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A REUSABLE STRUCTURAL SYSTEM FIT FOR GEOMETRICAL STANDARDISATION AND SERIAL PRODUCTION

Christoph Odenbreit[a], Jie Yang[a], Alfredo Romero[a] e Andras Kozma[a]

[a] *ArcelorMittal Chair of Steel Construction, University of Luxembourg, Luxembourg*

Abstract: A series of demountable connections for reusable composite flooring systems and a standardized adjustable steel connection have been developed and tested, to facilitate circular economy as well as the serial production of structural elements and the suitability to be added into BIM or other digital tools. Demountable beam and floor elements and adjustable steel connections form the basis of a Lego-liked 'plug and play' circular framed structural system. This paper presents the proposed circular system, the results from experiments and finite element analyses and indicates the analysing methods for structural engineers to open a path way for fully implementation of the structures 'as built' into digital tools, fabrication and construction.

1. Introduction

Recently in the building and construction sector, there have been technical developments and reuse strategies targeting for carbon neutrality and resource efficiency associated to building structures, to contribute to the move from a linear economy to the so-called circular economy. The developments covers sustainable materials dedicated to partial substitution of carbon-intensive constitutes such as cement [1], and use of recycled aggregates in concrete products [2], high-performance materials [3] which may reduce material usage and also have a higher end-of-life value, green materials such as timber [4], use of renewable energy for material production [5], and demountable structures for deconstruction of buildings and reuse of components [6, 7], etc.

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Compared to material reuse in making new building components and material recycling into new building materials, designing the building structure to be deconstructable and structural components reusable have certain advantages in terms of decarbonation in constructions. It provides better adaptability when it comes to the scenarios of building reuse in place (refurbishment) and building relocation. Particularly, it makes component reuse possible in a new building, which reduces the need for new materials and avoids unnecessary wastage, and therefore makes the components be part of the continuous chain of construction products ecosystem.

Composite structures are widely used for multi-storey buildings due to structural efficiency. However, the current practices are not compatible with the reclaim and reuse of building structural elements in their entity. In the current practices, building structures are demolished after service life with materials sent to recycling, down-cycling or land-filling. Among others, the EU RFCS project REDUCE [6] explored the strategy of design for deconstruction and reuse for steel-framed composite structures to maximize the potential of reuse of structural elements at the end-of-life of the building structures with minimum remanufacturing. The aim is to significantly reduce the emissions, energy usage associated to material reproduction, and eliminate waste after the end of service life of building structures.

A series of demountable connectors for composite flooring systems has been developed and tested within the frame of REDUCE in the form of push-out tests according to Eurocode 4 and beam tests. They are found to have comparable performance with the welded connectors but provide full demountability. Used in combination with prefabricated concrete composite floor slabs of a standardized, grid-oriented size, these elements are fully suitable for serial production. The viability of the demountable composite system has been proven by numerical simulations and laboratory tests. Detailed experimental test campaign, numerical simulations and calculation methods for the demountable shear connections and beams tested at the University of Luxembourg are given in the theses by Kozma [8].

The connections at beam-to-beam and beam-to-column play a key role and a standardized layout for the respective connections is proposed within REDUCE. This design is suitable for use in both beam-to-beam and beam-to-column connections with adjustable connecting elements. The design promotes the standardization of the connections and also the length of secondary beams, therefore facilitates the suitability for serial production of structural elements and the suitability to be added into BIM and other digital tools. The demountable beam and floor elements and the adjustable steel connections form the basis of a Lego-liked ‘plug and play’ circular system.

This paper presents the proposed circular system developed within REDUCE. The key results from experiments and finite element analyses and analysing methods are presented, which open a path way for fully implementation of the structures ‘as built’ into digital tools.

2. Demountable and reusable steel-framed structural system

Fig. 1 presents the developed demountable and reusable steel-framed structural system. The Lego model in Fig. 1 (a) illustrates (i) modular prefabricated composite slabs connected to their supporting steel beam by using bolted connections, (ii) a steel beam connected to column flange with an L-profiled steel connecting element, (iii) a steel beam connected to column web with an identical element used in (ii). This connecting element comprises an end plate with fit bolt holes and an fin plate with elongated bolt holes which allows the plate to bridge a wide range of column profiles and beams in various length. Fig. 1 (b) shows a composite slab detached from its supporting steel beam and demonstrates the demountability of the composite beam. Relating experimental test campaign includes fifteen standard push tests on the bolted connections, two full-scale 6-m-span beam tests, and one test on the beam-to-beam connection by using the L-element. The overview of the experiments and corresponding finite element simulations are given in Sections 3 and 4. More details about the experiments can be found in papers by Kozma et. al [9,10], and Odenbreit & Kozma [11].

The developed system may contribute to serial and standardized production in the following aspects:

- Typical floor grids: based on data collected, among 1.20m, 1.25m and 1.35m, the grid of 1.35m is the most typical planning grid with the typical column spacing of 5.4m or 8.1m. In this case, the width and length of the composite slabs and the nominal lengths of beams are the multiple of the basic module size 1.35m.
- Standardized steel connections: for beam-to-beam and beam-to-column connections within the same frame structure.
- Standardized nominal beam length: for secondary beams, the length may be standardized but the beams can still be re-used in the same grid later in another building but with a different column dimension thanks to the proposed adjustable L-profiled steel connection (the adjustment distance depends on the length of the slotted holes in the L-plate).
- Demountable shear connections between slab and beam: designed for pre-fabricated composite slabs which may have a standardized geometry.

a) 3D-printed model of steel frame with modular slab and adjustable connection

b) Demountable composite beam with composite slab detached from beam

Fig. 1: Demountable and reuseable steel-framed structural system

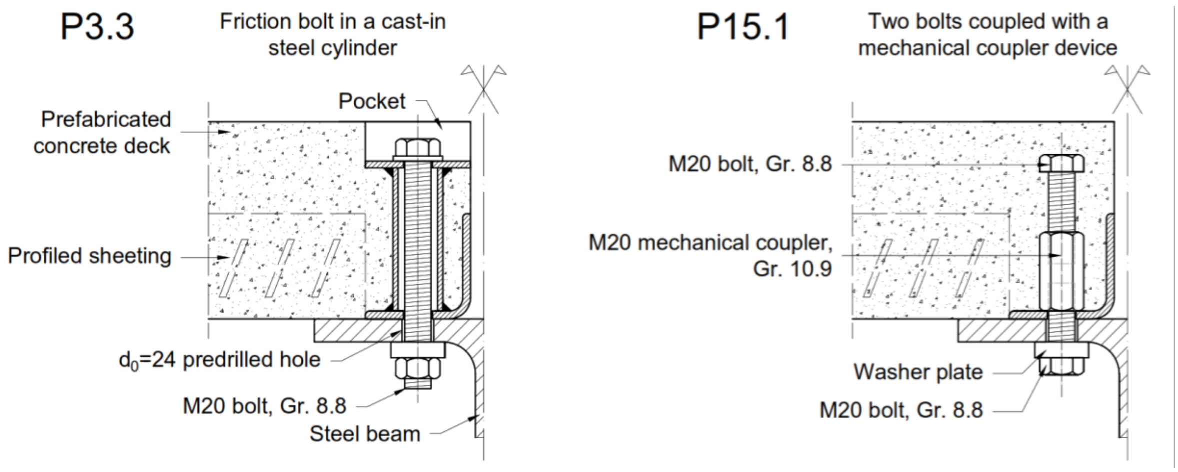
3. Demountable composite flooring system

3.1 Demountable shear connections

For structural efficiency, the floor slabs and their supporting steel beams are working compositely to improve stiffness and resistance. Conventionally, the slabs and beams are connected by using headed studs with the studs embedded in concrete and welded onto the top flange of the steel beams. This makes the slabs not detachable from the beams and the separation of the composite beams a cost- and labor-intensive work. With the use of bolted connections, the composite beams are demountable and the flooring system can be reassembled for re-use.

Fig. 2 illustrates two types of demountable shear connection designed for composite flooring system with pre-fabricated composite slabs. The shear connection type P3.3 allows installation access from the top of the composite slab, while both type P3.3 and type P15.1 allows the connecting bolts replaceable in case of any damage during assembly, disassembly of composite beams and after first use of structures. Noted that a metal L-profile is used to reinforce the concrete edge of the composite slab at the vicinity of the bolted connection. When bolts are used in cast-in cylinders (P3.3) that are welded to the L-profile, special care is required during the welding process to avoid any excessive deformation. The shear connectors may be pretensioned or using injection bolts to control initial slips between beam and slab.

The shear connections should provide certain resistance and ductility to ensure the combined use of composite slab and steel beam and enhanced beam resistance and stiffness. The performance of the proposed shear connections has been tested in the form of push tests and composite beam tests in accordance with EN 1994-1-1 [12] and validated by using finite element simulations.



a) Shear connection type P3.3 b) Shear connection type P15.1

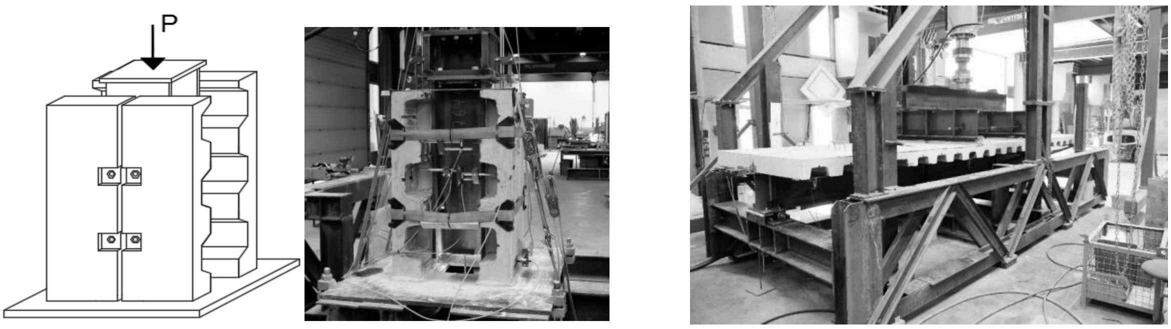
Fig. 2: Developed demountable shear connections

3.2 Experimental test campaign

Standard push tests can determine the most important characteristics of the shear connections such as shear resistance, deformation capacity, stiffness and ductility. The test specimen consists of a steel beam and symmetrical slabs connecting to both beam flanges, as shown in Fig. 3 (a). During the tests, a vertical load is applied from the top of the steel beam by using a hydraulic jack and the response of loads and displacements is measured which reflects the performance of the load-slips of the shear connection. In summary, the following outcomes are found from the conducted push-out tests:

- The tested demountable shear connections have comparable performance compared to welded headed studs: with higher resistance and deformation capacity, lower stiffness, and a brittle mode of failure. Noted that when the demountable shear connections are classified to non-ductile shear connections based on provisions specified in EN 1994-1-1, plastic redistribution of the internal forces is not allowed to be assumed in design, and the application of partial shear connection theory is not applicable.
- The tested demountable shear connections are robust: the failures are found occurred in shear fracture of the bolts which are replaceable later for re-use, while no damage in the steel beam and the concrete slab. Reuse tests have been performed on two most heavily loaded push test specimens with newly replaced bolts to represent the second life of the composite beam structure. The re-assembled specimens are found to have similar performance compared to the original specimens, and therefore demonstrates the reusability of the composite beams with the developed demountable shear connections.

Fig. 3 (b) illustrates the bending test set-up for composite beams comprising the developed demountable shear connections. The beam specimens have a clear span of 6 meters with a uni-form shear connection spacing of 600mm depending on the profile of the steel decking of composite slabs. The spacing corresponds to a nominal degree of shear connection of 37% which is slightly lower than the specified value for welded headed studs in EN 1994-1-1. The composite slab elements are pre-fabricated and bolted to the steel beam. The steel beam is supported along its length during the installation, which corresponds to a propped construction technique. During the bending tests, the composite beams are simply supported and are subjected to two-point loading by using a hydraulic jack with the help of spreader beams. The section between the spreader beams of the composite beam is subjected to a constant shear force. Loading cycles are applied. Shear connection failure and concrete crushing due to high deformation are found the governing mode of failure for each of the composite beam specimen, respectively. In order to compare the performance of beams using demountable shear connection and those using welded headed studs, the geometry, materials and loading setup and procedures are designed as nominally identical to a benchmark test performed within a preceding RFCS project named DISCCO [13]. Experimental results demonstrate that the demountable composite beams perform similarly to the conventional beams but have relatively larger deformations at the same load levels due to the low stiffness of the beams. After the tests, the demountable beams can be dismantled easily by using hand tools even through large loading displacement is applied and failures of specimens have occurred, which shows good demountability of the composite beams using the developed shear connections.

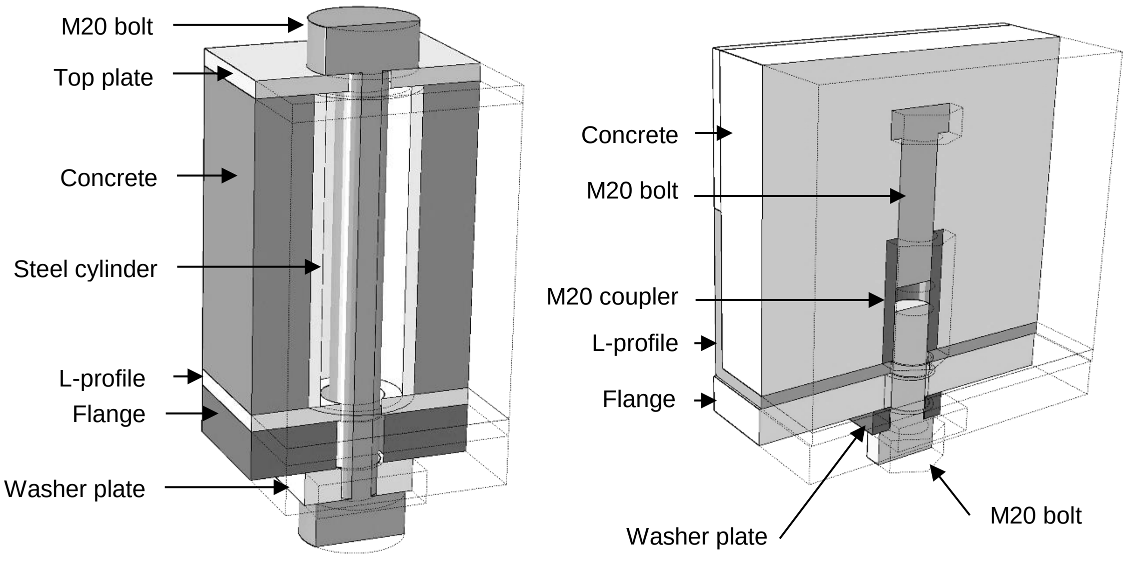


a) Push test on shear connections b) Bending test of composite beam

Fig. 3: Experimental test campaign

3.3 Finite element simulation

Fig. 4 presents the finite element models created by using ABAQUS© [14] to simulate the push tests. Only the vicinity of the shear connections are modelled as there is no damage observed from push tests elsewhere. The obtained FE results are found comparable to the experimental results with sufficient accuracy. Virtual experiments are performed to assess the parameters of materials grades, diameter of bolts, pretension loads, and surface treatments. It has been found that material strength, pretension load, the friction coefficient and the bolt hole clearance are the most important parameters for the load-slip behaviour of the demountable shear connections. The simulation work of the beam tests and the corresponding parametric studies are presented in paper by Odenbreit & Kozma [15].



(a) (b)

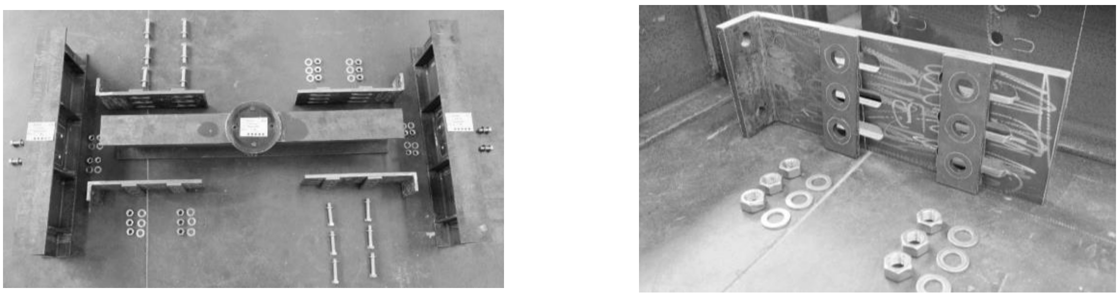
Fig. 4: Components of the FE model (a) System P3, (b) System P15

4. Adjustable steel connection

4.1 Design of the adjustable steel connection

Connections designed for standardizations may contribute to the serial production as well as the efficient reuse of steel members/components. The most commonly used connections such end plate and fin plate connections are usually – with end plate or fin plate welded at one side onto the column or beam member, and the other side bolted to the other connecting member. When these types of connections are used, the beam length is traditionally manufactured with only some millimeters of tolerances for erection and installation. In terms of reuse elsewhere within the same planning grid (column spacing) but connected to columns with different sizes, the beams will need to be re-manufactured (length modification), i.e. the beam length is not standardized.

To enable a “standardized nominal beam length” which is suitable for a wider range of column profiles and serial production, an extendable steel connection has been developed, as shown in Fig. 5 (a). This connection comprises an L-profiled plate, as shown in Fig. 5 (b), which has slotted holes that allows 100 mm adjustment. With the possibility of adjustment, the beam with standardized length may be connected to column flange, column web or to primary beam. The same principle may be applied when the beam is connected to a reinforced concrete wall.



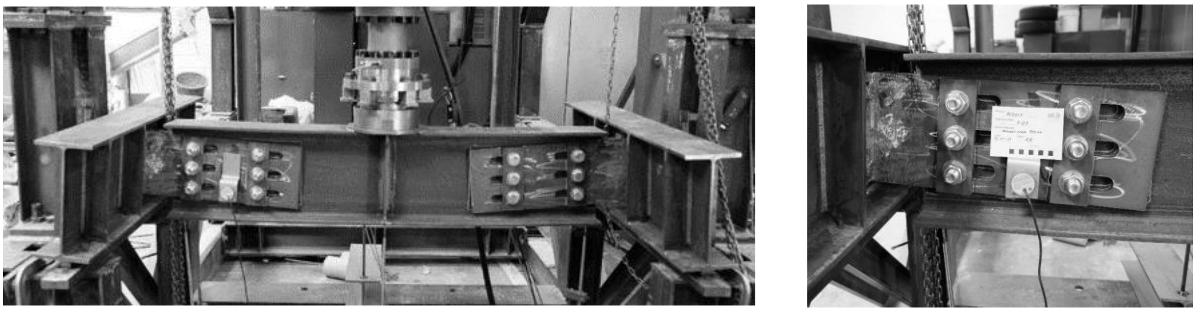
a) Steel connection kit b) Connecting elements

Fig. 5: Adjustable steel connection designed for use in both beam-beam and beam-column connections

4.2 Experimental test campaign

As shown in Fig. 6, the developed adjustable steel connection is connecting a secondary beam to primary beams and tested to failure. The primary beams are pin-supported, and the secondary beam is loaded at mid-span by using a 1000kN capacity hydraulic jack during the test. The following outcomes have been found:

- Governing mode of failure: bearing failure of the web of the secondary beam.
- Specimen can take further loading, up to twice as much as the bearing resistance.
- The connection element is capable of transferring the shear force without developing significant bending moments in the supporting members.
- The joint is classified as a nominally pinned joint based on EN 1993-1-8 [16] and can be designed using the current Eurocode 3 formulae.



a) Steel connection b) Connecting elements

Fig. 6: Adjustable beam-to-beam connection after test

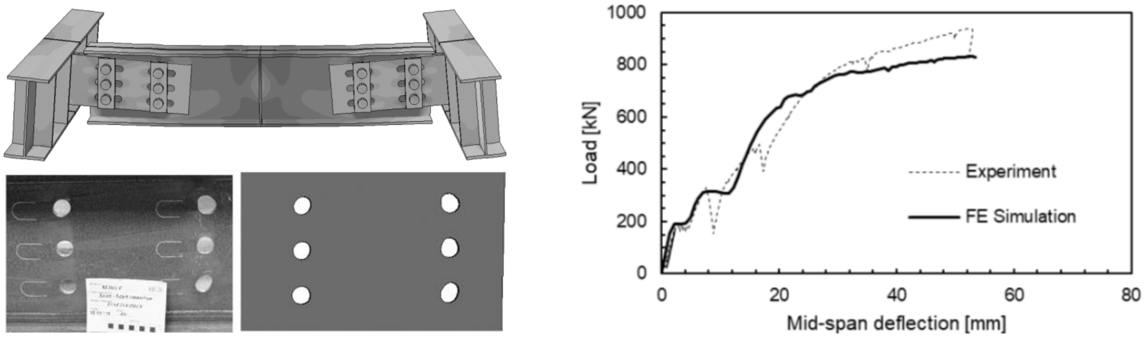
4.3 Finite element simulation

The experiment is simulated by using the nonlinear finite element software ABAQUS© and dynamic explicit solver technique. For simplicity, the radii of the sections and the threads of the bolts are neglected in the model.

Main modelling details are summarized as follows:

- "Damage for ductile materials" for steel elements with the material law calibrated against standard tensile specimens following similar approaches presented in Pavlovic [17].
- "C3D8R" finite elements (8-node linear brick, reduced integration).
- "General Explicit Contact" for the modelling of the contacts with interaction defined as "Hard Contact" in the normal direction and Coulomb friction with a friction coefficient of 0.2 in the tangential direction.
- Application of the pre-tension force to the bolts as a thermal contraction using a predefined filed of an artificial temperature difference and an artificial thermal expansion coefficient.
- A constant velocity of 0.2 mm / second in the vertical direction is applied at the loading point of the secondary beam.

The comparison of the results show a good agreement between the numerical simulation and the experiment in terms of deformations and load-deflection response, as shown in Fig. 7, and thus demonstrates the sufficient accuracy and reliability of the models for the prediction of the general behaviour of the connections. Further parametric studies are expected to expand the virtual data of the developed steel connection.



a) Deformated shape of connection and bearing deformation in fin plate

b) Connecting elements

Fig. 7: Comparison of load-deflection curves: Exp. vs. FEA

5. Analysing methods

The serviceability limit states (SLS) correspond to the functioning of the structure, comfort of people, and the usability/reusability of the structure. Reusable structures require additional serviceability criteria to ensure that no plastic deformation occurs during the first service life. Besides the deflection criterion at SLS, the end slip, the stresses in steel and concrete due to characteristic load combination are therefore should be limited, to avoid any plastic deformation for reuse. For calculations, the relatively low shear connection stiffness of the demountable shear connections compared to headed studs results has to be considered as it results in higher deflections in a composite beam. This can be taken into account by using the formula of Lawson et. al. [18] for the determination of the effective second moment of area $I_{y.eff}$ of the composite section. Among other parameters, this formula uses the stiffness k_{sc} of the shear connection. Analysing results suggested that: the secant stiffness at a load level of 70% of the experimentally obtained characteristic shear connection resistance P_{Rk} is a good approximation for serviceability calculations of deflections, end slip and stresses, Eq. (1). Formulae for the determination of the end slip based on the mid-span moment and for the determination of the location of neutral axes which are required for the elastic stress calculations can be found in the final report of the REDUCE project [6].

$$k_{sc} = 0.7\, P_{Rk}/s \qquad (1)$$

where s = value of the slip at 0.7 P_{Rk}.

The developed demountable shear connections in precast concrete decks has sufficient deformation capacity but an elastic-brittle with a monotonic increasing load-slip behaviour that differs from that of headed studs. For the ultimate limit states calculation of plastic moment resistance of composite beams, an effective shear connector resistance $P_{Rd.eff}$, given in Eq. (2), has been proposed for the demountable shear connections presented in this paper. With proper assumptions for the slip distribution and the end-slip, the developing compression force in the concrete can be estimated accurately by using $P_{Rd.eff}$, hence the EN 1994-1-1 [12] formulae for the determination of the plastic moment resistance of composite beams with partial shear connection remain applicable for the developed shear connections.

$$P_{Rd,eff} = k_{flex} P_{Rd} \qquad (2)$$

where k_{flex} is a specific parameter linked to the type of shear connection and depends on (i) the load-slip behaviour, (ii) the slip distribution, (iii) the loading situation, (iv) the number of shear connectors, and (v) the distribution of the shear connectors along the length, etc. It is generally in the range of 0.80 to 0.90 based on experimental and numerical analyses. For equidistantly placed shear connectors 0.85 is generally a good approximation. Detailed development of a design algorithm and respective analyses are presented in details by Kozma [8].

6. Conclusions

This paper presents a circular system suitable for geometrical standardization and serial production. This system involves (i) standardized beams, (ii) deck elements as well as (iii) slab-to-beam, (iv) beam-to-beam and beam-to-column connections. Experimental tests on demountable slab-to-beam shear connections on component and full-scale beam levels have been performed. The steel connections suitable for use in both beam-to-beam and beam-to-column connections have also been experimentally investigated. The laboratory tests are followed by advanced numerical simulations and extensive parametric studies. Main highlights are given as follows:

- The developed solutions are robust and are suitable for demountable and reusable steel-concrete composite structures.
- The demountable slab-to-beam shear connections can be designed for use in composite beams with partial shear connection according to the rules for plastic design specified in EN 19944-1-1 with the help of a newly proposed simple algorithm, i.e. the determination of the moment resistance of composite beams with partial shear connection remain applicable.
- The proposed adjustable steel connections for beam-to-beam and beam-to-column connections is within the scope of EN 1993-1-8, and thus is applicable and compatible with the current standard design rules.

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Notation

k_{flex}	Reduction factor for shear resistance of shear connectors
k_{sc}	Stiffness of a shear connector
s	Slip of a shear connector
$I_{y,eff}$	The effective second moment of area of composite section
P_{Rd}	Design shear resistance of a shear connector
P_{Rk}	Characteristic value of shear resistance of a shear connector
$P_{Rd,eff}$	Effective design shear resistance of a shear connector

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