Innovative Lightweight Cold-Formed Steel-Concrete Composite Floor System – LWT-FLOOR project

Ivan Lukačević, Ivan Ćurković, Andrea Rajić, Ivan Čudina
University of Zagreb, Faculty of Civil Engineering, Kačićeva 26, 10000 Zagreb, Croatia
ivan.lukacevic@grad.unizg.hr

Abstract. To provide the foundations for economic and social prosperity, countries worldwide need to be making a term investment in their building assets. However, there is a lack of a systematic approach, such as manufacturing innovations, to maximize the values of building components and materials throughout their entire lifecycle. Steel-concrete composite floor systems are one of the most cost-effective construction systems for multi-storey steel buildings because they combine structural efficiency with the speed of construction. These advantages depend on the efficiency of combining steel and concrete structural elements to avoid their inherent disadvantages. This paper presents a solution that integrates state-of-the-art knowledge in new, fast and productive spot-welding technology and innovative cold-formed steel-concrete composite solutions. The solution proposes a new construction method as a combination of built-up cold-formed steel members and cast-in-place concrete slab. The proposed floor system offers key benefits in terms of a high degree of prefabrication, reusability and long spanning capability.

1. Introduction
To provide the foundations for economic and social prosperity, countries worldwide should be making a term investment in their building assets. However, a lack of systematic approaches, such as manufacturing innovations, is needed to maximize the values of building components and materials throughout their entire lifecycle.

Steel-concrete composite floor systems are one of the most cost-effective construction systems for multi-storey steel buildings as they combine structural efficiency with the speed of construction. These advantages depend on the efficiency of steel and concrete system elements as well as on their interaction in order to avoid their inherent disadvantages. These advantages may be even more significant in the case of the proposed new steel-concrete composite floor systems constructed using innovative built-up cold-formed corrugated web steel girders and concrete slab connected using the innovative shear connections.

Corrugated web beams represent a relatively new structural element that has emerged in the past two decades and was developed for various applications, i.e., the main beams in single-storey steel frame buildings, secondary beams of multi-storey buildings, etc. Due to the thin webs, from 1.5 mm to 3 mm, corrugated web beams, compared to hot-rolled profiles or welded I-sections, allow significant weight reduction. The main benefit of this type of beam is that the corrugated web increases the beam’s stability against local and lateral-torsional buckling and against web crippling, which may result in a more
effective design from both technical and economical points of view. Within the paper, the planned activities of the LWT-FLOOR research project, funded by the Croatian Science Foundation, are presented. To investigate and validate components and the proposed system, extensive experimental, numerical and probabilistic research will be conducted. Within the investigation, a particular focus will be given to spot-welding connections and innovative types of shear connections with the possibility of design for dismantling and the potential for re-use or recycling at the end of design life through the application of lifecycle analyses. Calibrated and validated numerical models based on experimental tests of the entire system and its components will, through probabilistic methods, evaluate the system suitability for larger spans and establish the analytical proposal for design recommendations.

2. Background

When using corrugated web beams, because of the profiling, the corrugated web does not participate in the longitudinal transfer of bending stresses. Therefore, in static terms, the corrugated web beam behaves similar to a lattice girder, in which the bending moments and applied forces are transferred only through the chords, while the transverse forces are transferred only through the diagonals and verticals of the lattice girder, in this case, the corrugated web. Consequently, the girder’s flanges provide the flexural strength of the girder with no contribution from the corrugated web which, on the other side, provides the girder’s shear capacity. Furthermore, the use of thinner webs, without stiffeners, results in lower material cost, with an estimated cost savings of 10-30% in comparison with conventionally fabricated sections and more than 30% when compared to standard hot-rolled beams. For instance, the buckling resistance of 1 mm thick sinusoidal corrugated sheet web corresponds to buckling resistance of a plain flat web of 12 mm thickness or even more.

In previously developed solutions, already available on the construction market, the flanges are flat plates, welded to the sinusoidal web sheet, requiring a specific welding technology [1], [2]. Almost all research on this kind of girders was devoted to studying only bending and shear capacity [3]–[7]. The design of corrugated web beams is ruled by Annex D of the EN 1993-1-5:2006 [8]–[10].

Steel-concrete composite action has been widely used in civil engineering due to multiple benefits that occur through the combination of favourable mechanical properties of steel and concrete. The structural steel is characterized by high tensile strength and ductility, while the concrete is characterized by high stiffness and high compressive strength as it can be found in [11].

The main benefits of using composite beams are [12]:

- Weight savings of steel between 30 to 50% can be achieved when compared to non-composite beams;
- The increased stiffness of composite beams can result in the reduction of beam height when compared to non-composite beams of the same span which can lead to lower storey heights and a reduction of cladding costs or allowing more space for mechanical services.

The most common version of composite beam is constructed of hot-rolled steel beam connected to a composite slab using shear connectors where the floor slab increases local as well as lateral stability of the steel beam.

Here, the cold-formed profiled steel sheeting is an integral part of the structural system and it provides additional benefits [12]:

- It acts as a safe working platform in the construction phase and protects the workers below;
- It supports the loads during construction and may eliminate the need for temporary propping;
- It acts as permanent formwork for the concrete slab;
Through mechanical or frictional interlock, composite action with the concrete can be developed such that the sheet provides all or part of the main tension reinforcement of the slab;

Through the provision of through-deck welded stud shear connectors, the composite slab may be used to provide lateral restraint of the steel beams.

Despite the popularity of composite beams, composite members are still a subject of continuous development. An overview of the current development in steel-concrete composite beams and flooring systems can be found in [13]. Also, the suitability of using compact concrete with lightweight aggregates for composite steel and concrete beams has been investigated in [14]. The article is based on a parametric study and summarizes the results of numerical analyses of composite steel-concrete beams with normal and lightweight concrete slabs.

Furthermore, the shear connection represents an important aspect in the structural behaviour of steel-concrete composite beams to provide joint action of these two individual parts. It is characterised by a level of the shear connection which can be defined as the ratio between the shear connection capacity provided by the studs and the longitudinal capacity of the weakest component (steel beam or concrete slab) [11].

Despite many known methods of connection used in composite beams, research on new shear connection solutions is still very popular to improve the existing solutions or to develop new ones. One interesting shear connection solution uses demountable headed shear stud connectors. The Life Cycle Assessment allows quantification of the environmental benefits arising from the implementation of the demountable structural composite floor system, which could be disassembled and reused at the end of the building service life [15]. Results from this paper are encouraging when the demountable system is compared to the conventional monolithic ones destined for demolition and recycling. Such type of shear connector, e.g. special type of bolts, enable dismantling of the slab in case of renovation or modernization, which is impossible when traditional shear studs are used. In papers [16], [17] research on such demountable headed shear stud connectors together with the use of ultra-high performance concrete have been carried out. An example of demountable headed shear stud connectors is shown in figure 1.

![Figure 1. Examples of demountable headed shear stud connectors](image)

The proposed shear connectors show excellent ductility in comparison to traditional solutions. The push-out tests were conducted for various types of fasteners, changing their shape, diameter and bolt class, and the obtained results showed that the average slip was close to the value required by the EN 1994-1-1 [18]. In the paper [19] a series of push-out tests on profiled steel sheeting and beam with demountable shear connectors have been carried out. Comparison to the beam test with welded shear connectors showed that the beam with demountable shear connectors has similar stiffness and superior ductility.

An innovative type of shear connector, a continuous furring channel, has been presented in the papers [20], [21]. In that case, the structural system consisted of a steel beam comprising two cold-formed C sections, a corrugated steel deck, a furring channel and a concrete slab with transverse reinforcement. Self-drilling fasteners were used for the connection of the steel parts. This type of shear connector is
similar to composite dowel rib connectors, figure 2., which also represents an innovative and promising shear connection solution [22].

![Figure 2. Possible solutions using composite dowel rib connectors](image)

Other solutions of steel-concrete composite systems using cold-formed steel elements can be found in the literature [23]–[27]. Application of cold-formed sections in steel-concrete floor systems leads to some of the advantages as given below [28]:

- The possibility of reducing overall slab depth by using lighter sections at closer spacing;
- Easy variation of the cross-section for irregular layouts;
- Freedom in the design of cross-sections. Cold-formed sections are made from flat sheets and can be designed and manufactured to a specific need. It is relatively easy to produce built-up members from sections and flat strips that are screwed or spot-welded together;
- Flexibility in assembling the sections and attached components in the workshop and/or on-site;
- The technology for manufacturing cold-formed sections is simple and available in regions and countries where a large selection of hot-rolled profiles is not available in a short time, particularly for small or medium projects.

Through the years, composite elements consisting of steel and concrete have not, for various reasons, had the chance to be applied to a great extent – certainly not to the extent that they deserve [29]. However, bearing in mind all previously stated facts, the proposed LWT-FLOOR system, as an innovation which maximizes the values of each building component and material that are being used, can give a new opportunity for the application of composite elements.

As in the case of the shear connection for the overall composite behaviour of a system, the technique related to the connection of the cold-formed steel elements has also very important role. A wide experimental investigation on laser-welded connections based on both lap-shear and tension tests were performed in [30]. In [31] a comparative study was performed on the resistance of self-pierce riveting, resistance spot welding and spot friction joining, identifying the resistance of spot welding as a most favourable option. Guenfoud et al. [32] have 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.

The main benefits of build-up corrugated web elements using fixed supports have already been summarised and demonstrated through research investigation on such types of beams connected using screws [33]–[35], Spot Welding (SW) and Cold Metal Transfer (CMT) technique [36]–[38]. CMT, particularly, developed in the last years, is a new connection technology to be applied for building steel structures. Since the technical solution of such types of beams enables standardisation of detailing in design and fabrication, both SW and CMT welding techniques are appropriate for application where
Automated fabrication is used. Therefore, besides the structural advantages of such a system, the potential for automated serial fabrication of the new technological solutions is another great advantage.

In the proposed solution the connections between steel elements on built-up cold-formed steel members will be fabricated using the intermittent spot-welding technique, avoiding the difficulties of traditional arc welding and specific technologies, and thereby significantly increasing the speed of fabrication.

In [36]–[38], for the purpose of full-scale tests, two beam specimens were fabricated using the SW connection technique, i.e. CWB SW-1 and CWB SW-2. The components of the built-up beam specimens, which were 5157 mm long and 600 mm high, are shown in figure 3.

![Figure 3. Components of the built-up beams](image)

Except for the difference between the shear panel thickness of the two beams another aspect of interest was the connection between the corrugated web steel sheets. For that purpose, corrugated steel sheets were connected using the same number of spot welds but with a different configuration, i.e. the corrugated sheets of beam CWB SW-1 were connected on two rows, while the corrugated sheets of beam CWB SW-2 were connected on one row only.

Results show that the behaviour of both beams, CWB SW-1 and 2, was ductile with excellent load-bearing capacity. Compared to the previously studied solution, i.e. built-up beams using self-drilling screws [33]–[35], it can be seen that the beams connected using the spot-weld technique possess higher stiffness, as well as higher load-bearing capacity.

The numerical parametric research on such solution was a part of Unity Through Knowledge Fund (UKF) Gaining experience project “Investigations on spot-welded built-up cold-formed steel beams”. The focus of the UKF project was calibration and validation of the numerical models with additional experimental tests considering the influence of web openings on previously tested beams which was, again, followed with parametric numerical studies [39]–[41].

3. LWT-FLOOR project
This project aims to investigate and validate a new technological solution for steel-concrete composite floor system composed of built-up cold-formed steel members with webs made of trapezoidal cold-formed steel sheets and flanges of back-to-back lipped channel sections and cast-in-place concrete slab in corrugated steel deck which acts as formwork for the concrete slab having an innovative type of shear connector.

The project integrates state-of-the-art knowledge in new, fast and productive spot-welding technology and innovative cold-formed steel-concrete composite solutions proposing a new
construction method as a combination of built-up cold-formed steel members and cast-in-place concrete slab. This potentially cost-effective floor system offers vital benefits in terms of a high degree of prefabrication, reusability and long spanning capability.

To investigate and validate components and the proposed system, extensive experimental, numerical and theoretical research is planned. Within the research, a particular focus will be given to spot-welding connections and innovative types of shear connections with the possibility of design for dismantling and the potential for re-use or recycling at the end of the product design life through the application of lifecycle analyses. Calibrated and validated numerical models based on experimental tests of the system and its components will, with the support of probabilistic methods, allow evaluation of the system suitability for larger spans. All the accumulated knowledge will be the basis for further structural detailing, including the possibility of automated mass production. Analyses and performance evaluation of the proposed floor system solution will be crucial for establishing an analytical proposal for the design of the system.

The research methodology within this project consists of experimental, numerical, analytical and probabilistic methods. It is presented for each of the research objectives as follows:

Within the literature survey, state-of-the-art knowledge at the beginning of the project will be followed by preliminary numerical research and the design of specimens for experimental testing. Experimental research will be divided into five phases. In the first two phases, experimental research of LWT-FLOOR system materials and spot welds between different cold-formed sheet thicknesses will be performed. Because of the great importance of the shear connection between the steel and concrete part of the system the third phase will include experimental tests on the shear connection. To obtain a reliable numerical model for further parametric research (to choose optimal solution) the proposed two alternative solutions of shear connection (see figure 4.) will be experimentally tested using standard push-out test procedure according to EN 1994-1-1 [18]. The results from the push-out test will be implemented in the numerical models and it will be compared with the result of the bending test of large-scale specimens for calibration of the numerical model of the overall system. Finally, probabilistic analyses based on collected data will be performed to investigate the influence of particular basic variables on the reliability of the system components with specific attention to different shear connections.

Within phases 4 and 5 of the experimental research of full scale LWT-FLOOR system will be conducted. The span of tested elements will be approximately 6 m which corresponds to typical spans of floor systems in multi-storey buildings. Elements will be loaded with four equal concentrated forces according to figure 5. In order to understand the behaviour of corrugated built-up cold-formed girder without and with web openings tests of the girders without concrete slab will be conducted.

![Figure 4. Proposed solutions for shear connection](image-url)
Figure 5. LWT-FLOOR system (proposal for test set-up)

The numerical part of the research, based on calibrated numerical models, will allow parametric research of the proposed solution. Running numerical models, generally, is more cost-effective solution instead of conducting experimental tests, particularly ones in full scale. Reliable, calibrated and validated numerical models will be used to conduct parametric numerical studies. The stresses and displacements in the steel and concrete parts as well as cracking in concrete will be assessed. In the first phase, the numerical models of shear connection in combination with probabilistic analyses will provide a selection of the optimal solution of the shear connection. The second phase of numerical research will consist of numerical modelling of built-up corrugated web beams without and with web openings. Calibrated numerical models will provide a foundation for parametric studies to find the optimal solution for larger spans, and different configurations of web openings. Furthermore, calibration of a numerical model for composite LWT-FLOOR system and numerical parametric studies in combination with probabilistic analyses will be used to evaluate the suitability of such system for larger spans and to find optimal dimensions of particular system components by accounting for different configurations of the shear connection and boundary conditions. Finally, the proposed system will be analysed through lifecycle analyses using a holistic approach combining Lifecycle Assessment (LCA), Lifecycle Costs (LCC) and Lifecycle Performance (LCP) analyses.

According to [13], nonlinear analysis models of composite elements and frames can be generally categorised into micro-models using continuum finite elements, and macro-models using macro-elements such as line elements and spring connections. The micro-modelling approach can be used to simulate the behaviour of composite members with better resolution than the macro-modelling approach. However, micro-models consume more time especially for the nonlinear analysis of a structural system or a complete structure. They use extremely fine meshing techniques which involve finite elements with dense distributions and such models will be used in the proposed research.

Analytical models for design recommendations are desirable to explain the load-bearing process in a comprehensible way. To implement the LWT-FLOOR system a design guide for the shear connection types and steel and composite system behaviour is necessarily required. Based on probabilistic analyses and life cycle analyses, evaluation of the analytical proposal will be established for: analysed types of shear connections, steel girders with and without web openings, and composite LWT-FLOOR system without and with web openings.

4. Conclusions
Due to their significance in the political economy the request for sustainable structures and structural systems, meaning highly advanced, cost-effective, environmentally friendly and long-lasting, is outstanding. Steel-concrete structural systems are, therefore, due to their efficiency, increasingly used in the construction industry and are becoming the subject of intensive research by the world's leading universities and companies.
The LWT-FLOOR project integrates state-of-the-art in new and productive spot-welding technology and innovative cold-formed steel-concrete composite solutions in order to develop a cost-effective and sustainable floor system. The system offers vital benefits in terms of a high degree of prefabrication, reusability and long spanning capability to maximize the values of building components and materials.

The system consists of built-up cold-formed steel members with webs made of trapezoidal cold-formed steel sheets and flanges of back-to-back lipped channel sections and cast-in-place concrete slab in corrugated steel deck which acts as formwork for the concrete slab. The system will also result in the development of innovative types of shear connections to obtain a competitive composite floor system.

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