Experimental Investigations on Spot Welded Built-Up Cold-Formed Steel Beams

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Abstract. Within the WELLFORMED research project, ongoing at the CEMSIG Research Center of the Politehnica University of Timisoara, a new technological solution was proposed 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. The research project integrates an extensive experimental program on such beams, using full scale specimens, to demonstrate the feasibility of the proposed solutions and to assess their performance, followed by numerical simulations to characterize and optimize the connecting details. The present paper presents the results of a large experimental program, on small specimens subjected to shear, consisting of two or three layers of steel sheet connected by spot welding.

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 noticed 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 sinusoidal corrugated steel sheet used for the web is comparable to a 12 mm thick 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 new technological solution of such a 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 Research Center CEMSIG (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. It is important to emphasize that the new solution, as a whole, is composed of 100% of cold-formed steel elements, avoiding the combination of two types of products, namely cold-formed elements for the web and hot-rolled for the flanges. A detailed presentation of this solution, the state-of-art related to this type of element, and the different connecting technologies, was presented by Dubina et al. [4,5].

The technical solution presented above [4] was also extended for trapezoidal steel beams [6,7]. 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 very important aspect related to the cold-formed steel components or structures is the connecting technique.

In order to meet the high standards of the automotive industry, new welding processes have been developed that further push the physical and mechanical limits of welding technology. Fronius is the market leader in the field of robotic welding systems, with more than 50 years of experience in the automotive and components supply industry. These technologies, due to their advantages, have also begun to be used in the steel structure domain. Among these technologies, one can notice: (1) the Cold Metal Transfer (CMT) welding, that guarantees the most stable electric arc in the world and precise control of the process, offering welded bead and soldering without welding drops, and able to weld thicknesses from 0.6 mm; (2) Laser hybrid welding, combining the advantages of a fully digital MIG/MAG process with those of laser welding in a single process, but without their disadvantages. This allows the automatic joining of various steel parts at a speed of up to 8 meters per minute with high quality connection; (3) Spot welding, a technique for joining of two or more sheets, usually steel, without additional material. In the welding area, with the use of two copper alloy electrodes, a compressive force is applied and electric current is transmitted, which locally heats the parts. Thus, the material between the electrodes is melting and after the welding current has stopped, the materials solidify and the joint results, creating a welded spot.

Urbikain et al. [8] present a new method for the rapid and economical production of 'nutless' bolted joins, using a combination of two hole-making techniques, namely, form drilling and form tapping.

In [9], Calleja et al. evaluates the steps to be followed before accomplishing 5 axis laser cladding operations. The work represents a useful tool for the industrial application of 5 axis laser cladding.

Briskham et al. [10] performed a comparative study on self-pierce riveting, resistance spot welding and spot friction joining, identifying the resistance spot welding as a more favourable option.

Guenfoud et al. [11] tested welded specimens fabricated through one, two or four layers of thin steel sheets using the shear resistance and tension resistance of multi-layer arc spot welds.

Snow [12] conducted a research in order to establish a relationship between arc spot weld shear strength and the arc time used while forming the weld. Testing was performed on steel gauge sheets of 0.85 mm, 1 mm, 1.3 mm and 1.6 mm. Each gauge material was tested in single-, double- and four-layer configurations. The research has proven that arc time has a tremendous influence on arc spot weld shear strength.

Strength tests were performed by Chao [13] to reveal the failure mechanisms of spot weld in lap-shear and cross tension test samples. Based on the observed failure mechanism, stress distribution was assumed. A theoretical model was developed to the mixed normal/shear loading condition.

In [14], finite element modelling and fracture mechanics calculations were used to predict the resistance spot weld failure mode and loads in shear-tension tests of advanced high-strength steels. The results of the work confirmed the existence of a competition between two different types of failure modes, namely full button pull-out and interfacial fracture. The study indicates that the load-bearing capacity of the welds is not affected by the fracture mode. Therefore, the mode of failure should not be the only criteria used to judge the quality of spot welds. The load-bearing capacity of the weld should be the primary focus in the evaluation of the shear-tension test results.

Miyazaki and Furusako [15] investigate the dependency of fracture position and maximum load of laser welded lap joints through tensile shear test of joints, and a mechanical prediction model for the test results was developed.

Research progresses on arc welding techniques are described by Kodama et al. [16], focusing on the automotive members. Static strength and fatigue strength performance of welded joints are improved for high-strength steels by CMT applied arc spot welding.

In [17], low carbon steel plates, joined by friction stir spot welding (FSSW) with lap configuration were investigated. It was found the tool penetration depth exerted a strong effect on the failure mode of the joined samples and a weak effect on the joint shear strength. With increasing tool penetration depth, and consequently with increasing depth of the tool shoulder pressing into the top sample, the failure mode in a lap-shear test changed from brittle to ductile and concentrated near the pinhole located away from the weld towards the base metal.

In [18] are proposed alternative methods like abrasive waterjet, wire electrodischarge machining and laser that could be used instead of the standardised milling process in order to obtain tensile specimens. The work aims at determining any effects on surface state and tensile test performance occurred as a result of manufacturing method, working with low-carbon steel as the study material. Results show that some changes on surface state appeared, but the effect on tensile strength was lower than 5%. The use of alternative processes to milling presents two main advantages, it shortens the time needed to produce tensile test specimens, and the same technology finally applied in the final manufacturing step is used to prepare testing specimens.

A wide experimental investigation on laser welded connections based on both lap-shear and tension tests were performed by Landolfo et al. [19].

Rusinski et al. [20] present selected problems which emerged from axial compression tests of thin-walled beams joined by spot welding. They investigate the effect of the size of the diameter of the weld and the pitch of the weld on the amount of absorbed energy. A discrete model was built and FEM strength computations of the thin-walled beams, taking into account physical and geometrical nonlinearities, were performed.

The CEMSIG Research Center is currently carrying out the WELLFORMED research project, funded by UEFISCDI, which proposes a new jointing solution to be used for built-up cold-formed steel beams with the cross-section made of corrugated steel webs and flanges made of thin-walled cold-formed steel profiles, namely spot welding. The research project involves a large experimental program on small spot-welded specimens subjected to shear, consisting of two or three layers of steel sheet, and tests on full scale beams, to demonstrate the feasibility of the proposed solution and to assess their performances, followed by numerical simulations to optimize the connecting technique and to extend the solution by parametric studies. This new solution can be used as steel supporting framework in building construction: as roof girders, portal and low rise multi-story frames, short span pedestrian bridges. It is expected from this solution to cover medium spans, up to 24 m length. Also it can be a reliable alternative to purlins or secondary beams, where these have to cover large bays.

The paper presents the intermediate results of the experimental program done on the small specimens subjected to shear, consisting of two or three layers of steel sheets connected by spot welding.

Technical solution. Details and technologies for connections

The proposed new solution is based on an experimental program previously developed within the CEMSIG Research Center of the Politehnica University of Timisoara, 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 [4,5].

The components of the standard solution are shown in Fig. 1 and are detailed below:

- back-to-back lipped channel sections for flanges - 2×C120/2.0 (grade S350GD+Z);
- corrugated steel sheet with a nominal thickness of 0.7 mm - A45/0.7 (gradeS320GD+Z);
- additional shear plates - flat plates of 1 mm thick and 830 mm long, placed at the ends of the beam, where the shear force is maximum (grade S320GD+Z);
- reinforcing profiles U150/2.0 under load application points (grade S350GD+Z);
- self-drilling screws for web-to-flange connection - STP-6.3×25;
- self-drilling screws for connecting shear plates - STP-5.5×25;
- self-drilling screws for overlapping the corrugated webs - STT-4.8×20;
- bolts M12 gr. 8.8 for flange to endplate connection.

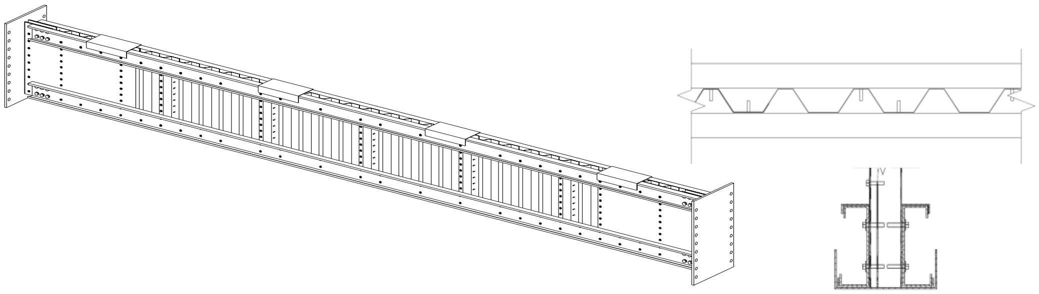

Fig. 1. Standard solution – corrugated web beam and specific web and flange details [4,5]

The experimental program was completed with tensile tests on specimens extracted from beam components (profiles and corrugated sheet), both in the flat areas and the corners of the elements, and tests on connections, for the different combinations of thicknesses, to determine their behaviours.

Currently, within the WELLFORMED research project, a new connecting solution is proposed, namely the spot welding that replaces self-drilling screws, reducing the workmanship and the cost of joining technology, increasing the degree of automation of fabrication of the proposed beam. Four types of beams with cold-formed steel profile for flanges and corrugated steel webs, with a span of 5157 mm and a height of 600 mm will be tested, as shown in Fig. 2, considering different spot welding arrangements/configurations and different thicknesses for the web and for the shear panels.

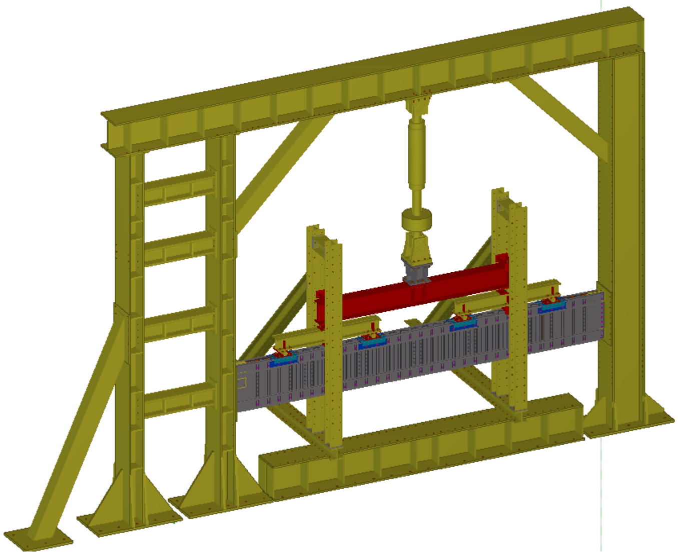

Fig. 2. Spot-welded built-up corrugated web beam. Test setup

In order to determine the behaviour of all types of joints used for the built-up beams, six different types of connections will be investigated (see Fig. 3), namely: (1) SW1 – seam fastening for the overlapping of corrugated steel sheets; (2) SW2 – seam fastening for the connection between the corrugated steel sheet and shear panels; (3) SW3 – connection between the shear panels and the flanges; (4) SW4 – connection between the shear plates and the end support; (5) SW5 – connection between the flanges and the end supports; (6) SW6 – connection between the flanges and the corrugated web. The thicknesses to be investigated are 0.7 mm, 0.8 mm, 1.0 mm, 1.2 mm, 1.5 mm, 2.0 mm and 2.5 mm. A total number of 340 small specimens subjected to shear, consisting of two or three layers of steel sheets connected by spot welding have been tested.

In order to determine the mechanical properties of the corrugated web beam components, a set of samples were cut out from the same base material used to produce the components of the beam. A total number of 35 specimens have been tested according to [21], 5 for each type of thickness.

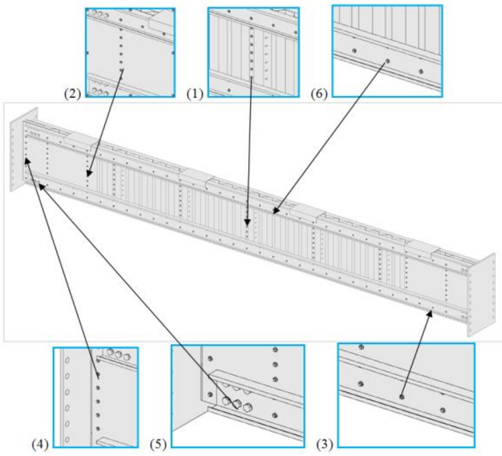

Fig. 3. Position in the beam of welding connections

Experimental tests on small specimens connected by spot welding

In order to increase the speed of manufacturing of such beams, spot welding was adopted as a connecting technique for both the corrugated steel sheets of the web, as well as for the connection between the web and the flanges. The spot welding 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 d_s is the diameter of the spot-welding. A total number of 340 specimens were tested. The dimensions of the specimens (see Fig. 4) were chosen in accordance with the specifications given in Chapter 8.4 of EN1993-1-3 [3]. According to Table 1 and EN1993-1-3 [3], all types of connections have been tested using a single welding spot.

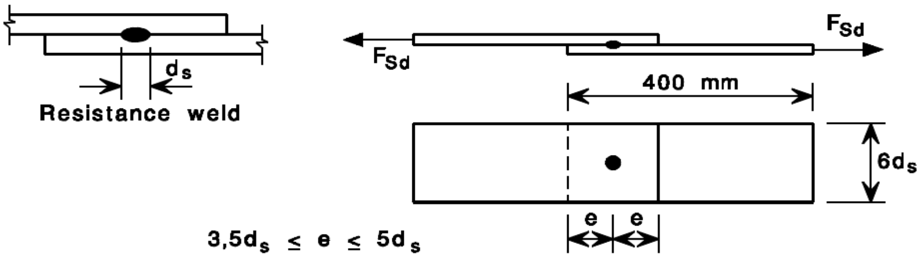

Fig. 4. The dimensions of the specimens according to EN1993-1-3 [3]

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

Name	t_1 [mm]	t_2 [mm]	No. of tests	d_s [mm]	Name	t_1 [mm]	t_2 [mm]	No. of tests	d_s [mm]
SW-0.7-0.7	0.70	0.70	7	4.2	SW-1.0-1.0	1.00	1.00	7	5.0
SW-0.7-0.8	0.70	0.80	7	4.2	SW-1.0-1.2	1.00	1.20	7	5.0
SW-0.7-1.0	0.70	1.00	7	4.2	SW-1.0-1.5	1.00	1.50	7	5.0
SW-0.7-1.2	0.70	1.20	7	4.2	SW-1.0-2.0	1.00	2.00	7	5.0
SW-0.7-1.5	0.70	1.50	7	4.2	SW-1.0-2.0	1.00	2.50	7	5.0
SW-0.7-2.0	0.70	2.00	7	4.2	SW-1.2-1.2	1.20	1.20	7	5.5
SW-0.7-2.5	0.70	2.50	7	4.2	SW-1.2-1.5	1.20	1.50	7	5.5
SW-0.8-0.8	0.80	0.80	7	4.5	SW-1.2-2.0	1.20	2.00	7	5.5
SW-0.8-1.0	0.80	1.00	7	4.5	SW-1.2-2.5	1.20	2.50	7	5.5
SW-0.8-1.2	0.80	1.20	7	4.5	SW-1.5-1.5	1.50	1.50	7	6.1
SW-0.8-1.5	0.80	1.50	7	4.5	SW-1.5-2.0	1.50	2.00	7	6.1
SW-0.8-2.0	0.80	2.00	7	4.5	SW-1.5-2.5	1.50	2.50	7	6.1
SW-0.8-2.5	0.80	2.50	7	4.5	SW-2.0-2.0	2.00	2.00	7	7.1
					SW-2.0-2.5	2.00	2.50	7	7.1

The diameters of the welding points, d_s, 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. The possible failure modes are the full button pull-out and the interfacial fracture of the spot welding.

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

Experimental tests were conducted using the UTS universal testing machine. The distance between the extensometer's sensors was 80 mm. Fig. 5 shows a tested specimen with one spot welding of the SW-1.2-1.5 set, developing the full button pull-out failure.

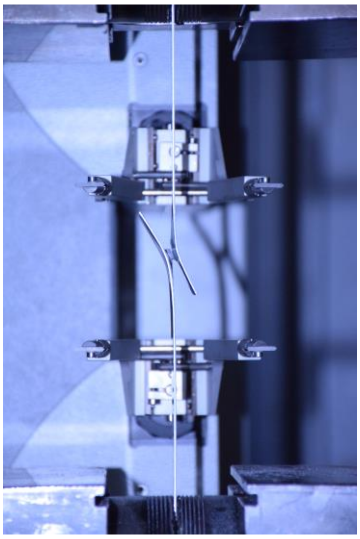

Fig. 5. Full button pull-out failure mode

Another important aspect of the investigation was the welding regime. The welding equipment has default factory settings counting for different thickness combinations, the so-called "SMART" setting, but also allows the possibility to use user-defined programs. Table 2 shows, as an exemplification, the parameters analysed for the set of SW-1.2-1.5 specimen.

Table 2. Welding regimes for the set SW-1.2-1.5

	Name	I_s [A]	Power [%]	F [daN]	pressure [bar]	t_s [ms]
REG 1	SW-1.2-1.5-1	10366	70	365	6	380
REG 2	SW-1.2-1.5-2	10336	70	365	-	380
REG 3	SW-1.2-1.5-3	11088	75	483	6.8	600
REG 4	SW-1.2-1.5-4	11088	75	472	6.6	600
REG 5	SW-1.2-1.5-5	11055	-	457	6.4	600
REG 6	SW-1.2-1.5-6	11775	80	449	6.2	600

The following parameters were considered: welding current I_s (A), force between the electrodes F (daN), pressure (bar) and welding time, t_s (ms), for electrodes of 13 mm diameter and 32 mm radius of the tip.

Fig. 6 shows the set of six SW-1.2-1.5 specimens with the parameters shown in Table 2, before and after testing. It can be noticed that in all cases the failure mode was the full button pull-out.

Fig. 6. Specimens SW-1.2-1.5 before and after testing, using different welding regimes

Fig. 7 depicts the comparison of the force-displacement curves for the specimen set above. It can be seen that the specimens shown in Fig. 7 have very good capacity and ductility, the maximum recorded force exceeding 12 kN.

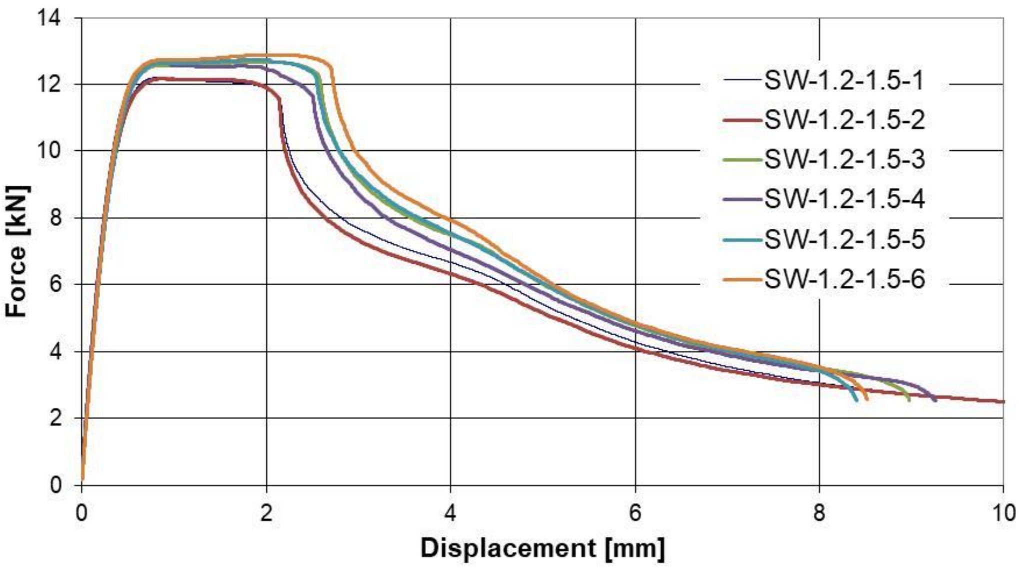

Fig. 7. Force-displacement curves for SW-1.2-1.5 specimens (one spot weld)

Based on the tests performed on all the specimens presented in Table 1, the following general conclusion can be drawn, i.e. both the capacity and the ductility obtained for 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.

Numerical simulations

Based on the results obtained above and considering the validated FEM models presented in [4], the aim of this chapter is to evaluate the capacity and the behaviour of a beam spanning 12 m, with parallel flanges by using numerical simulations. The beam height was considered constant along the length, with a height of 1000 mm. The beams components considered are: (1) back-to-back lipped channel profiles as flanges - 2×C150/2.0, S350GD+Z steel grade; (2) corrugated web with a corrugation height of 45 mm and 0.7 mm thickness, S320GD+Z steel grade; (3) Shear panels, 1 mm thick and 2000 mm long, at the ends of the beams, S320GD+Z steel grade; (4) self-drilling screws for the web-to-flange connections - 6.3×25 (3 self-drilling screws on the profile height); (5) self-drilling screws for fixing the shear panels to the end supports - 5.5×25; (6) M16 class 8.8 bolts for joining the flanges to the endplate (6 screws for each flange).

For the analysis, the following three different situations were considered for the web: CASE 1 – the web is made of corrugated sheet panels joined with self-drilling screws to ensure the continuity at the overlapping of the web panels (16 self-drilling screws 4,8×20 on the height of the web); CASE 2 – the web is made of corrugated sheet panels joined using spot welding to ensure the continuity at the overlapping of the web panels (16 welding points with diameter of 4.5 mm on the web height); CASE 3 - the web is a continuous corrugated sheet over the entire length of the beam. The beam was considered in the analysis with the upper flange fixed to the roof purlins.

The advanced numerical model was defined using the FE ABAQUS/CAE v.6.14 commercial program. Detailed information related to the finite element type, material behaviour, contact parameters, connectors and bolt modelling are presented in [4]. The force-displacement curves (see as an exemplification Fig. 7) obtained for the different types of connections (see Fig. 3) have been used in the advanced numerical model to count for the connections' behaviour.

Fig. 8 presents the force-displacement curve for the analysed beam in the three cases described above. It can be seen that the influence of the connections is very small, both in terms of beam capacity and flexibility. As expected, the beam using self-drilling screw is the most flexible. In all cases, the maximum force is approximately 402 kN.

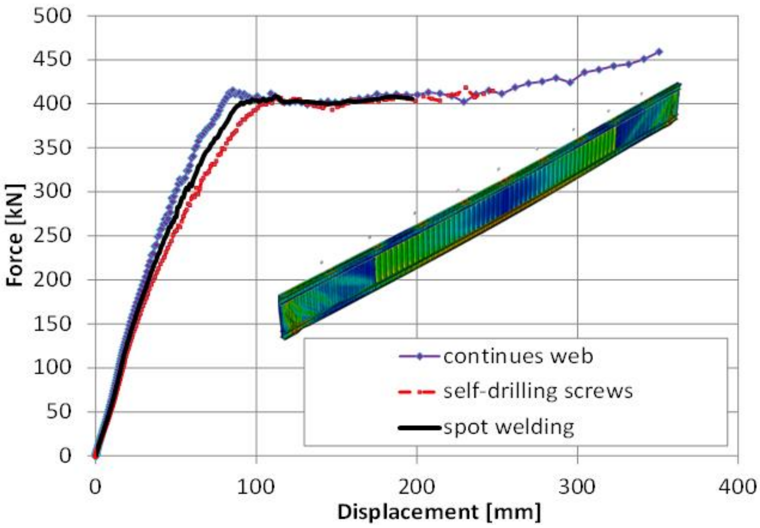

Fig. 8. Force-displacement curve for the corrugated web beam of 12 m

Conclusions

Within the WELLFORMED research project, carried out at the CEMSIG Research Center of the Politehnica University of Timisoara, a new experimental program was started on built-up cold-formed steel beams, made of corrugated webs and back-to-back lipped channel profiles for flanges, connected by spot welding.

The paper presents the experimental results on small specimens subjected to shear, consisting of two or three layers of steel sheets, connected by spot welding, in order to characterize the behaviour of these joints.

The experiments shown:

- both the capacity and the ductility obtained for the tested specimens are very good;
- compare to similar specimens tested in [5] using self-drilling screws, the capacity of the tested specimens is double but the ductility is decreased;
- all tested specimens developed full button pull-out failure.

Ongoing activities are carried out for four full-scale beam specimens to be tested in order to demonstrate the feasibility of the proposed solution and to evaluate their performance.

The experimental research will be followed by numerical simulations to optimize the distribution/arrangement of the connections and parametric studies to see the limits of the system.

In the second part of the paper, based on the experimental results on small specimens that characterise the connections' behaviour, a 12 m span beam with parallel flanges was numerically evaluated. The influence of three different web configurations was considered, i.e. (1) web panels connected with self-drilling screws, (2) web panels connected with spot welding, (3) continuous web. It has been found that the influence of the connections at the level of web is very small in terms of both the capacity and flexibility of the beam.

The results are encouraging and demonstrate the potential of this solution for standardization and industrial manufacturing.

Acknowledgements

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