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Numerical study of cold-formed steel-concrete composite floor system with demountable shear connectors

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Abstract

Except for the main advantage of the composite systems, which is the efficient utilisation of used materials, these structural systems are known for reusability, high degree of prefabrication and long-span capability. Because of these advantages, the range of applications of composite structures is continuously expanded. Since cold-formed steel sections have many benefits compared to hot-rolled sections, their implementation in composite systems has become more attractive to researchers in recent years. This paper represents numerical research on the bending behaviour of composite cold-formed steel-concrete beams. Spot-welding technology for connecting cold-formed steel elements and innovative demountable shear connections with bolts were used as a part of the LWT-FLOOR project at the Faculty of Civil Engineering, University of Zagreb, Croatia. Cold-formed steel elements are built-up beams with back-to-back profiles as flanges and corrugated webs. The obtained results provide the basis for implementing laboratory research on the proposed system. Experimental results of tensile base materials and spot welds behaviour were used to support numerical research. Numerical analyses were conducted in Abaqus/CAE, where the influence of the degree of shear connection, spot weld density, concrete type, steel cross-section thickness and the diameter of the shear connector were analysed. The performed analyses showed that the influence of the degree of shear connection and spot weld density have a significant impact on system behaviour. The influence of concrete type is negligible when comparing the models with the same spot weld density and full shear connection. The same influence becomes greater for models with the partial shear connection. In addition, results show that the thicknesses of the corrugated web and C profile highly influence the bending resistance of the analysed system. Corrugated web thickness results in the highest flexural stiffness and bending resistance in the case of tied steel elements. Furthermore, for steel beam elements connected by spot welds, the corrugated web thickness had a more significant influence on the beam resistance. Regarding the diameter of the shear connector, it is concluded that it has a negligible influence on the bending resistance of the analysed system due to the crushing of concrete for both diameters.

1. Introduction

Considering that cold-formed steel (CFS) sections behave well in combination with concrete slabs, the idea of forming a section composed of mentioned sections has become very popular in recent years. Because of increased architectural requirements for longer spans and/or the openness of space, the main aim for architectural and structural engineers in the design of high-rise buildings is to reduce the self-weight of the floor system as much as possible. The floor system's self-weight reduction is possible by using cold-formed steel sections and lightweight concrete. Besides mentioned requirements, green building design has also become an important requirement. Furthermore, the green building design, which reduces/eliminates the negative impacts on the natural environment, is possible to achieve by enabling the demountability of the system at the end of its service life. Demountable connection is a new contribution to composite systems because traditional shear connectors were welded to the steel beam without the possibility of demounting.

A wide range of shear connector types has been presented so far. The stiffness and bending resistance of CFS floor systems are mainly caused by the number and arrangement of shear connectors. Some types of shear connectors are presented by Shi et al. in the paper [1], where the flexural behaviour of CFS composite beams was analysed. Three different types of shear connectors were observed – slab-to-deck interfacial epoxy, screw and Z-tab connector. A comprehensive review of various shear connectors is shown in the paper [2], where eight different shear connector types

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are presented. Every shear connector is classified as ductile or nonductile, considering the load-slip characteristics. Ductility is also analysed within the paper [3], where the bending resistance of composite beams with nonductile shear connectors is observed. The methods based on the nonlinear theory and the simplified method that assumes a linear relation between elastic and plastic bending moment resistance were employed. The shear connection is realised with bolts in most of the previously mentioned studies. Bolts could be welded to the steel beam [4] or can be mounted through holes, enabling demountability requirements [5–8].

In order to increase the stability of the steel beam, a corrugated web is implemented in the steel beam girders [9]. The shape of a corrugated web can vary, and its application causes an increase in steel beam resistance [10,11]. The corrugated web steel girder is implemented in a composite steel-concrete system in the paper [12].

Considering that cold-formed steel elements have great benefits compared to hot-rolled and that combining different shapes/types of CFS elements is possible to achieve greater stability of the cross-section, built-up cold-formed steel cross-sections have become popular. Built-up CFS cross-sections are usually created from typical sections connected by a web of an unusual shape, such as the corrugated web. The corrugated web and other parts of built-up cold-formed steel elements must be connected in some way. One of the popular connecting techniques of cold-formed steel elements, which enables the automation of the process, is spot welding. This way of connecting the steel elements in built-up corrugated web cold-formed beams is analysed by Ungureanu et al. [13,14]

From all mentioned advantages and considering the available literature collected in the paper [15], the idea of integrating built-up corrugated web cold-formed beams connected using spot welds in the composite system with innovative demountable shear connectors was born. Research is a part of the LWT-FLOOR project [16] at the Faculty of Civil Engineering, University of Zagreb, Croatia. The obtained results provide the basis for implementing laboratory research on the proposed system. This paper represents numerical research on the bending behaviour of this system. Experimental results of tensile base materials and spot welds behaviour were used to support numerical research. The application and influence of normal and lightweight concrete, the influence of different bolt diameters and spot weld density are investigated. Furthermore, the thickness of the cold-formed C profiles and the corrugated web is varied, and their influence was discussed.

2. Laboratory tests of base materials and spot welds

Laboratory research as a part of the LWT-FLOOR project [16] is ongoing in the Structural testing laboratory at the Faculty of Civil Engineering, University of Zagreb, Croatia. Some of the laboratory test results are used to calibrate the numerical model in this paper to achieve more realistic behaviour.

Used tests are performed on the Zwick/Roell Z600 static testing machine. The base materials of steel sheets and base material of bolts which will be used as demountable shear connectors, together with characteristics of different configurations of spot welds (SW), were tested. Used standards are EN ISO 6892-1 [17] for base materials and EN 1993-1-3 [18] for SW characteristics. A short description of the performed tests is described in the following sections.

2.1 Base material testing

The steel sheets' base material tests were conducted for different thicknesses necessary for numerical model preparation. The tested thicknesses are 0.8 mm, 1.0 mm, 1.5 mm, 2.0 mm, 2.5 mm and 3.0 mm. Figure 1 shows the test specimen during the test.

Figure 1: Steel sheet base material testing

Test results from 7 identical specimens were used to calculate the mean true stress-strain curve. The true stress-strain curve is calculated for each thickness as presented in Figure 2 for a sheet thickness of 3.0 mm.

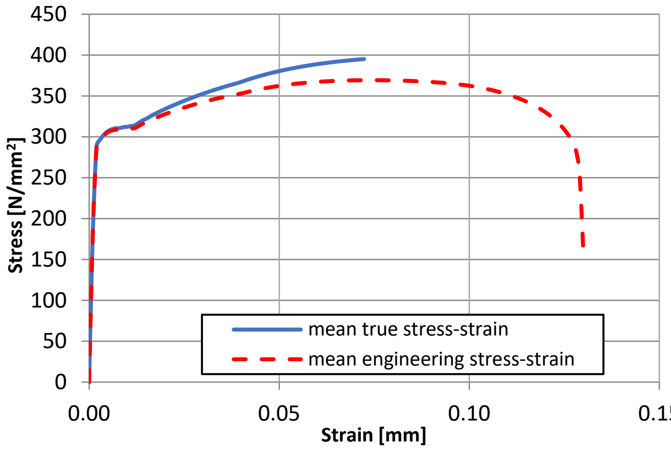


Figure 2: Experimentally obtained mean true and engineering stress-strain curves for 3.0 mm thick steel sheet

Bolts M12 made of steel grade 8.8 were used for a demountable shear connection. Six bolts were machined on the lathe machine according to the standard [17] and tested in tension to obtain bolt material characteristics. Figure 3 shows one specimen after testing. Experimentally obtained mean true and engineering stress-strain curves, Figure 4, are used in Finite Element (FE) analyses.

Figure 3: Tested specimen of the bolt as a demountable shear connector

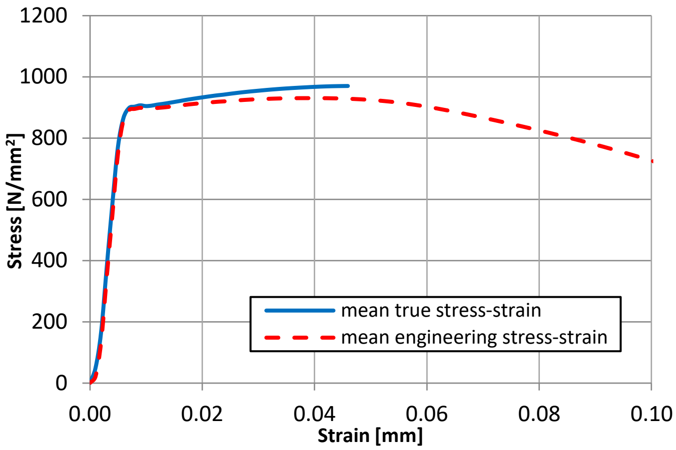


Figure 4: Experimentally obtained mean true and engineering stress-strain curves for the shear connector (bolt)

2.2 Spot weld testing

Figure 5 shows the test of one spot weld configuration. Metal sheets which are connected by spot welds are made from tested metal sheets in different configurations of thicknesses. The sizes of tested specimens are in accordance with EN 1993-1-3 [18], depending on the thinner sheet in the configuration.

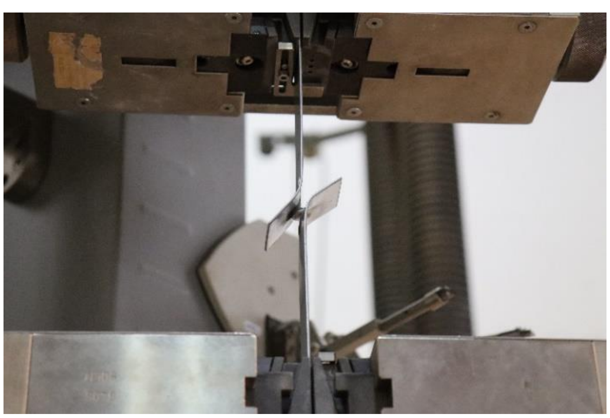


Figure 5: Spot weld testing

Tested and analysed configurations of spot welds are presented in Table 1. From each configuration, at least nine nominally identical specimens were tested. Those configurations are necessary for FE model preparations.

Table 1: Used spot welds

No	Name	The thickness of the first sheet [mm]	The thickness of the second sheet [mm]
1	SW 0.8-1.0	0.8	1.0
2	SW 0.8-2.5	0.8	2.5
3	SW 0.8-3.0	0.8	3.0
4	SW 1.0-1.5	1.0	1.5
5	SW 1.5-2.5	1.5	2.5
6	SW 1.5-3.0	1.5	3.0
7	SW 2.5-2.5	2.5	2.5
8	SW 2.5-3.0	2.5	3.0

Two different types of failure occurred: the interfacial fracture of the spot welding and full button pull-out. Full button pull-out failure mode is characteristic for thinner sheets, approximately up to 2 mm; see Figure 6. Configurations with a metal sheet of 2 mm and thicker had the spot-welding interfacial fracture, as shown in Figure 7.

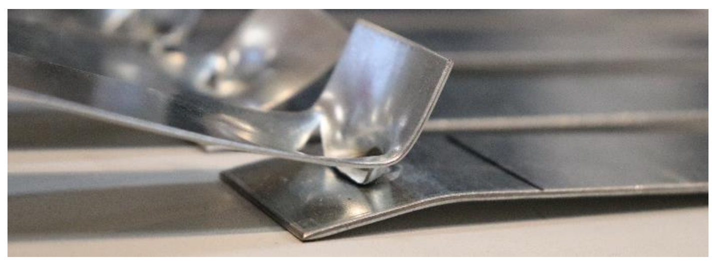


Figure 6: Full button pull-out failure mode of the spot welds

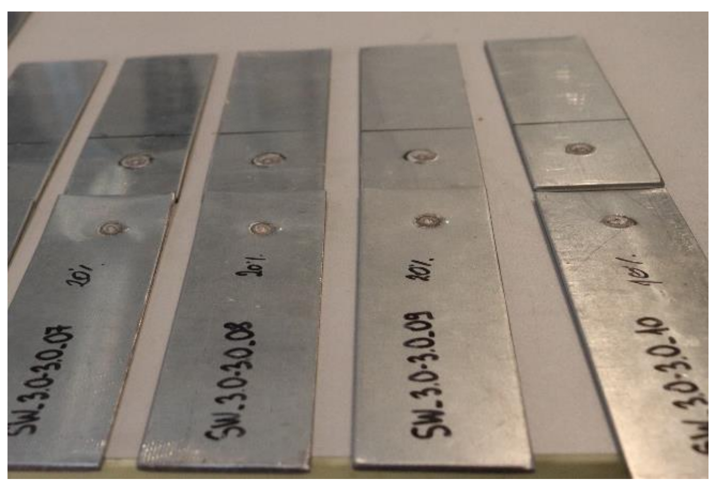


Figure 7: The interfacial fracture of the spot welds

Numerical models in ABAQUS/CAE [19] were calibrated for each combination of base materials in spot weld configuration according to Table 1. The example of calibrated results for specimens with sheets thicknesses of 0.8 mm and 1.0 mm is presented in Figure 8.

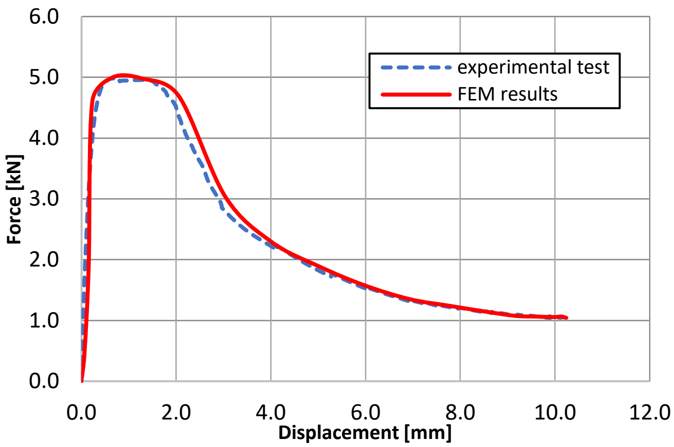


Figure 8: Spot weld testing for specimen SW 0.8-1.0

3. Numerical models

The numerical FE analyses were conducted in ABAQUS/CAE software [19] by using an Explicit analysis because of the large number of nonlinearities. The loading speed is kept at an acceptable level by monitoring kinetic and overall energies during analysis to avoid dynamic effects.

The floor system steel girder is formed from four cold-formed C120 profiles, which are connected in a steel beam by a corrugated web which is reinforced with shear plates at the end of the steel beam, Figure 9. Demountable shear connectors are used to achieve the composite action and to transfer the load between the steel girder and concrete slab. The concrete slab lays on the metal deck, which has openings for the shear connectors. The connection between steel elements, as mentioned before, is achieved by SW.

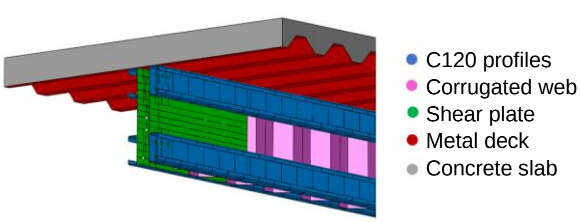


Figure 9: Floor system model in Abaqus/CAE

The length of the analysed system is 6 m, and its overall height is 520 mm. Two different thicknesses of C profiles are observed –2.5 mm and 3.0 mm. Supports are modelled by coupling steel beam elements to one reference point (RP) with allowed rotation and axial displacement to simulate pinned conditions at the holes on the upper C profiles of the composite section (shown in Figure 10).

The loading of the system is realised through a leverage system of four points loading and a vertical displacement in the middle with the maximum value of 100 mm, as shown in Figure 11. Loadings are positioned at distances of 750 mm from the ends of the composite system and 1500 mm from each other.

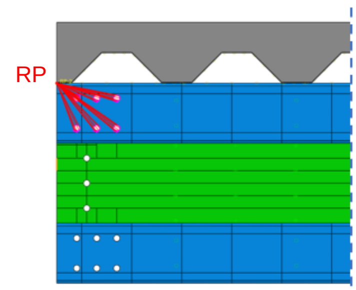


Figure 10: Support conditions

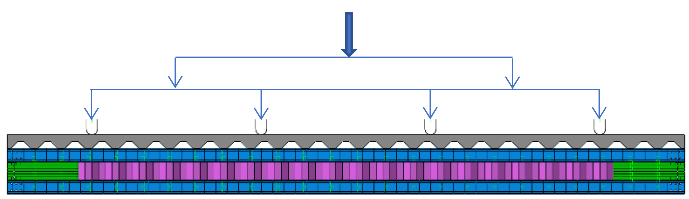


Figure 11: Load transfer

3.1 Materials, finite element types and mesh sizes

In this study, two different concrete classes and types were analysed: normal concrete (NC 25/30) and lightweight concrete (LC 25/28). The Concrete Damage Plasticity model, according to the paper [15] for normal concrete characteristics modelling and its adaptations according to the EN 1992-1-1 [20], were used.

For the preparation of the steel cold-formed elements, shear connectors, and SW characteristics in the FE models, experimentally obtained characteristics from section 2 were used.

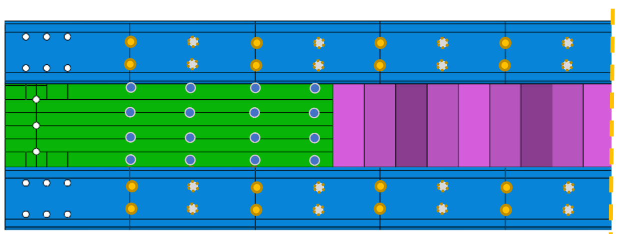
The concrete slab in FE models is defined as an 8-node linear brick with reduced integration with an approximate mesh size of 30 mm. All steel elements are defined as 4-node doubly curved thin or thick shell elements with an approximate mesh size of 20 mm.

3.2 Connection between steel elements

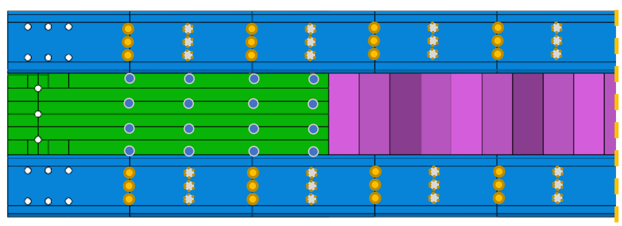
Steel elements are connected in two different ways - by spot welds in two different arrangements or by tie connection, symbolising glue between elements.

Tie connection is formed between contact areas in the models, and it ties the nodes only where surfaces are close to each other. Spot welds are defined by attachment point-based bushing-type connectors with assigned connector sections behaviour from calibration in section 2. Every connector section behaviour is defined by elasticity, plasticity, damage and failure characteristics obtained by calibration with experimentally obtained results presented in section 2. Different connector sections are used depending on the thickness of the elements that are connected.

The vertical arrangement of SW on C profiles to connect corrugated web and/or shear plates is defined by two or three spots, as presented in Figure 12.



a) two SW between C profile and shear plate/corrugated web



b) three SW between C profile and shear plate/corrugated web
Figure 12: Vertical arrangement of SW on C profiles

The longitudinal distance between SW positioned on the same C profiles is 240 mm, which corresponds to the axial distance between the ribs of the corrugated web.

The vertical distances of SW in the cross-section are shown in Figure 13 for both mentioned cases – two and three SW in the cross-section.

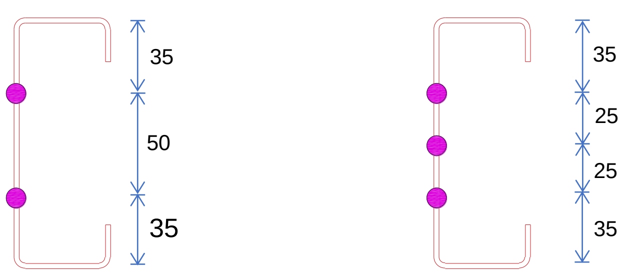


Figure 13: Vertical arrangement of SW in C profiles cross-section

3.3 Demountable shear connection

The shear connection between the C120 section and the concrete slab is established by tie connection and by different arrangements of demountable shear connectors. Tie connection presents the case when the full shear connection is achieved. Demountable shear connectors are defined as B31 elements (a 2-node linear beam in space) with 12 mm and 16 mm diameters. The height of shear connectors is 84 mm according to the condition given in EN 1994-1-1 [21], which requires the height of the shear connector to be at least 2d (d - diameter of shear connector) above the rib of the metal deck. The heights of the concrete slab, demountable shear connectors and steel girder are shown in Figure 14. As a simplification, all shear connectors are modelled without a bolt head. Shear connectors are embedded in the concrete slab, so their lower end is connected to the upper flange of the steel section by a wire element with an MPC Beam connection type.

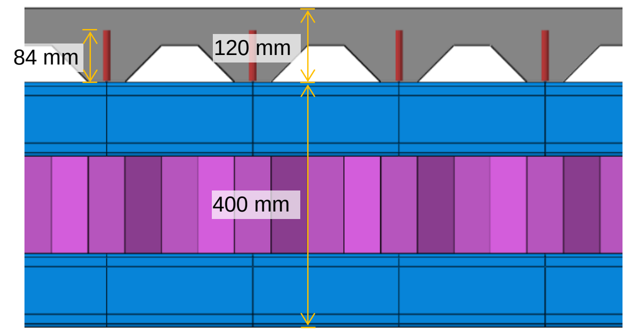
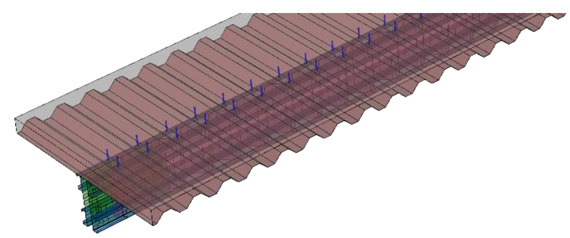


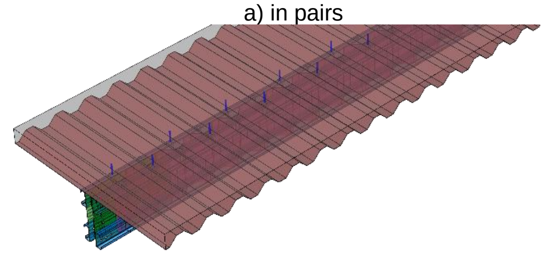
Figure 14: Floor system elements' heights

The longitudinal distance of shear connectors is defined by the ribs of the metal deck which is 240 mm. In the cross-section, connectors are positioned in the middle of the upper flange of the C profile. The distance between connectors within the rib is 112.8 mm.

In order to achieve different degrees of shear connection, shear connectors are positioned in pairs or in a staggered position, as shown in Figure 15.



a) in pairs



b) staggered position
Figure 15: Longitudinal arrangement of shear connectors

4. Results and discussion

In the following subsections, the results of the influence of the degree of shear connection, spot weld density, type of concrete class, steel-section thickness and the diameter of the shear connector are presented and discussed.

Every model has a specific name which gives information about the geometry, type of shear connection, and type of connection between steel elements and concrete class. For example, model 30_400_SP10_CW08_TIE_02_LC2528 has a C profile with a thickness of 3.0 mm, the height of the steel section is 400 mm, and the thickness of the shear plate (SP) is 1.0 mm, while the thickness of corrugated web (CW) is 0.8 mm. The type of shear connection is "TIE", which symbolises the full shear connection, and the number of spot welds is two (02). Other types of shear connection are named SC12C or SC12S, which means that shear connection (SC) is established by shear connectors with a diameter of 12 mm, which are positioned in pairs continuously (C) or staggered (S) arrangement. Analysed diameters are 12 and 16 mm. The used concrete class is LC 25/28.

4.1 Influence of the degree of shear connection

Figures 16 and 17 show the influence of the degree of shear connection on models with normal and lightweight concrete with all steel girder elements connected with tie connection. Diagrams show that the degree of shear connection has a great influence on the bending resistance. Comparing the results from Figures 16 and 17, it can be concluded that the concrete type also greatly influences beam flexural stiffness and bending behaviour. Consequently, the models with normal concrete show higher bending capacity. The highest bending capacity is observed for models with tie, i.e. full shear connection, while shear connectors in staggered positions result in the lowest bending capacity.

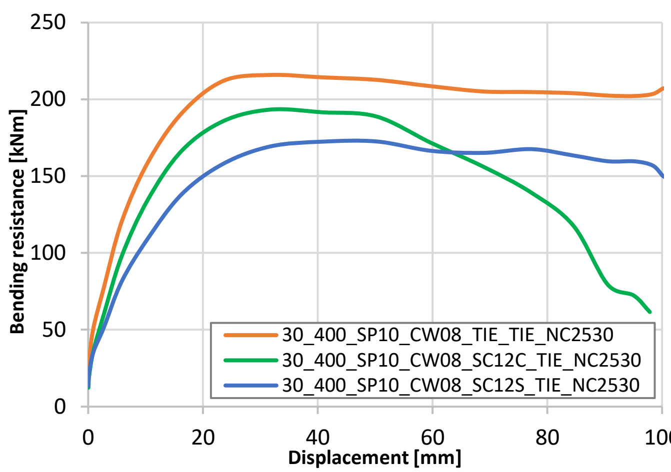


Figure 16: Influence of the degree of shear connection on models with normal concrete NC 25/30

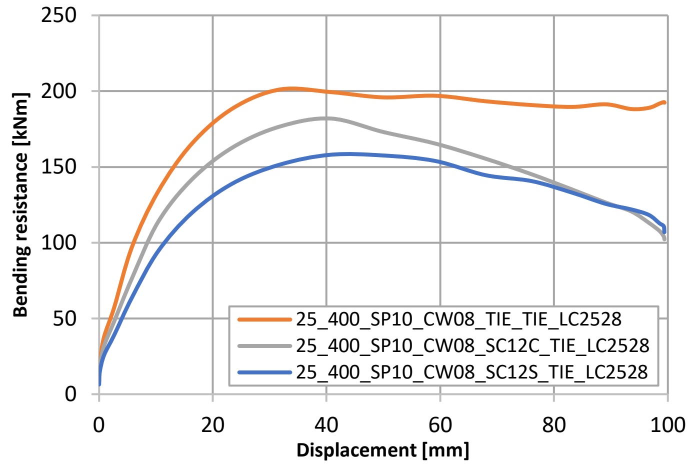


Figure 17: Influence of the degree of shear connection on models with lightweight concrete LC 25/28

4.2 Influence of spot weld density

Figure 18 shows the great influence of SW density for floor system models with the C profiles thickness of 2.5 mm, the corrugated web thickness of 1.5 mm, shear connectors positioned in pairs and lightweight concrete.

The difference between models is in the way of connecting steel elements – by tie connection, by two (02) or three (03) SW.

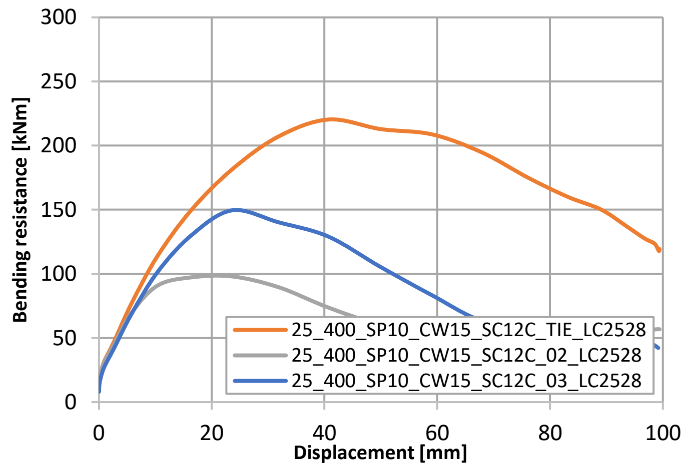


Figure 18: Influence of SW density for models made of corrugated web thickness of 1.5 mm and shear connectors positioned in pairs (SC12C)

In Figure 19, the same influence of SW density is shown on models on tied models and models with bolts in a staggered position with lightweight concrete LC 25/28. It is concluded that spot weld density greatly influences the bending resistance of the analysed system.

Figures 20 and 21 show that similar bending resistance can be achieved in the case when steel elements are tied and when three (03) SW are used.

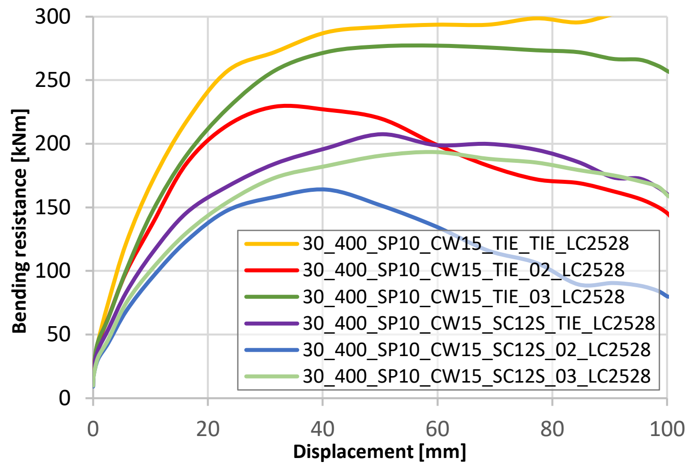


Figure 19: Influence of spot weld density on tied models and models with bolts in a staggered position with lightweight concrete LC 25/28

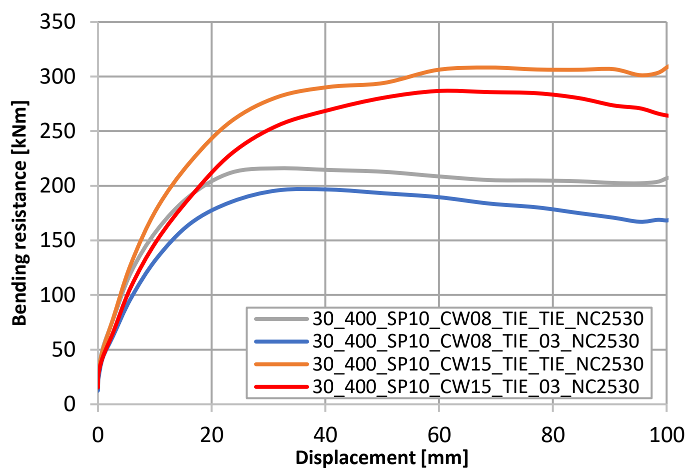


Figure 20: Influence of spot weld density on models with full shear connection

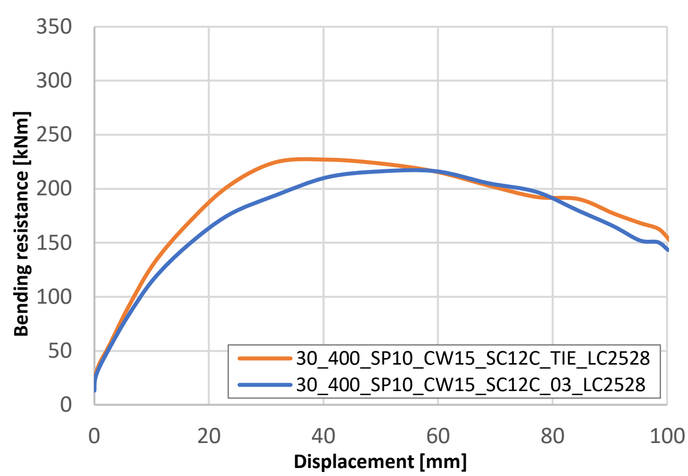


Figure 21: Influence of spot weld density on models with shear connectors positioned in pairs

In the cases presented in Figure 20, when full shear connections were used, three (03) SW resulted in a little bit reduced bending resistance and flexural stiffness, while the results presented in Figure 21 show that in the case of partial shear connection, the bending resistance is almost identical. However, it must be emphasised that such influence is observed only for 3 mm thick C profiles.

4.3 Influence of the concrete type

As previously defined, two different concrete classes were used in analyses – normal concrete (NC 25/30) and lightweight concrete (LC 25/28). In Figure 22, the influence of the type of concrete class is shown in the cases when two and three SW are used. The influence of concrete type is negligible when comparing the models with the same spot weld density and full shear connection.

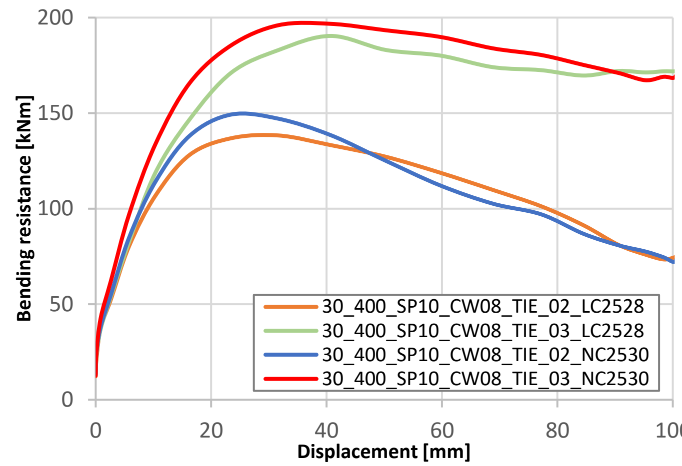


Figure 22: Influence of concrete type in the case of tied shear connection

The same influence occurred for models with partial shear connection (SC12C), which are presented in Figure 23.

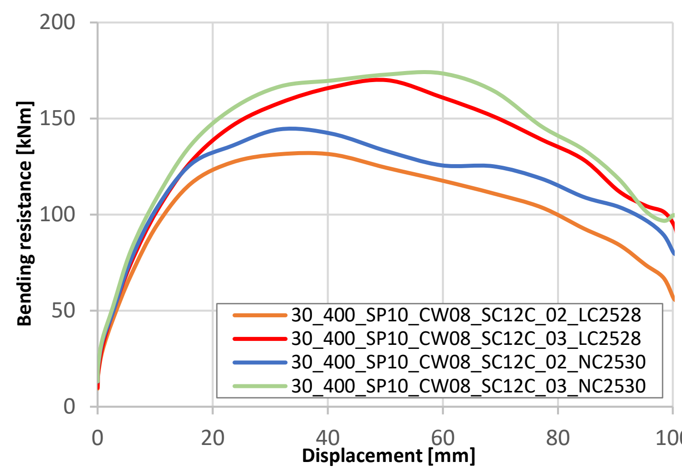


Figure 23: Influence of concrete type for shear connectors positioned in pairs

Comparing the models with the same SW density from Figure 23, the difference in bending resistance is 10-15 kNm.

From the curves presented in Figure 24, it is possible to see a similar influence on tied models and in the case of partial shear connection and different spot densities. Similar results were already presented in Figures 16 and 17.

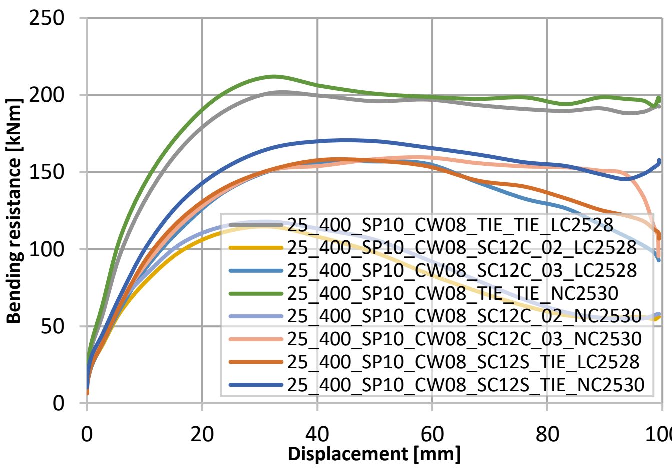


Figure 24: Influence of concrete type for tied models and in the case of partial shear connection and different spot densities

4.4 Influence of steel cross-section thickness

Figures 25 and 26 show the influence of steel cross-section elements' thicknesses. Figure 25 shows the influence of the thickness of corrugated web (0.8 mm and 1.5 mm) for partial shear connection when shear connectors are positioned in pairs for lightweight concrete.

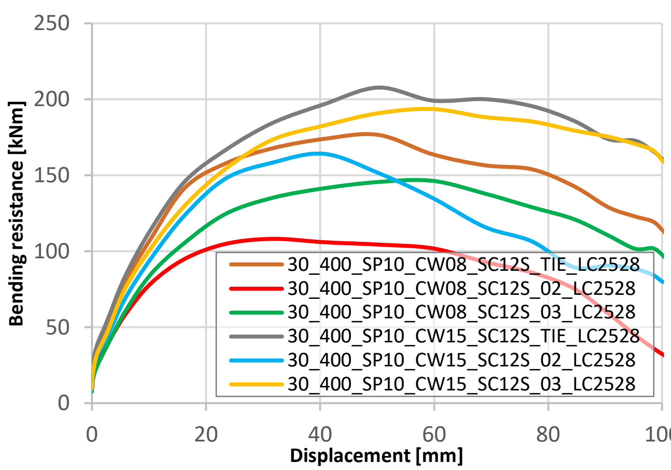


Figure 25: Influence of the thickness of the corrugated web

Figure 26 shows the influence of the thickness of the cold-formed C sections (2.5 mm and 3.0 mm) and corrugated web (0.8 mm and 1.5 mm) for the partial shear connection when shear connectors are positioned in pairs for normal concrete. Results show that the thickness of both analysed elements, i.e., corrugated web and C profiles, highly influences the bending resistance of the analysed system. From Figures 25 and 26, it can be observed that corrugated web thickness in the case of tied steel elements results in the highest flexural stiffness and bending resistance, but in the case of reduced corrugated web thickness to 0.8 mm, the resistance is not significantly decreased. In contrast, for SW-connected steel girder elements, the corrugated web thickness had a more significant influence on the girder resistance. In addition, results from Figure 26 show that increased C section thickness can result in almost identical results for tied and steel elements connected with three (03) SW.

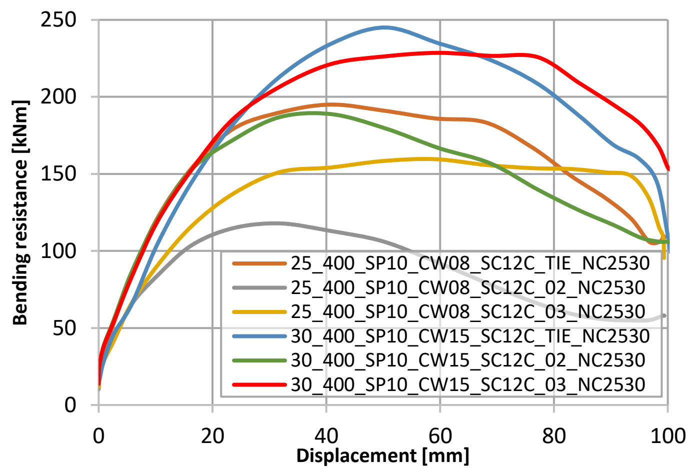


Figure 26: Influence of the thickness of corrugated web and C section

4.5 Influence of the diameter of the shear connector

Figure 27 shows the influence of the shear connector's diameter. As previously mentioned two shear connectors diameters were used, 12 mm and 16 mm.

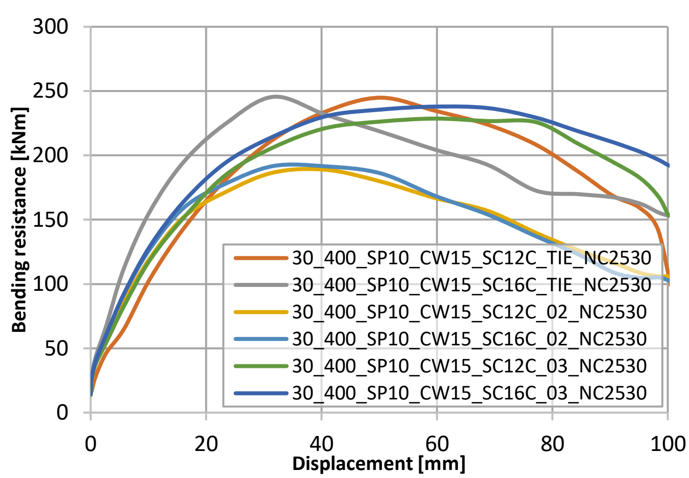


Figure 27: Influence of the diameter of the shear connector

Observing the results shown in Figure 27, it is concluded that the diameter of the shear connector has a negligible influence on the bending resistance of the analysed system. It is assumed that the failure mode of concrete is crushing, and the diameter of the shear connector does not significantly influence this failure mode. As a contribution to this assumption, the PEEQ (Equivalent plastic strain in material - a scalar variable that is used to represent the material's inelastic deformation) values for M12 and M16 bolts were analysed. The values are similar, and the assumption of the concrete crushing failure mode can be confirmed.

5. Conclusions

This paper represents numerical research on the bending behaviour of cold-formed steel-concrete composite floor system. Experimental results of tensile base materials and spot welds behaviour were used to support numerical research. The application and influence of normal and lightweight concrete, the influence of different bolts' diameters and spot weld density are investigated. Furthermore, the thickness of the cold-formed C profiles and the corrugated web is varied, and their influence was discussed. From the performed parametric study within this paper, the following conclusions can be drawn:

- The influence of degree of shear connection has the greatest influence between analysed parameters on the bending resistance.
- Spot weld density was analysed for two different arrangements and in the case when the elements are connected by the whole surface. It is concluded that spot weld density has a great influence on the bending resistance of the analysed system.
- Two different concrete types were analysed – normal concrete (NC 25/30) and lightweight concrete (LC 25/28). The influence of concrete type is negligible when comparing the models with the same spot weld density and full shear connection. The same influence becomes greater for models with the partial shear connection.
- Results show that the thickness of both analysed elements, i.e. corrugated web and C profiles, highly influences the bending resistance of the analysed system. In the case of tied steel elements, corrugated web thickness results in the highest flexural stiffness and bending resistance, but in the case of reduced corrugated web thickness to 0.8 mm, the resistance is not significantly decreased. Furthermore, for SW-connected steel beam elements, the corrugated web thickness had a more significant influence on the beam resistance.
- The diameter of the shear connector has a negligible influence on the bending resistance of the analysed system due to the failure mode, which is concrete crushing.

The obtained results provide the basis for implementing laboratory research on the proposed system.

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