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EXPERIMENTAL INVESTIGATIONS ON RESISTANCE SPOT WELDING OF BUILT-UP COLD-FORMED STEEL CORRUGATED WEB BEAMS

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Abstract. *Corrugated web girders emerged in the past two decades. Their main advantages consist in the possibility to use slender webs avoiding the risk of premature local buckling. Consequently, higher moment capacity might be obtained increasing the beam depth with really thin webs, which are stiffened by the corrugations. Increased interest for this solution was observed for the main frames of single-storey steel buildings and steel bridges. A new solution, in which the beam is composed of a web of trapezoidal steel sheet and flanges of back-to-back lipped channel steel sections, connected using self-drilling screws, was proposed at the Politehnica University of Timisoara. Starting from this solution the paper extends and investigates the use of spot welding as seam fastening to build the web, in order to increase the degree of automation of fabrication. Experimental work on specimens in shear having two or three layers of steel sheets connected by spot welding will be presented in this paper.*

1 INTRODUCTION

Corrugated web girders emerged in the past two decades. In the existing solutions on the market, the flanges are flat plates, welded to the sinusoidal web sheet, requiring a specific welding technology and highly automated manufacturing process. The main benefits of these beams with sinusoidal webs are that their webs increase the beam's stability against buckling, which may result in a very economical design via the reduction of web stiffeners. As a result, the web does not participate in the longitudinal transfer of bending stresses. Therefore, in static terms, the corrugated web beam behaves similarly to a lattice girder, in which the bending moments and applied forces are transferred only via the flanges, while the transverse forces are only transferred through the diagonals and verticals of the lattice girder, in this case, the corrugated web. So, the girder's flanges provide the flexural strength of the girder with no contribution from the corrugated web which provides the girder's shear capacity. The failure of the corrugated web occurs by steel yielding, web buckling (local or distortional or their interaction). Lateral-torsional buckling of the girder and local flange buckling of corrugated web, separately or in interaction, represent other possible failure modes.

The dimensioning of corrugated web beams (CWB) is ruled by Annex D of the EN 1993-1-5:2006 [1], together with specific aspects of EN 1993-1-1:2006 [2] and EN 1993-1-3:2006 [3].

A new technological solution of such a system, composed by webs made of trapezoidal cold-formed steel sheets and flanges of built-up cold-formed steel members (back-to-back lipped channels) has been developed at the CEMSIG Research Centre (http://www.ct.upt.ro/en/centre/cemsig) of the *Politehnica* University of Timisoara [4,5]. The connections between flanges and web were made with self-drilling screws. Five beams with different arrangements for self-drilling screws and shear panels have been experimentally tested.

It should be emphasize the new solution, as a whole, is 100% composed of cold-formed steel elements, avoiding the combination of two types of products, i.e. cold-formed for webs and hot-rolled for flanges.

By extending the application of the technical solution described in [4,5] for parallel flanges girders, promising experimental results have been obtained on trapezoidal beams made of cold-formed steel profiles and corrugated web [6]. Monotonic tests were performed on two beams of 12 m span, having different connections between the flanges and the web.

A similar solution has been proposed and analysed in the frame of PRECASTEEL project [7], but using blind rivets as seam fasteners for the corrugated web and bolts for web-to-flange connections. For flanges, back-to-back lipped channel or two types of hat-sections have been used. Deep corrugation web sheeting of longitudinal intermediate stiffeners have been applied in this solution. However, looking to the test results, one observes the sensitivity to distortion of corrugation still remains high.

An extended literature review has been presented in [4] and [5]. On the following, some particular aspects related to spot welding as connecting technique will be emphasized only.

Briskham et al. [8] performed a comparative study on of self-pierce riveting, resistance spot welding and spot friction joining for aluminium automotive sheet. Quantitative comparisons have been made on the basis of tensile strength, process time, equipment price and running cost. The results identified resistance spot welding as a more economically favourable option than self-pierce riveting or spot friction joining. For resistance spot welding, the largest cost factors identified were energy consumption and frequency of electrode replacement. Even the material is aluminium similar conclusions can be drawn for steel too.

Guenfoud et al. [9] tested welded specimens fabricated through one, two or four layers of steel sheets with thicknesses ranging from 0.76 mm to 1.52 mm. A total of 72 tension tests and 107 shear tests were completed. The idea was the initiation of a research program on the shear resistance and tension resistance of multi-layer arc spot welds. They found that the type of electrode, high current setting, and proper welding technique affect the quality of arc-spot welds in multi-layer connections.

Snow [10] conducted a similar research in order to establish a relationship between arc spot weld shear strength and the arc time used while forming the weld. Each gauge material was tested in single-, double- and four-layer configurations. Two types of diameter arc spot welds were tested. Comparisons were made between shear strength and weld geometry, including average diameter, effective diameter, and penetration. The research has proven that arc time has a tremendous influence on arc spot weld shear strength.

Chao [11] investigates experimentally the ultimate strength and failure mechanism of resistance spot welding subjected to tensile, shear, or combined tensile/shear loads. The objective of his study was to develop an engineering failure criterion for spot welding in thin sheet metals under nugget pull-out mode.

Rusiński et al. [12] investigate by numerical simulations the problems which emerged from axial compression tests of thin-walled members joined by spot welding under quasi-static crash tests. The effect of the size of the weld's diameter and the pitch of the weld on the amount of absorbed energy was studied. Twenty experimental tests [13], each made from two thin-walled omega-shaped sections, of 1.5 mm thick steel sheet, have been selected for the analysis. The profiles were joined together by resistance spot welding using two spot weld diameters: d = 4 mm and 8 mm and for two distances between the spot welds: t = 25 mm and 50 mm. They found that the diameter of the spot weld is a significant factor determining the strength and mode of fracture of each specimen.

Starting from the new technological solution [4,5], the paper extends and investigates the use of spot welding as seam fastening to build the web, in order to increase the degree of automation of fabrication. Experimental work on specimens in shear having two or three layers of steel sheets connected by spot welding will be presented. The results will be implemented on a numerical model in order to study the behaviour of built-up beam.

2 THE NEW TECHNICAL SOLUTION: SPECIMENS, MATERIAL AND CONNECTION PROPERTIES

An experimental program was carried out at the CEMSIG Research Centre of the *Politehnica* University of Timisoara (http://www.ct.upt.ro/en/centre/cemsig) on five beams with corrugated webs and back-to-back lipped channels for flanges, with a span of 5157 mm and a height of 600 mm, have been tested, considering different arrangements for self-drilling screws and shear panels [4,5].

Figure 1(a) presents the components of the CWB-1 beam with the corrugated web, i.e.:

- back-to-back lipped channel sections for flanges - 2×C120/2.0;
- corrugated web with the corrugation depth of 43 mm and the thickness of 0.7 mm - A45/0.7;
- reinforcing shear panels - plates of 1 mm thickness and 830 mm length, at the beam ends where the shear force is maximum;
- reinforcing U150/2.0 profiles used under the load application points;
- self-drilling screws for flange-to-web connection - STP-6.3×25;
- self-drilling screws for shear plates to end support - STP-5.5×25;
- self-drilling screws as seam fasteners for corrugated webs - STT-4.8×20;
- bolts M12 class 8.8 for flanges to the end support connection.

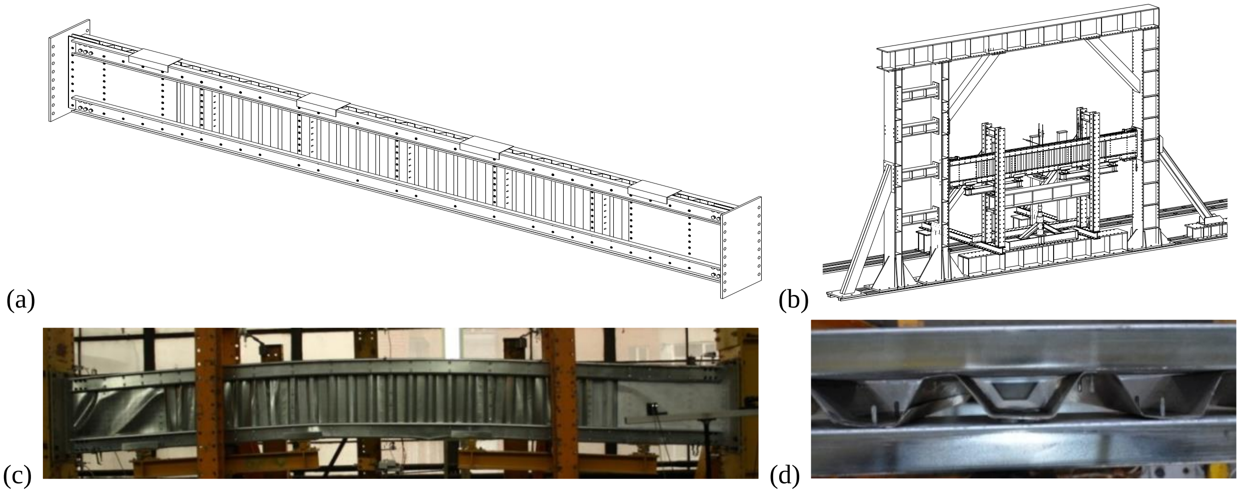


Figure 1. (a) Configuration of the specimens; (b) Experimental arrangement;
(c) Deformed shape of CWB-5 beam at failure; (d) Distortion of the web corrugation

Six points bending tests were applied monotonically for each specimen with a loading velocity of 2 mm/min (see Figure 1(b)). The full-scale testing program was completed with tensile tests to determine both the material properties for beam components and the behaviour of connections. Detailed information related to the behaviour of each tested specimen, including the initial stiffness, $K_{0\text{-}Exp}$ and maximum load F_{max}, as well as the failure mode were reported in [4] and [5]. Figure 1(c,d) shows, as an exemplification, the deformed shape of the CWB-5 beam at the collapse and the distortion of the web corrugation in the region with the reduced number of screws.

In order to determine the mechanical properties of the CWB components, a set of samples were cut out from the lipped channels, corrugated sheet, both from the flat regions and corners and reinforcing shear panels, according to EN ISO 6892-1:2009 [14] specifications.

Six types of connections were tested according to Publication 124 of ECCS [15] in order to determine the behaviour of all types of connections found in the beam, as shown in Table 1 [4,5], i.e.:

(1) T1-1.4, seam fasteners for corrugated sheets (see Figure 4(a));
(2) T2-1.7, seam fasteners for shear plates and corrugated sheets;
(3) T3-3.7, self-drilling screws for shear plates and flanges;
(4) T4-9.0, self-drilling screws for shear plates and end supports;
(5) T5-11.0, bolts for flanges to end-supports;
(6) T6-2.7, self-drilling screws for flanges to corrugated webs at mid-span.

Name	t_1 [mm]	t_2 [mm]	No. of tests	d_{nom} [mm]
T1-1.4	0.7	0.7	6	4.8
T2-1.7	1.0	0.7	5	4.8
T3-3.7	2.0+1.0	0.7	6	6.3
T4-9.0	1.0	8.0	5	5.5
T5-11.0	2.0+1.0	8.0	5	M12
T6-2.7	2.0	0.7	10	6.3

Table 1. Types of tested connections [4,5]

3 EXPERIMENTAL SHEAR TESTS FOR SPOT WELDING

In order to increase the speed of fabrication of such beams, spot welding was adopted as seam fastening technique for connecting the corrugated sheets to build the web. In this sense, all types of seam fastenings presented in Table 1 were experimentally tested using spot welding [16]. According to Table 1, the connection types T1-1.4 and T2-1.7 will be tested using with one or two spots of welding (see SW1-1.4 and SW3-1.7 in Table 2). More, in order to enlarge the database for numerical modelling three new combinations of thicknesses have been tested, as shown in Table 2. Finally, ten series of specimens have been tested.

Name	t_1 [mm]	t_2 [mm]	No. of tests	d_s [mm]
SW1-1.4	0.7	0.7	5	4.5
SW2-1.5	0.7	0.8	5	4.5
SW3-1.7	0.7	1.0	5	4.5
SW4-1.8	0.8	1.0	5	4.5
SW5-2.5	0.7+1	0.8	5	4.5

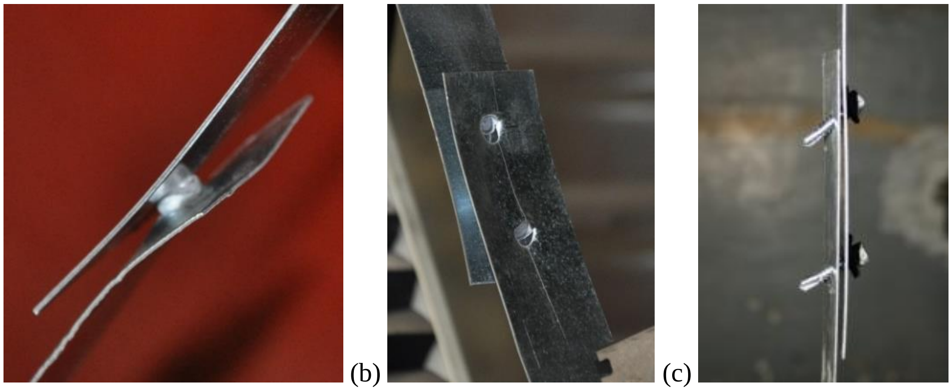
Table 2. Types of seam fastenings using spot welding (one and two spots of welding per specimen) [16]

Figure 2 presents the main stages in preparing the specimens and the parameters for the spot welding.

Figure 2. Spot welding process

The interface diameter d_s of the spot welding has been determined according to EN 1993-1-3 [3], for resistance welding, i.e. $d_s = 5\sqrt{t}$ [with t in mm], where t is the thickness of the thinner connected part or sheet. The dimensions of the specimens have been chosen according to EN 1993-1-3.

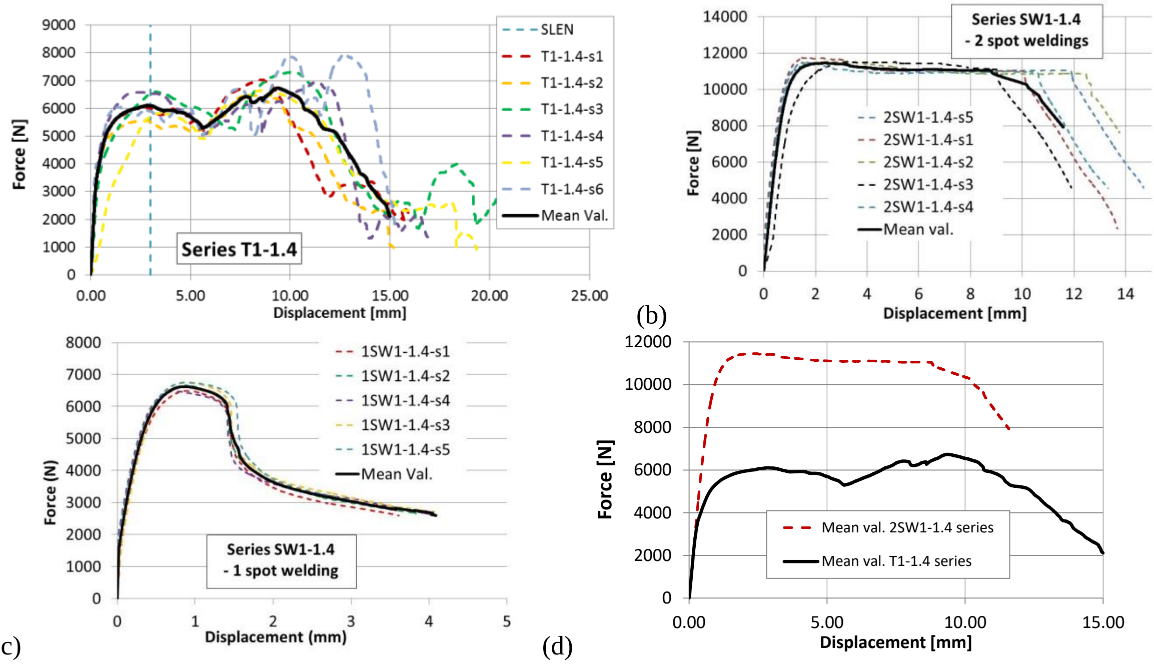
Figure 3 presents the specimen SW1-1.4 with (a) one spot of welding and (b) two spots of welding at failure, in comparison with the same specimen but with self-drilling screws. It can be easily seen that both the self-drilling screw and spot welding specimens have similar failure modes.



(a) (b) (c)

Figure 3. Specimens at failure: SW1-1.4 (a) one spot of welding; (b) two spots of welding; (c) Specimen T1-1.4 with self-drilling screws

Figure 4 presents comparatively the force-displacement curves for the specimen T1-1.4 (see Table 1) and specimen SW1-1.4 (see Table 2), with corresponding mean value curves, in order to be used for relevant models in numerical simulations.



(a) (b) (c) (d)

Figure 4. Force-displacement curves for (a) T1-1.4 (2 screws); (b) SW1-1.4 (2 spots of welding); (c) SW1-1.4 (1 spot of welding); (d) mean value curves for T1-1.4 and SW1-1.4 specimens

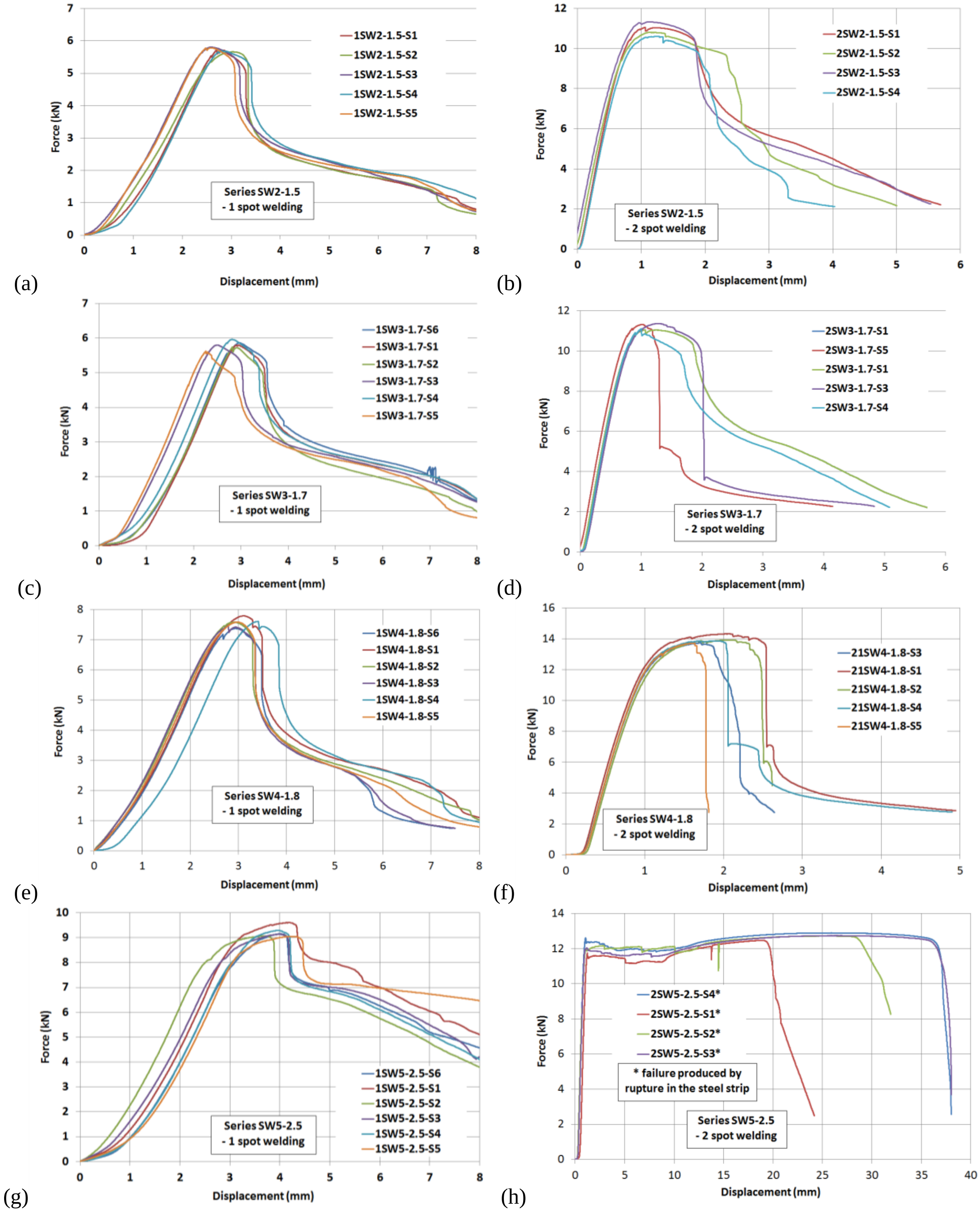


Figure 5. Force-displacement curves for: (a) SW2-1.5; (c) SW3-1.7; (e) SW4-1.8; (g) SW5-2.5 (1 spot of welding) and (b) SW2-1.5; (d) SW3-1.7; (f) SW4-1.8; (h) SW5-2.5 (2 spots of welding)

It should be mentioned once that, in case of T1-1.4 specimens, two screws have been used for each specimen according to Publication 124 of ECCS [15] while, in case of SW1-1.4 specimens, two cases have been tested, i.e. with one (as recommended by EN 1993-1-3 [3]) or two spots of welding.

Very good ductility can be observed in both cases presented in Figure 4(a) and 4(b), being one of the causes for the significant redundancy of the tested beams. Also, it can be noted that the capacity of specimens with 2 spots of welding (see Figure 4(b)) is almost two times higher than the similar one with 2 self-drilling screws (see Figure 4(a)), but less ductile compared to the second one.

Figure 5 presents the force-displacement curves for (a) SW2-1.5; (c) SW3-1.7; (e) SW4-1.8; (g) SW5-2.5 specimens with one spot of welding, while (b) SW2-1.5; (d) SW3-1.7; (f) SW4-1.8; (h) SW5-2.5 for specimens with two spots of welding. It should be underlined that in the case of Figure 5(h) the failure was produced by the rupture of the steel strip.

4 NUMERICAL SIMULATIONS

Based on the above results and considering the FEM models validated in [4], the next step is to evaluate the behaviour and capacity of a beam of 12 m span with parallel flanges using numerical simulations. Pinned lateral supports have been considered in the analysis, at the top flange, in the position of purlins of Z200/2 cross-section. The numerical model has been created using the commercial FE program ABAQUS/CAE v.6.7.1 [17]. Details regarding the type of finite elements, material behaviour, contact parameters, modelling of screws and bolts are presented in [4].

The beam components are:

(1) back-to-back lipped channel sections for flanges - 2×C150/2.0, steel grade S350GD+Z;
(2) corrugated web with the corrugation depth of 43 mm and the thickness of 0.7 mm, steel grade S320GD+Z;
(3) reinforcing shear panels, plates of 1 mm thickness and 2000 mm length, at the beam ends, steel grade S320GD+Z;
(4) self-drilling screws for flange-to-web connection - STP-6.3×25 (3 self-drilling screws per height of the profile);
(5) self-drilling screws for shear plates to end support with a nominal diameter - STP-5.5×25;
(6) M16 bolts class 8.8 for flanges to the end support connection (6 bolts for each flange);
(7) the height of the beam was constant along the length, i.e. 1000 mm.

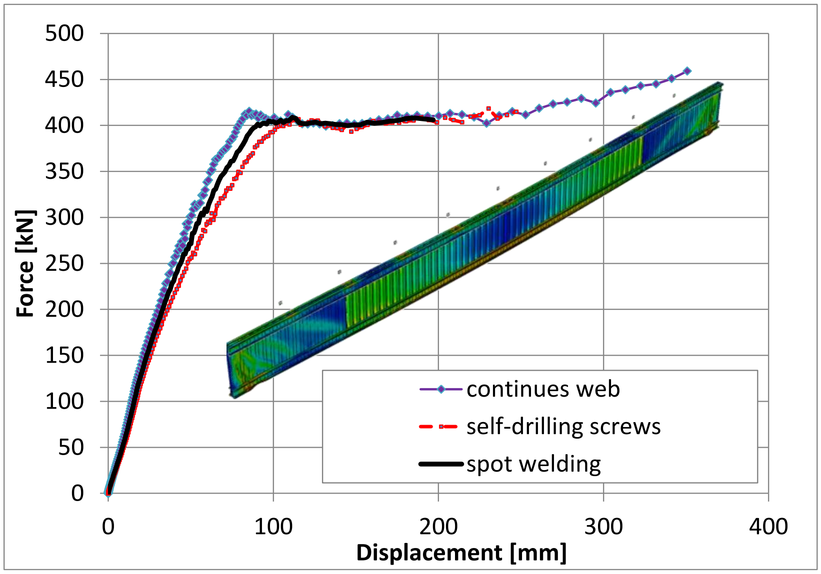


Figure 6. Stress distribution and load-displacement curve for a 12 m span beam with corrugated web

The influence of the following component has been studied, i.e.:
(8.1) self-drilling screws as seam fasteners for corrugated webs with a nominal diameter - STT-4.8×20 (16 self-drilling screws per height of the profile);
(8.2) spot welding as seam fasteners for corrugated webs with a nominal diameter of 4.5 mm (16 self-drilling screws per height of the profile);
(8.3) no seam fasteners have been considered, the corrugated web being continuous.

Similar failure modes have been obtained as in the case of the tested beams. Figure 6 presents the stress distribution and the load-displacement curve for this beam. It can be observed the influence of seam fastening is very small, both in terms of capacity and flexibility of the beam. As was expected, the beam using self-drilling screws is the most flexible one. The maximum load in all the cases is around 402 kN.

5 TECHNICO-ECONOMIC FEASIBILITY

Based on the numerical results obtained above, a technico-economic assessment for a 12 m span beam with trapezoidal shape (see Figure 7a) and for parallel flanges sloped beam of 16 m span (see Figure 7b) will be presented, in comparison with the traditional trusses composed of cold-formed steel profiles connected with bolts.

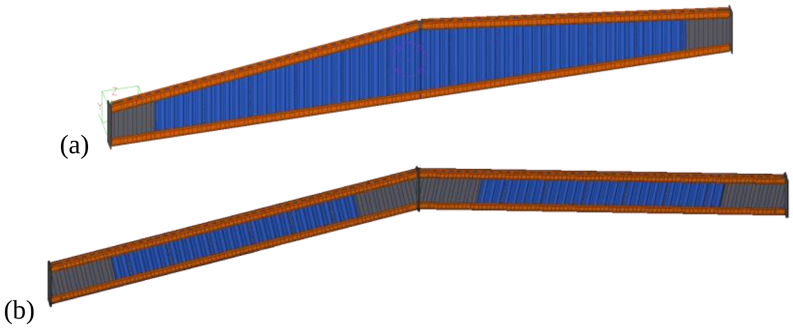


Figure 7. (a) 12 m span trapezoidal beam with corrugated web; (b) 16 m span parallel flanges sloped beam

The truss beams have been calculated for the same sizes and loading conditions as corrugated web beams and are composed of back-to-back cold-formed steel lipped channel profiles for the top (TC) and bottom (BC) chords and single lipped channel profiles for diagonal (DW) and vertical (VW) web members, connected with M12 and M16 bolts, as shown in Figure 8 and Table 3.

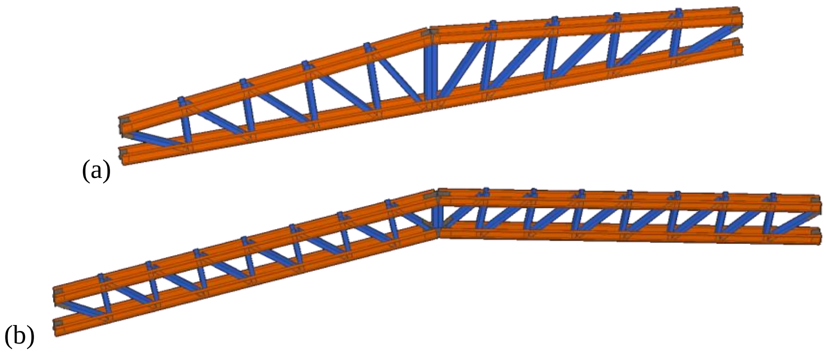


Figure 8. (a) 12 m span trapezoidal truss; (b) 16 m span parallel flanges truss

Element	Truss	
	12m	16m
TC	2C200×2	2C200×3
BC	2C200×2	2C200×3
DW1*	C150×2 – 6M16	C150×2.5 – 6M16
DW2*	C150×1.5 – 4M16	C150×2.5 – 6M16
DW3*	C150×1.5 – 4M16	C150×2.5 – 6M16
DW4; DW5*		C150×2.0 – 4M12
DW6 – DW8*		C150×1.5 – 4M12
VW1*	C150×2 – 4M16	C150×2.5 – 6M16
VW2*	C150×1.5 – 4M16	C150×2.5 – 6M16
VW3*	2C150×1.5 – 4M16	C150×2.5 – 6M16
VW4 – VW7*		C150×2.0 – 4M12
VW8*		2C150×1.5 – 4M12
* the numbering of the web members starts from ends to the midspan		

Table 3. Cross-sections and connecting bolts for the truss beams of 12 m and 16 m span

Figure 9 shows the weight performances for the 12 m and 16 m beams in both solutions (steel consumption for the profiles and their connections).

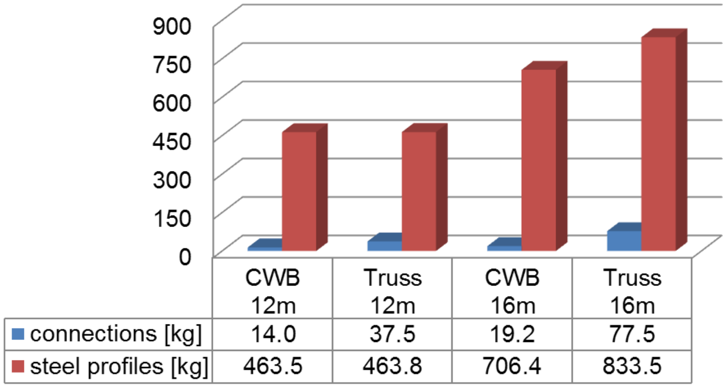


Figure 9. Steel consumption for the corrugated web beams of 12 m and 16 m span and the equivalent trusses

It is very clear that the corrugated web beams solutions in both cases are lighter, but the main advantage is the connecting system which uses self-drilling screws or spot welding, leading to fast and industrialised fabrication. The main disadvantage in case of trusses, even using a lower number of bolts than screws, is the connecting systems, implying the predrilling process of members and difficulties in assembling.

6 CONCLUSIONS

In order to increase the speed of fabrication of such beams, spot welding might be adopted as seam fastening technique for connecting the corrugated sheets to build the web. In this sense, all types of seam fastenings have been experimentally tested, using the spot welding.

Based on the above results the behaviour of a beam of 12 m span, with parallel flanges, has been evaluated. It was observed the influence of seam fastening is very small both in terms of capacity and flexibility of the beam. On the other hand, looking to Figure 4(d) and Figure 6, it is clear the potential of spot weld connections, both in terms of strength and stiffness, have not been exploited to obtain a higher capacity of the beam. It is for sure the number and distribution of connections can be optimised, reducing their number, to enhance the economic efficiency.

The results are encouraging and prove the potential of this solution to standardized beams and industrialized fabrication.

A new experimental program on connecting details (using spot and Cold Metal Transfer welding) and full-scale beams, extended by numerical simulations, has started at the CEMSIG Research Centre of the *Politehnica* University of Timisoara (www.ct.upt.ro/centre/cemsig/), on the purpose to demonstrate and evaluate the performances of proposed solutions.

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REFERENCES

[1] EN1993-1-5 (2006), *Eurocode 3: Design of steel structures - Part 1-5: Plated structural elements*, CEN, Brussels.

[2] EN1993-1-1 (2005), *Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings*, CEN, Brussels.

[3] EN1993-1-3 (2006), *Eurocode 3: Design of steel structures. Part 1-3: General Rules. Supplementary rules for cold-formed thin gauge members and sheeting*. CEN, Brussels.

[4] Dubina, D., Ungureanu, V. and Gîlia, L. (2013), "Cold-formed steel beams with corrugated web and discrete web-to-flange fasteners", *Steel Construction*, 6(2), pp. 74-81.

[5] Dubina, D., Ungureanu, V. and Gîlia, L. (2015), "Experimental investigations of cold-formed steel beams of corrugated web and built-up section for flanges", *Thin-Walled Structures*, 90, pp. 159-170.

[6] Nagy, Zs., Ungureanu, V., Dubina, D. and Ballok R. (2016), "Experimental investigations of cold-formed steel trapezoidal beams of screwed corrugated webs", *Proceedings of the International Colloquium on Stability and Ductility of Steel Structures – SDSS'2016*, Timisoara, Romania, 30 May -01 June 2016, pp. 387-394.

[7] RFSR-CT-2007-00038 (2013), *Prefabricated steel structures for low-rise buildings in seismic areas (Precasteel)*, Final report, Research Fund for Coal and Steel, EU.

[8] Briskham, P., Blundell, N., Han, L., Hewitt, R., Young, K. and Boomer, D. (2006), "Comparison of self-pierce riveting, resistance spot welding and spot friction joining for aluminium automotive sheet", *Proceedings of the SAE 2006 congress*, Technical paper, 2006-01-0774.

[9] Guenfoud, N., Tremblay, R. and Rogers, C.A. (2010), "Arc-Spot Welds for Multi-Overlap Roof Deck Panels", *Proceedings of the Twentieth International Specialty Conference on Cold-Formed Steel Structures*, St. Louis, Missouri, USA, 3-4 November 2010, pp. 535-549.

[10] Snow, G. (2008), *Strength of arc spot welds made in single and multiple steel sheets*, M.Sc. Thesis. Blacksburg, Virginia, USA.

[11] Chao, Y.J., *On the Failure of Resistance Spot Weld*, Department of Mechanical Engineering, University of South Caroline, Columbia, SC 29208.

[12] Rusiński, E., Kopczyńskib, A. and Czmochowskia, J. (2004), "Tests of thin-walled beams joined by spot welding", *Journal of Materials Processing Technology*, 157-158, pp. 405-409.

[13] Sperle, J.-O., *High Strength Steel for Light Weight Structures*, Report No 84-8, The Royal Institute of Technology, Stockholm, Sweden.

[14] EN ISO 6892-1 (2009), *Metallic materials - Tensile testing - Part 1: Method of test at room temperature*, CEN, Brussels.

[15] ECCS (2008), *The Testing of connections with mechanical fasteners in steel sheeting and sections*, Publication 124, ECCS, Brussels, Belgium.

[16] Benzar, S., Ungureanu, V., Dubina, D. and Burca M. (2015), "Built-up cold-formed steel beams with corrugated webs connected with spot welding", Advanced Materials Research, Vol. 1111, pp. 157-162.

[17] ABAQUS (2007), *Theory manual*, Hibbit, Karlson and Sorenson Inc.