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Proof of concept of a demountable steel-concrete composite flooring system

Ioan Andrei Gîrbacea[*,a], Martin Paul Nijgh[b], Milan Veljkovic[c]

[*,a]Master Student, Delft University of Technology, e-mail: girbaceaandrei@gmail.com
[b]PhD Candidate, Delft University of Technology, e-mail: M.P.Nijgh@tudelft.nl
[c]Professor, Delft University of Technology, e-mail: M.Veljkovic@tudelft.nl

ABSTRACT

Environmental concerns steer the construction industry towards more sustainable developments such as demountable and reusable structures. Composite structures are a frequent solution for multi-story buildings and bridges, however the use of welded shear connectors requires labour and energy intensive disassembly. Two bays of a demountable flooring system for a multi-storey car park building were erected in the laboratory. The flooring system consists of large prefabricated concrete decks connected to tapered steel beams. The feasibility of assembly and disassembly of the flooring system was tested under laboratory condition. Shear interaction was achieved by an embedded bolt and coupler which are connected to the top flange of the steel beam by an external injection bolt. Oversized holes are used in the top flange of the steel beam to accommodate fabrication and execution deviations and the deformations occurring during construction. Extensive imperfection measurements and finite element models were used to design the oversized hole diameter to 32 mm. The hole clearance must be compensated either by pretensioning or injecting the bolt-to-hole clearance with an epoxy resin to enable instantaneous composite action under live loads. Experimental injection of 150 injection bolts confirms that epoxy resin can reliably fill the hole clearance, and that the injection process takes 30 seconds per bolt. Various non-uniform shear connector arrangements were considered to minimize construction costs and maximize the speed of execution. The mechanical behaviour of the demountable composite beam was tested experimentally and numerically.

Keywords: demountable composite beams, construction tolerances, resin injection, experiments

1 INTRODUCTION

Figures from 2009 show that the construction industry generates 5.7 billion tons of CO_2 emissions, equivalent to 23% CO_2 emission of the global economic activities (1). According to Eurostat (2) the waste attributed to construction and demolition is 36.4% of the total waste generated at a European level. A step towards reducing waste and prevention of harmful emissions can be made by moving from a linear economy philosophy towards a circular one.

The design of a circular building focuses on future reuse by integrating the building in a closed-loop cycle (3). According to Addis (4) and Arnim (5), a structure must still be able to interact with other components and it should not be worn-out and/or out-dated in order to be reused. Besides the requirements, the cost-effectiveness and competitiveness of the structure should ideally be as high in the first lifecycle as for a linear, traditional solution.

Steel-concrete composite beams are intensively used due to their competitive construction and efficient material use. Shear interaction is commonly achieved by headed studs welded on the top flange, on which concrete is cast in-situ. This type of shear connector obstructs the non-destructive separation of the concrete slab from the steel beams. Demountable shear connectors in the form of a bolted connection offer the possibility to demount and reuse the components of the composite beam.

2 PROOF OF CONCEPT OF CONSTRUCTION

2.1 Bolt coupler connectors in prefabricated solid decks

The assembly and disassembly of steel-concrete composite floorings can be achieved by a novel bolt coupler connector. This type of connector comes as a solution to regular embedded bolts which are vulnerable to damage during transportation and construction. Extensive experimental research has been performed to study the behaviour of the bolt coupler connector by Gîrbacea (3), Arnim (5), Nijgh et. al. (6-8), Kozma et. al. (9), Gritcenko (10) and Sarri (11).

The connector is embedded in prefabricated solid concrete decks which are designed as big as practically possible to reduce the amount of work at the construction site (6). To protect the concrete edges during transportation, assembly and disassembly angle profiles are installed along the perimeter of the deck. The shear connector consists of an embedded bolt and coupler connected through the top flange by an external injection bolt. The coupler has a higher grade (10.9) compared to the external bolt to avoid damaging the coupler in case of overloading, which ensures the reusability of the concrete decks. The injection bolt is used to fill the bolt-to-hole clearance, allowing for great execution and fabrication tolerances without sacrificing the structural efficiency of the composite beam (8). The embedded bolt provides the pull-out resistance of the connector, whereas the coupler transfers the shear force between the steel beam and the prefabricated concrete deck.

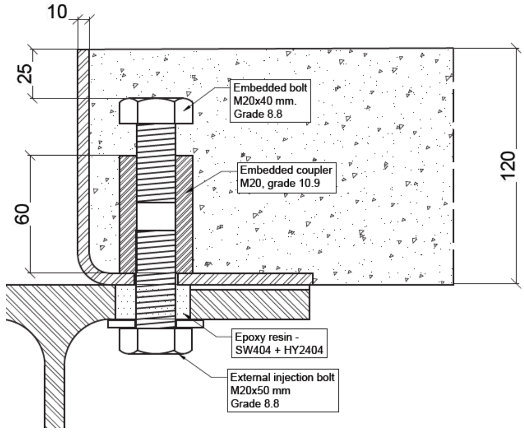

Fig. 1. Resin injected bolt coupler connector in prefabricated concrete solid deck (6)

2.2 Demountable car park

An experimental setup was manufactured, based on the design carried out by Nijgh et. al. (7), to study the feasibility of construction of the demountable steel-concrete composite flooring system for a typical multi-storey car park building layout. The composite flooring system is formed by installing four large prefabricated decks (7.2 x 2.6 m) onto three tapered beams with a clear span of 14.4 m. To prevent instability effects during construction the structure was braced. One of the exterior beams was supported at three positions along the span to account for possible influences of façade columns on the construction.

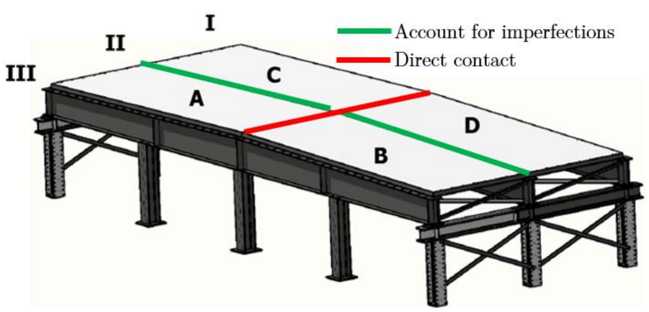

Fig. 2. a) Schematic overview of test set-up (3); b) Experimental car park specimen

To achieve composite action under live loads the prefabricated concrete decks were designed to be in direct contact at mid-span, as shown in *Fig. 2a*. Finite element analysis performed by Gîrbacea (3) confirms that composite action is established only if the compression force in the concrete flange can be transferred.

2.3 Construction tolerance design

Construction tolerances required to ensure the assembly of the flooring translate in oversized holes in the top flange of the steel beam. The hole clearance is influenced by imperfections arising from manufacturing and erection, deformations of the structure during assembly and the speed of construction. The steel beams were manufactured with 26 mm holes based on preliminary estimations of the imperfections and deformations. However, the initial hole clearance proved insufficient. Based on 1300 imperfection measurements according to EN1090-2 (12) and finite element models a new magnitude for the oversized hole was determined and redrilled.

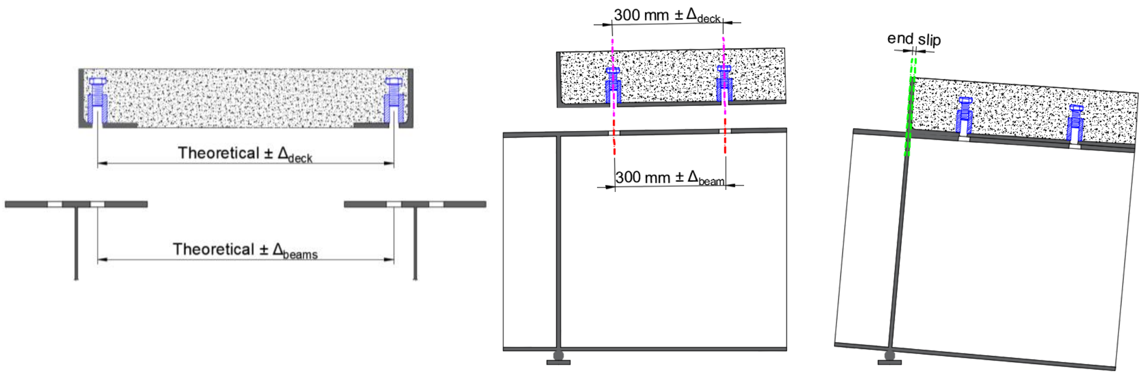

Fig. 3. a) Transversal imperfections (3); b) Longitudinal manufacturing imperfections (3); c) Interface slip (3)

The design of the hole clearance must consider both the longitudinal and transversal direction of the flooring. In transversal direction (see *Fig. 3a)*, the hole diameter is influenced by deviations from the beam spacing and coupler position. Measurements confirm that long angle profiles are prone to large out-straightness deviations up to 4mm. Beam spacing deviations as much as 10 mm were measured towards midspan. Construction braces welded next to the top flange between adjacent webs reduced the beam spacing deviations to less than 3 mm, which is sufficient to ensure the assembly with the initial 6 mm hole clearance. Considering that the installation of the beams was performed in laboratory conditions and the influence of column imperfection was excluded due to the configuration of setup (see *Fig. 2 a*) the installation of construction braces in practical situations is required.

In longitudinal direction the manufacturing imperfections shown in *Fig. 3b* will add up to the interface slip generated by the installation of the prefabricated concrete decks shown *Fig. 3c*. The maximum measured hole spacing deviation for both the flange and couplers was 2 mm. Finite element modelling of the sequential construction performed by Gîrbacea (3) indicates an end slip of 1.45 mm after the fourth slab is installed. Accounting for the measurements and finite element results the holes were redrilled to provide a clearance of 12 mm. The assembly process of the composite flooring was successfully executed for the new bolt-to-hole clearance. Numerous assembly attempts confirm that an increased construction tolerance will greatly reduce the assembly time.

Measurements indicate that lengthwise imperfections due to manufacturing of the angle profiles have to be accounted in order to install the decks. In practical situations this influence can be reduced by using special formworks to constrain the dimensions of the decks. If necessary, an addition to the hole clearance can be prescribed by the quality control process. During experiments the excess material was removed to allow for the assembly of the flooring. Steel shims were forced in between the decks to ensure a continuous compression force transfer.

2.4 Construction method

The novelty of the shear connection requires a suitable construction method to handle the installation of the large prefabricated decks in the required position. The method must ensure complete safety for the workers and machinery, prevent any damage to the components of the flooring and a fast construction. To fulfil the safety requirements at any moment in during construction, the deck should be either fixed to the crane or to the steel beam.

Fig. 4. a) Rod acting as support (3); b) Punched connector (top view) (3); c) Construction method using long bolts (3)

To aid the positioning of the deck and to prevent it from slipping-off the beams threaded rods were installed in some of the couplers. Due to large fabrication imperfections the rods did not fit in the top flange holes and acted as a support for the prefabricated slab, as shown in *Fig. 4a*. The large concentrated force lead to the punching of the connector. The vulnerability of embedded bolt was therefore confirmed experimentally given the similarities. Prefabricated slabs with embedded bolts will require the simultaneous alignment of top flange holes with the bolts on the both sides of the slab, which is practically not possible without an excessive hole clearance.

The flooring was successfully installed by progressively aligning the deck position with the help of long bolts as seen in *Fig. 4c*. While the deck was lifted long bolts were installed from below into the couplers through the top flange holes, on both sides of the deck. As the prefabricated deck was lowered the long bolts corrected its position while at the same time preventing it from slipping of the beams.

2.5 In-use phase

Due to the oversized holes the bolt shank will not be in direct contact with the hole wall after construction. Without additional measures composite action is obtained only when the gap is closed by interface slip. During the experimental program resin injection was used as a measure to achieve composite behaviour. Resin injection was never used for full-scale composite beams and its reliability of filling the hole clearance was confirmed only for small scale push-out specimens by Kozma et. al. (9). A number of 150 bolt were injected by a two component epoxy resin. The overhead injection was easily performed by unskilled workers at a heights up to 2.5 meters using a readily available manual caulking gun at a pace of 30 seconds per bolt. The epoxy resin fully filled the hole clearance with minor air inclusions as shown in *Fig. 5*. To prevent the adhesion of the resin on the steel beams and bolts a release agent was applied.

Fig. 5. Injected bolt holes

Limiting the beam behaviour to the elastic range ensures the reusability of the structure in second life cycle. Four point bending tests were performed to assess the efficiency of different connector distributions as show in *Fig. 6*. It was confirmed experimentally that injecting epoxy resin into the bolt-to-hole clearance, instantaneous and simultaneous composite action is achieved for all of the shear connectors (6).

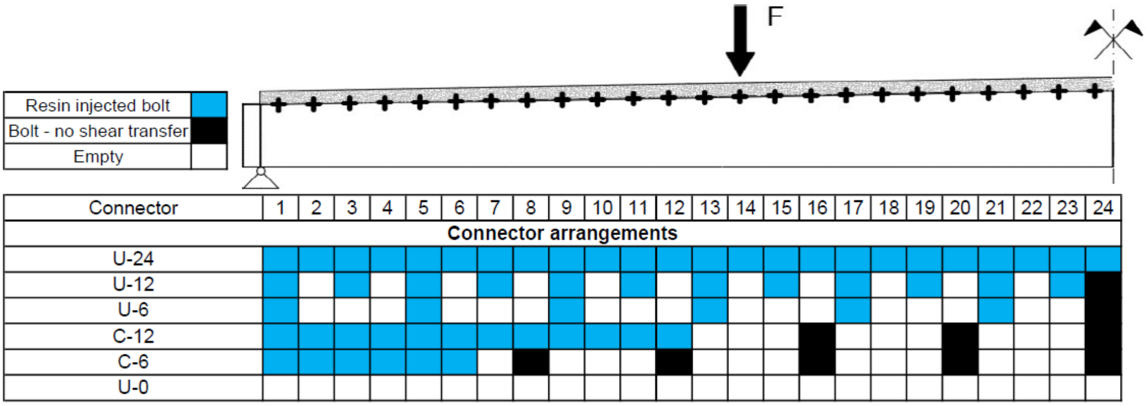

Fig. 6. Four-point bending testing program

Comparing the tests C-12 with U-12 and C-6 with U-6, confirms that concentrating the connectors towards the supports brings a benefit of roughly 5% in terms of bending stiffness for the same number of shear connectors. Installing the connectors where they are most effective will reduce construction time and costs without influencing the bending stiffness. Experimental results are closely matched in terms of bending stiffness, stresses and curvature by an analytical model developed by Nijgh et. al. (13) and finite element results from (6) as seen in *Fig. 7a*. The interface slip is overpredicted on average by 43% by finite element models. Finally the structure was loaded up to failure to investigate its demountability after it is subjected to extreme loading. Finite element analysis performed by Gîrbacea (3) captured its plastic behaviour (see *Fig. 7b*).

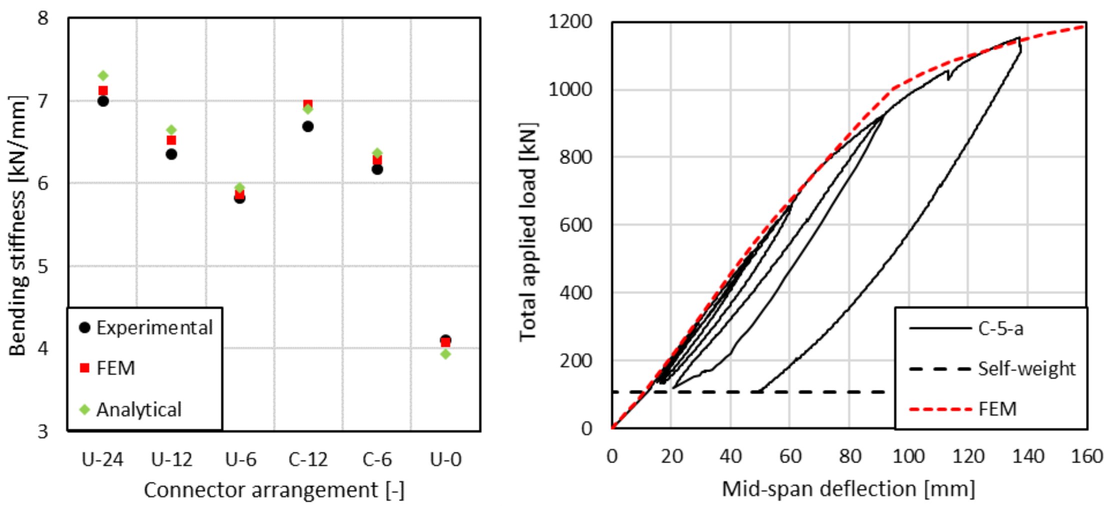

Fig. 7. a) Comparison of the bending stiffness b) Load-deflection curve four-point bending test (3)

The flooring was easily demounted even after plastically deforming the steel beams. In practical situations a time consuming and potentially dangerous demolition can be avoided. The bolts were untightened using hand tools and the remaining resin was cleaned. Consequently, the steel beams, concrete decks and bolts can be reused if the elastic behaviour of the is not exceeded.

3 CONCLUSIONS

Full-scale experiments confirm the possibility of assembly and disassembly of demountable steel concrete composite beams spanning 14.4 m. The flooring was constructed from large prefabricated decks (7.2 m x 2.6 m) and tapered beams connected by means of a bolt coupler connector. The construction of demountable floorings is possible only if the construction tolerances are designed appropriately. It was confirmed experimentally that the hole clearance is determined by the magnitude of the imperfections and deformations of the system. The 12mm hole clearance of the specimen was designed based on extensive imperfection measurements and finite element models. Experiments show that the bolt coupler connector comes as a suitable solution to the vulnerabilities of regular embedded bolts.

Four point bending tests confirm the suitability to reuse the flooring if the elastic range is not exceeded. The flooring can be easily demounted even after plasticly deforming the steel beams. Resin injection can be used reliably and economically to mitigate the initial slip in case of large hole clearances. Non-uniform connector arrangement can bring benefits in terms of bending stiffness, construction time and costs compared to regular uniform distributions. Analytical and numerical models closely match experimental results in terms of bending stiffness, stresses and curvature.

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