Dismountable Flooring Systems for Multiple Use

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Abstract. Steel shapes our modern world as an integral part of the global construction economy. In the last decades, the sustainability of steel grew and turned from a linear to a circular business, where the material is fully recovered and recycled after use. The RFCS Research Project “REDUCE” of the European Commission goes one step beyond the mere material recycling and investigates, how the circular economy’s philosophy can be used to reduce the carbon footprint furthermore. On that basis, one target of the research was to develop basic modular and standardised structural load bearing elements which can be adapted in the building or assembled, properly disassembled and partly or entirely be reused again in a subsequent building. This paper presents the respective research results of demountable flooring- and beam systems: 15 large scale push-out tests and two large scale composite beam tests as well as numerous finite element simulations with ABAQUS have been performed at the Laboratory of the ArcelorMittal Chair of Steel and Façade Engineering. The suitability for dis- and re-assembly as well as the strength, stiffness, slip capacity and ductility have been determined. The investigated systems included pre-stressed and epoxy injected systems, as well as solid slabs and composite slabs with profiled decking. The results showed sometimes higher resistances and smaller displacement capacities than conventional systems. The numerical simulation results were presented as well as the results of the laboratory tests. First assessments were given about the respective consequences and about how these consequences could be considered in the layout of future steel composite structures.

Keywords: Demountable flooring systems, composite structures, shear connectors, experimental study, finite element simulation

1. Introduction

The circular economy is essential for a sustainable, resource-efficient and low-carbon future [1]. The basic principle is to reduce or totally eliminate waste and carbon dioxide production with the help of a multiple, efficient usage of resources. It is achieved by tracking materials throughout their life cycles so that their location is known and designing them in such a way that their future reuse is possible.

With proper considerations at the design stage, whole buildings or parts of it can be deconstructed and re-erected elsewhere. If the structural steel elements are not worn, yielded or corroded, they are ideal candidates for re-use with no melting and new hot rolling process.
However, the deconstruction of steel-concrete composite structures in buildings and the later separation of the materials is a labour- and cost intensive work. A large amount of cutting work is necessary because the shear studs are welded on the steel beam and imbedded in the concrete deck. As a result, recycling is difficult and the potential for reusing entire elements is lost. The carbon footprint of composite structures could be decreased by application of the principles of “design for deconstruction and reuse”.

This paper presents a part from the results of a research project analysing reuse and demountability using steel structures and the circular economy. Within the framework of the European research project “REDUCE [RFCS-GA-710040]”, funded by RFCS, push-out tests, beam tests and numerical studies have been conducted in order to determine the properties of the demountable shear connector systems that are studied in this research.

The application of the principles of the circular economy can take place on different levels. Crowther [2] differentiates the following levels for the built environment: material recycling, component remanufacture, component reuse and building relocation. This project aims to facilitate the component reuse and building relocation in the case of steel-concrete composite structures.

The ability to reuse building components depends on the ability to recover them. In current construction practice, after a building reaches the end of its life, usually demolition takes place and the ability to reuse entire components is lost. The demolition process should be replaced by a deconstruction process, which is possible only if the building was designed for deconstruction.

In order to make steel-concrete composite structures demountable, bolted connections should replace the commonly used welded headed studs. Furthermore, the reusable parts should be designed to withstand repeated use.

2. Methodology

The aim of the presented research is to develop structural solutions for demountable flooring systems that facilitate reuse, and to provide a design guidance that helps engineers to design reusable composite structures. Figure 1 presents the flow chart of the applied research methodology.

In the case of composite structures, one big obstacle in the way of reuse is the shear connector itself, as it is traditionally welded to the top flange of the steel beam and encased fully in the concrete. Therefore, in order to facilitate reuse, the development of new type of shear connectors was necessary. The next step was to determine the developed shear connectors’ strength, stiffness, ductility and deformation capacity. This was done with standard push-out tests defined in EN1994-1-1. Afterwards, full-scale beam tests were built and tested to assess the shear connectors by the means of feasibility, reusability and the ease of assembly and disassembly. The beam tests have been rebuilt numerically. The numerical simulations permit to extend the experimental study with virtual experiments and to gain a better understanding of the structural behaviour. The results of these studies will serve as an important basis for the development of the design guidance for reusable composite flooring systems.

![Figure 1. Flow chart of the research methodology](image)

3. Shear connectors

Two types of demountable shear connectors for prefabricated composite flooring systems have been tested at the University of Luxembourg. Taking into account that the slab elements were meant to be reusable, L-shaped steel profiles were cast inside. These profiles provided edge protection to the elements.
3.1. Friction bolts with cast in cylinders (P3)
Shear connector type P3 consists of a cast-in steel cylinder welded to the L-profile, a top plate welded to the cylinder and a pre-tensioned M20 bolt with a grade of 8.8. This connection provides accessibility from the top of the slab through pockets in the concrete. The layout of the shear connector system is presented in figure 2. In the forthcoming, this shear connection type is referred to as “cylinder system”.

3.2. Embedded coupler device (P15)
Shear connector type P15 uses an embedded bolt coupler, an embedded bolt and a removable bolt placed from below. The coupler has a grade of 10.9, while the bolts are made of 8.8 material. The reason behind the higher material strength of the coupler is, that this way we can ensure that if the threads are damaged, then the damage will occur in the bolt, which is replaceable, and not in the coupler, which is not. In the forthcoming, this shear connection type is referred to as “coupler system”. Two variants of this connection type were developed. The two variants are mostly identical, but P15.1 uses pre-tensioned bolts and P15.2 uses epoxy resin injected bolts i.e. the gap between the bolt and the bolt-hole is filled with resin. Figure 3 shows the layout of the shear connector system.

Figure 2. Layout of the “cylinder system” P3

Figure 3. Layout of the “coupler system”, left: P15.1, right: P15.2
4. Push-tests

4.1. Test specimens, measurements and test setup
A total of 15 push-out test specimens have been performed with a geometrical layout similar to the one recommended by Eurocode 4 [3]. Five different test configurations were fabricated, and for each configuration, three identical specimens were tested. Three series used solid slabs, and two used ComFlor® 80 metal decking. Each specimen consisted of 4 pre-fabricated slab elements and an HE 260B steel beam. Four series used pre-tensioned bolts, and one series was conducted using epoxy resin injected bolts.

The tests were conducted using a hydraulic jack with a load capacity of 1000 kN. During the test, belts were put around the specimens to prevent the parts from falling apart once the failure happened (see figure 4). During test conduction, the force in the hydraulic jack and the displacements were continuously monitored.

![Figure 4. The test setup of a specimen with solid slabs (left) and with metal decking (right)](image)

For each specimen 15 displacement transducers (LVDTs) were employed to measure the relative vertical displacement between the steel beam and the slab elements, the vertical displacement of the beam measured to the ground floor, the transversal separation between the steel beam and the slab elements, the relative horizontal displacement between the adjacent slab elements and the relative horizontal displacement between the slabs on the different flanges of the beam.

4.2. Results, observed failures and reusability
As presented in [4], the failure in every cases happened due to bolt shear. All tested shear connectors had higher strength and lower deformation capacity than the traditionally used welded studs. Besides the sheared bolts, only minor damages could be observed: bearing failure of the L-profiles and thread penetration in the hole of the steel beam (see figure 5). The reinforced concrete slab elements remained intact after the failure of the bolts. In the case of series P15.2, where the gap between the bolt and the hole of the steel beam was injected using epoxy resin (see figure 3, right), no damages were observed on the steel beam.

In order to see how these minor damages affect the load bearing capacity and the structural behaviour in general, and to prove the capability for reuse, the most heavily loaded specimens were selected for a second life cycle testing. These specimens were reassembled with new bolts and the tests were repeated. In the second tests, the failure mode was again bolt shear leading to similar resistance values and deformation capacity as the original tests. Based on the aforementioned observations, it was concluded that the developed flooring systems are suitable for reusable composite structures.
5. Beam tests

5.1. Tested Configurations
Two beam tests have been performed on 6 m span composite beams with demountable shear connectors. The beams used IPE360 sections in S355 steel and were subjected to a 2-point loading so that a defined zone of the beam was subjected to constant shear. A similar series of tests was completed under the RFCS project DISCCO; therefore, it was possible to make a direct comparison of the results with conventional welded shear connectors.

The beams were designed for a 37% degree of shear connection. This value was calculated using the expected values of material strengths and 94.65 kN strength for the shear connector. This value was the average load level at 6 mm slip of push-out test series P3.3. The calculated $\eta=0.37$ value corresponds to a uniformly distributed shear connector arrangement with 600 mm spacing. This degree of shear connection is less than the minimum permitted by Eurocode 4 [3] which is 40%. In the RFCS project DISCCO, the degree of shear connection in the beam tests ranged from 25 to 38%. The tested configurations are presented in table 1.

| Test No. | Clear span | Section | Slab | Shear connection type | Degree of shear connection | Distribution of shear connectors |
|---------|------------|---------|------|-----------------------|---------------------------|----------------------------------|
| B7      | 6 m        | IPE 360 | CF80 | P3.3 Cylinder system  | 0.37                      | Uniform along the length          |
| B8      | 6 m        | IPE 360 | CF80 | P15.1 Coupler system  | 0.37                      | Uniform along the length          |

5.2. Test specimens
The two beam tests were fabricated using a similar geometrical layout to the beam tests performed in the frame of the RFCS project DISCCO. Each specimen comprised of a 6.3 m long IPE 360 steel beam and 2 pre-fabricated composite slab elements with a depth of 150 mm and a width of 790 mm.

The total width of the specimens was 1600 mm, which corresponds to the effective width, defined by Eurocode 4 [3]. The shear connectors were placed in pairs with a spacing of 600 mm. The slab elements were stabilised with diagonal struts so that no tension force arose in the shear connectors from the self-weight of the composite slabs. Figure 6 shows the cross-section of the tested beams. Specimen B7 used shear connection type P3.3 – Cylinder system and specimen B8 used shear connection type
Both specimens used M20, 8.8 high strength pre-tensioned bolts. Holes were drilled inside the top flange of the steel beam with a diameter of 24 mm.

![Figure 6. Cross-section of the tested beams](image)

### 5.3. Fabrication, assembly and measurements

Both beams were cast on the same day with the same concrete mixture. After the concrete had hardened, the slabs were lifted and placed on the top of the steel beam. Then, the composite slab elements were fixed to the beam with high strength bolts through the pre-drilled holes in the top flange of the beam. During the assembly the beams were continuously supported along their lengths. This type of construction corresponds to a propped construction method. In both cases the bolts were tightened by rotating the bolt head using a pneumatic impact wrench. Direct tension indicator (DTI) washers were applied in accordance with the requirements of EN 1090 [5] in order to control the pre-tension force and were checked using a feeler gauge with a thickness of 0.25 mm.

For each specimen 28 displacement sensors were applied to measure the end slip of each composite slab, the slip values at the shear connectors, the transverse separation of the slabs relative to the beam and the deflection values of the beam in different positions. The displacement measurements were supplemented by an inclinometer and 10 strain gauges measuring the strains in the steel beam and in the reinforcement bars encased in the concrete. Furthermore, the travel and the force values of the hydraulic jack were continuously monitored during the tests. Figure 7 shows the measurement setup.

![Figure 7. Measurement setup of the beam tests](image)

### 5.4. Results and observed damages

In the conducted beam tests the following damages were observed: specimen B7 failed due to concrete compression damage and specimen B8 produced shear connector failure.
In both cases cracks were observed on the concrete slabs in the vicinity of the shear connectors, at the crests of the sheeting near to the loading points, and longitudinal cracks appeared in the line of the shear connectors.

The results of the beam tests using demountable shear connectors were evaluated based on a comparison with a beam test using the traditionally applied welded studs of the DISCCO project. The demountable shear connectors provided higher strength and lower stiffness than the welded studs.

6. Finite Element Simulations
A finite element model of the investigated beams was developed using the commercial software ABAQUS. The model consisted of an IPE360 steel beam with a length of 6 m and a 1.6 m wide concrete slab with a depth of 150 mm. The steel beam was modelled with 4-node, reduced integration shell elements (S4R) with 5 integration points through the thickness.

For the modelling of the concrete slab the same element type (S4R) was used as for modelling the steel beam. The ribs and the profiled sheeting were neglected in the model. Only the concrete part above the sheeting was modelled. The solid concrete strip above the steel beam was modelled using different shell thicknesses (see figure 8).

![Finite element model of the tested beams](image)

**Figure 8.** Finite element model of the tested beams

The concrete strength was determined using standard cube tests at the day of testing. The shear connectors were modelled using the “Fastener” built-in feature offered by Abaqus. These connectors allowed modelling the nonlinear behaviour of the shear connectors. The shear connectors’ behaviour could be described with the “Slot + Align” connection type where the longitudinal behaviour is described by simplified nonlinear spring laws obtained by the push-out tests of section 4.

The obtained numerical results were compared to the experimental observations. This comparison showed a sufficiently accurate correlation in the means of load-deflection curves (see figure 9) and the observed damages (see figure 10). Therefore, the developed numerical model is capable of capturing the real behaviour of the demountable flooring system.

![Comparison of numerically and experimentally obtained load-deflection curves](image)

**Figure 9.** Comparison of numerically and experimentally obtained load-deflection curves
7. Conclusions and Outlook

The results of the conducted 15 push-out tests, 2 beam tests and the corresponding finite element simulations were briefly presented. Based on these results, the structural characteristics of bolted connections were assessed. The following conclusions were made:

- the developed solutions are robust and adequate for reusable composite flooring systems,
- the demountable shear connector systems provide higher strength and lower stiffness than the conventional welded studs,
- the nonlinear finite element simulations could accurately reproduce the experimental results and are suitable for parametric studies.

The developed finite element models will be used for extending the experimental studies with virtual experiments. The outcome of these studies will serve as an important basis for the development of a future design guidance for reusable composite flooring systems.

8. References

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