of the beam started with the buckling of shear panel (see Figure 12), followed by the distortions of the corrugated web as presented in Figure 13 and, after reaching the maximum force, the breaking of some spot-welding connections (see Figure 14). The behaviour of CWB SW-1 beam was ductile, with an initial stiffness of $K_{0\text{-}Exp}$ = 11352.6 N/mm and the maximum load was reached at F_{max} = 283.8 kN. The collapse appears for a displacement of around 123 mm. The recorded force-displacement curve at the mid-span is depicted in Figure 15.

Figure 11: CWB-SW1 beam – global deformation during the testing.

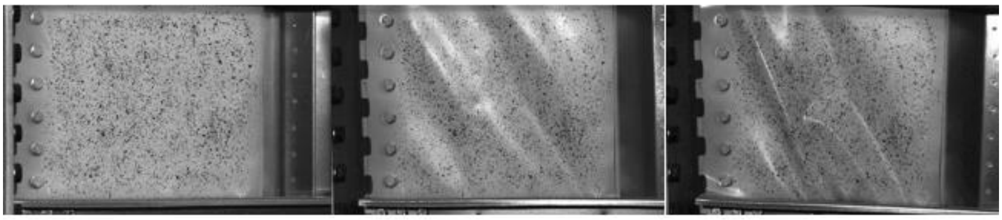


Figure 12: Development of the shear buckling at the end panels for CWB SW-1 beam.

Figure 16 presents some details of the web distortion. Due to the two connected points between the web and the flange (see Figure 11), under the shear stresses, the corrugations have been distorted between the two flanges with respect to the axis between the two spots of the welding.

Figure 13: Distortion of the web corrugation of the CWB SW-1 beam.

Figure 14: Nugget pull-out.

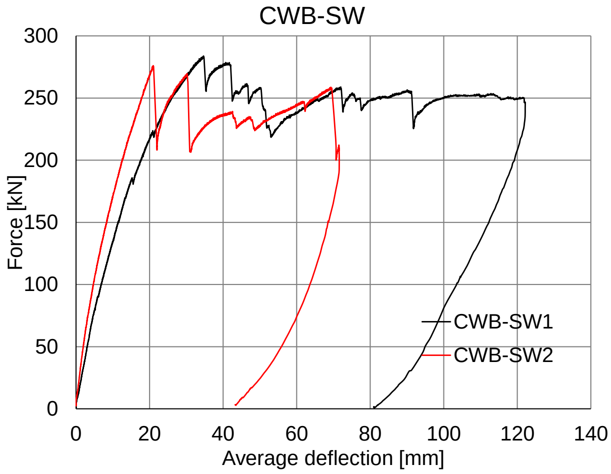


Figure 15: Force-deflection curve for the full scale built-up beams.

In the final stage of the tests, both beams exhibited local deformation under the load application points, as presented in Figure 16.

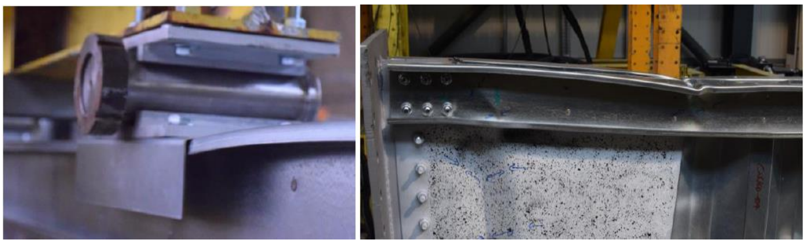


Figure 16: Local deformations under the load application point.

Compared to the previous studied solution, built-up beams with self-drilling screws [4,5], it may be seen that the beams connected by spot welding present a higher stiffness (see Table 4), as well as a higher capacity.

Table 4: Results of the corrugated web beams: spot welding vs. screws.

Beam type	$K_{0\text{-}Exp}$ [N/mm]	F_{max} [kN]
CWB SW-1	11352.6	283.8
CWB SW-2	15846.5	276.0
CWB-1 [4,5]	6862.2	219.0
CWB-2 [4,5]	7831.5	230.6
CWB-3 [4,5]	7184.9	211.9
CWB-4 [4,5]	3985.0	161.8
CWB-5 [4,5]	5516.2	215.5

4 NUMERICAL ANALYSIS

In order to calibrate a numerical model based on experimental tests, finite element analyses were conducted using the commercial software Abaqus v. 6.14 [9].

4.1 Input data

Each part of the built-up beam was defined as a 3D shell element extruded according to the shape of the part. An approximate global size of 15 mm was set for the definition of the element dimensions, Figure 17. The S4R, 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains) was selected as the finite element type.

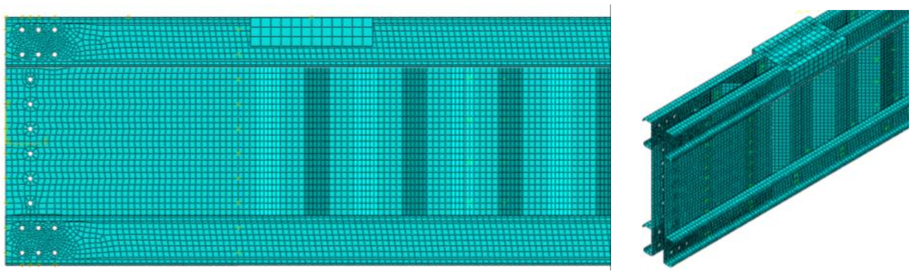


Figure 17: Finite element mesh.

The material model was defined considering the results of the tensile tests performed on the base material and transformed to the True-Stress-Strain relations according to EN1993-1-5, Annex C [1].

While the support conditions were defined on the nodes of the holes provided for the bolts that connects the beam to the end plate assembly as null displacements and rotations, the loading of the beam was defined as a vertical displacement in a set of multipoint constraints MPC that forms a leverage system to transmit the deflection to the 4 loading points (Figure 18). The link between the control points and the pressure surface was defined by a Kinematic coupling constraint for all DOFs.

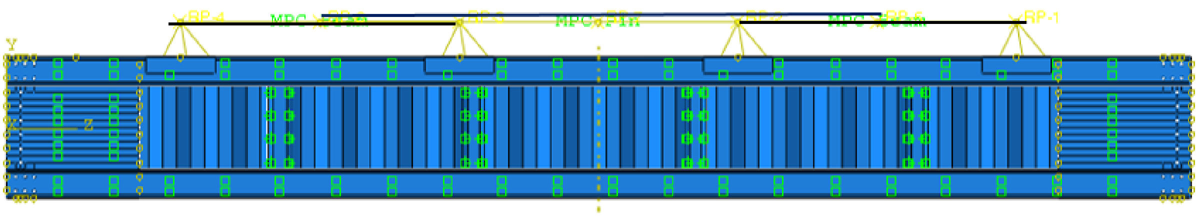


Figure 18: Leverage constraint system.

Due to the multitude of contact areas, the *All*with self* option was used for the interaction between parts with a *Penalty* formulation of 0.1 friction coefficient, for the tangential behaviour and *Hard contact* for the normal one.

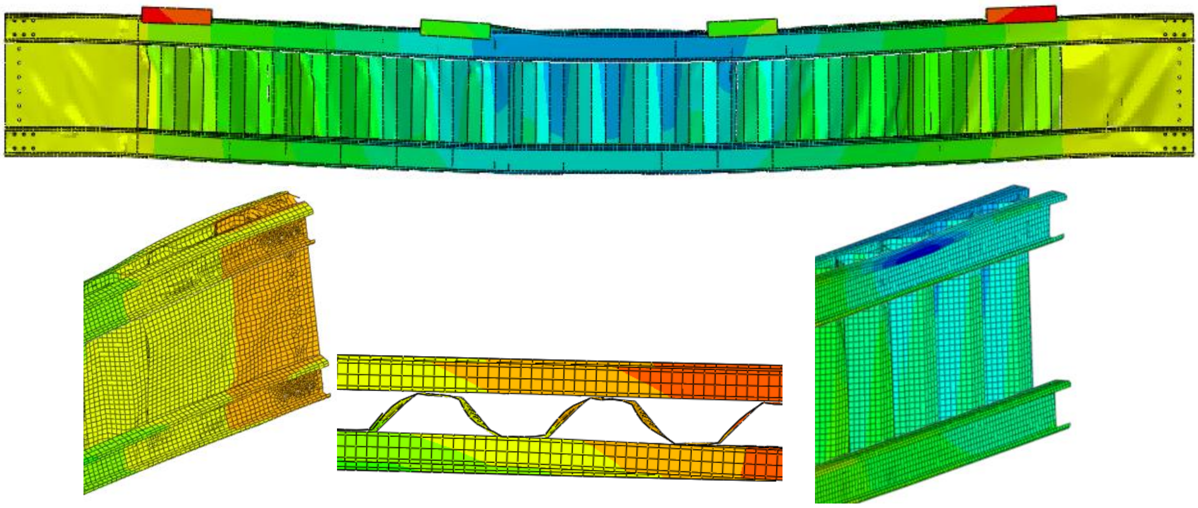
The spot welds between different parts of the built-up beams were defined function of the tensile-shear tests of the simple specimens as follows. *Attachment points* were defined on each part were SW was applied. The connection between the *attachment points* was defined using *Point Based Fasteners* with the *Connector* response of the SW initially calibrated from the tensile-shear tests results. The connector was considered by the Elasticity, Plasticity, Damage and Failure parameters.

4.2 FEA results

Due to the thin walled elements stability deficiency, the results of the numerical simulations should asses the failure mechanism as well as the response relation in terms of force displacement.

The deformed shape of the numerical model, Figure 19 replicates the phenomena encountered during the experiments: shear panel buckling (a), distortion of the corrugated web (b) and the local buckling of the flange in the load application points (c).

The quantitative results depicted in Figure 20 with dashed lines for the numerical model also present a good correlation to the experimental results.



a) b) c)

Figure 19: Deformed shape of the numerical model: a) buckling of the shear panel, b) distortion of the corrugated steel plate, c) local buckling of the flange.

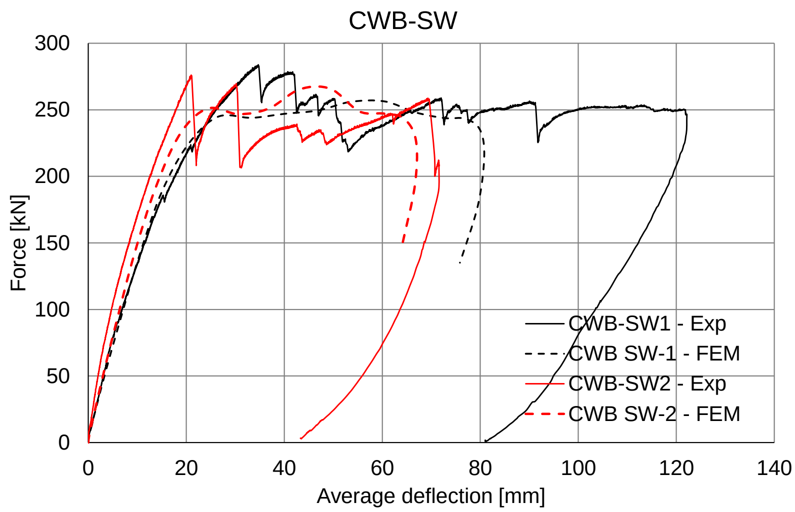


Figure 20: Experimental and numerical results.

5 CONCLUSIONS

Within the WELLFORMED research project, carried out at the CEMSIG Research Center of the Politehnica University of Timisoara, an extensive experimental program on built-up cold-formed steel beams using resistance spot welding as connecting technology occurred.

The paper presents the experimental results on tensile-shear tests on lap joint spot-welded specimens, in order to characterize the behaviour of these connections and on full scale tests of two beams subjected to bending. The experiments were accompanied by tensile tests, to characterise the material behaviour.

The most common failure mode for the tensile-shear tests on lap joint spot-welded specimens was the full button pull-out. Also, can be noticed that for each combination of thicknesses, the maximum force is not limited by the minimum thickness; the force increases if a smaller thickness is connected to a thicker one, but exists an upper limit which is given by the plastic force of the smaller thickness. Both the capacity and the ductility obtained for the tested specimens are very good and compare to similar specimens tested using self-drilling screws [4,5], the capacity is double but the ductility is decreased.

The experimental results of full scale shown:

- both the capacity and the ductility obtained for the tested specimens are very good;
- compared to the solution studied in [4,5], they show an increased capacity but, the deformation is consistent less that the deformation of built-up beams using self-drilling screws.

Both the experimental and numerical results are encouraging and demonstrate the potential of this solution for standardization and industrial manufacturing. The present validation of the numerical model represents the initial step for a parametric study of the built-up cold-formed beams for their use in large spans structures.

ACKNOWLEDGEMENT

This work was supported by a grant of the Romanian National Authority for Scientific Research and Innovation, CNCS/CCCDI -UEFISCDI, project number PN-III-P2-2.1-PED-2016-1684 / WELLFORMED - Fast welding cold-formed steel beams of corrugated sheet web, within PNCDI III

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