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Towards a demountable composite slab floor system

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ABSTRACT

Composite slab consisting of in-situ casted reinforced concrete on profiled sheeting, which is connected to steel beams by shear connectors, is a common structural flooring system in office buildings and car parks. The headed welded studs are inexpensive and rather easy to use in-situ because they can be welded to the steel beam through the metal sheeting. A permanent link is created between the composite slab and steel beams leading to rather time-consuming and expensive deconstruction process.

Various types of bolted shear connections, recently investigated by various researchers in Europe, Australia, USA, provide a demountable alternative for the flooring system. This paper describes the experimental study using a bolted shear connector consisting of an embedded bolt/coupler and external bolt, originally developed for a prefabricated concrete deck.

A full-scale composite beam was tested under working loads up to 6.25kN/m^2 in a 4-point bending. In addition to bolted shear connectors a timber joist is embedded in the composite slab over the web of the steel beam. After the first life cycle, the timber joist provides the cut edge of the slab. The experiment is used to model behaviour in the first life cycle. The composite slab was then cut, demounted, re-assembled and tested again in the second life cycle. The load was applied up to 6.25kN/m^2 and finally to the failure. Multiple arrangements of shear connectors were investigated to analyse performance of "a modified composite slab".

Experience gained on the experiments of testing the composite beam in the first and the second life cycle is accompanied by FE analysis.

Keywords: demountable structures, composite structures, composite slabs, flooring systems

1 INTRODUCTION

An essential component of a composite beam is the shear connection between the concrete slab and the steel beam. This connection is achieved by means of a mechanical shear connector, which transfers shear forces between concrete and steel beam and resists the vertical separation at the steel-concrete interface. Shear connection is traditionally achieved by welded headed studs, which prohibit non-destructive separation of the concrete slab from the steel beam. A wide range of connectors has been developed in the past, however comparing to the traditional welded headed studs connectors, there is a limited research available in the field of alternative demountable bolted connectors.

Experiments using high-strength friction grip bolts as shear connectors were conducted by (1) in which precast concrete slabs were attached to a steel frame with semi-rigid bolted connections. This study showed that beams demonstrated very significant ductility and interface slips being developed and sustained during the testing. Similarly (2) and (3) investigated the behavior of high-strength grip bolts as composite shear connectors, however, an attempt to demount the shear connectors was not undertaken in any of above investigations.

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An application of blind bolts as shear connector in composite beams was investigated by (4) and (5). Full-scale beam tests have shown that blind bolts exhibit comparable behavior to welded studs connectors in terms of stiffness, strength and ductility (4). However, according to findings by (5) blind bolts exhibit relatively brittle behavior compared to welded connectors.

According to research conducted by (6), experiments have shown that shear resistance and load-slip relation of welded headed studs and bolted shear connectors with single embedded nut are similar if they have the same dimensions. In research conducted by (7) 8.8 M20 bolted shear connector with embedded nut were tested in composite beams tests with profiled sheeting. The experiments demonstrated that composite beam with bolted connectors performed in similar manner as beam with welded studs. Push-out and beam experiments using connectors machined from traditional studs with threads on a composite slab formed with profiled metal decking were conducted by (8). The conclusion was that the behavior of demountable composite flooring system is very similar to conventional welded shear connector, additionally the composite beams were demounted and successfully reused after service load.

The research presented in this paper investigates the structural behavior and demountability of composite slab floor system using novel bolted shear connectors through both experimental and numerical study.

2 EXPERIMENTAL STUDY

2.1 Details of tests specimen

A full-scale experiment was conducted on a composite beam with demountable shear connectors. The specimen consisted out of IPE400 steel beam, 150 mm thick concrete slab with ComFlor95 profiled sheeting, timber joist (90x20mm) embedded in the composite slab over the steel beam web and demountable shear connectors. The demountable shear connector is built up of an embedded M20 bolt (grade 8.8) and embedded M20 coupler (grade 10.9), which are connected to the beam flange using an external injection bolt M20 (grade 8.8), as shown in *Fig. 1 a).*

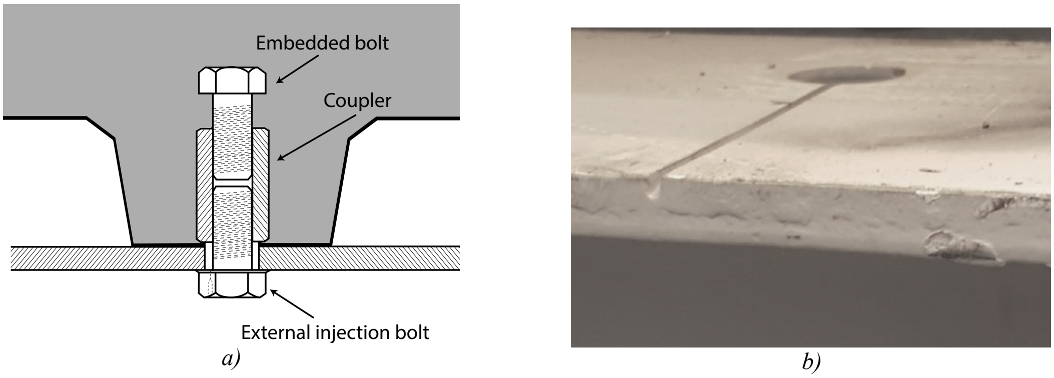


Fig. 1. a) Bolted shear connector; b) Air escape groove

The shear connectors were installed in pairs every 300mm through predrilled holes Ø26 mm in the profiled metal sheeting and beam flange. The nominal bolt-to-hole clearance of 6 mm was injected with a two-component epoxy resin through the head of the external injection bolt. After curing, the epoxy resin provides a slip resistant connection. To ensure a complete filling of the bolt-to-hole clearance, an air escape groove on top of steel flange was used, which is shown in *Fig. 1 b)*. The injection process was considered successful when resin would start to come out of the air escape groove. The assembled specimen before casting (propped) is shown in *Fig. 2*. The specimen was cured for 28 days before carrying out tests.

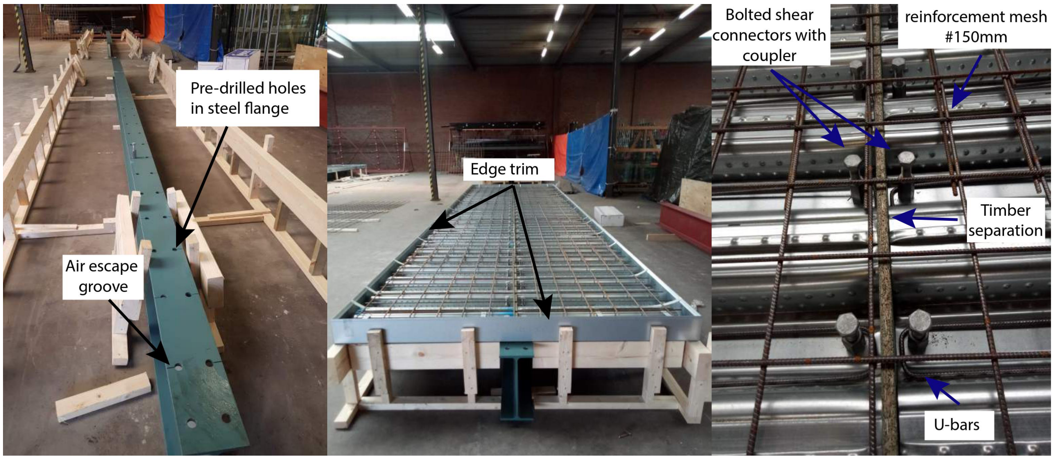


Fig. 2. Assembled specimen before casting

2.2 Experimental program

The specimen was tested under a two-point loading system, as shown in *Fig. 3.* The vertical loads were applied by two displacement controlled hydraulic jacks. The displacement was applied with a constant rate of 0.2 mm/s during 5 subsequent cycles.

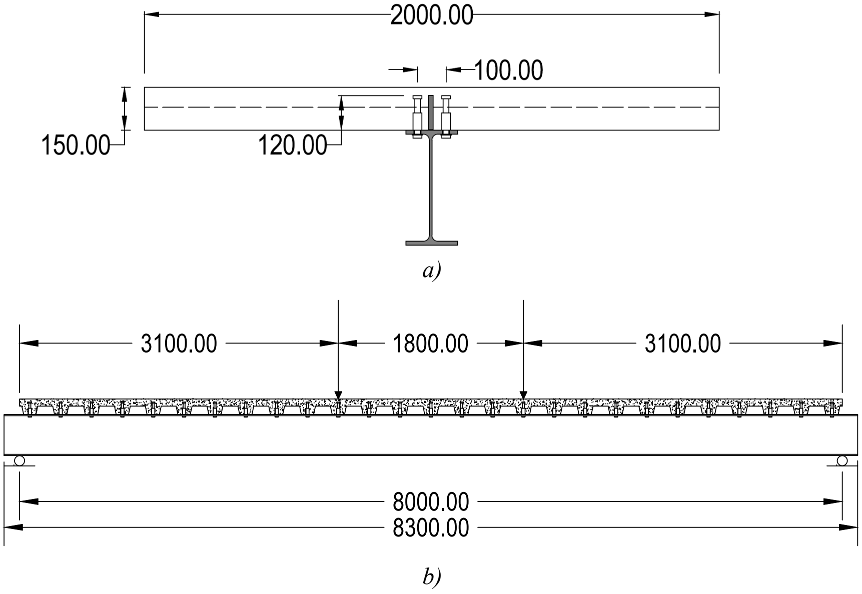
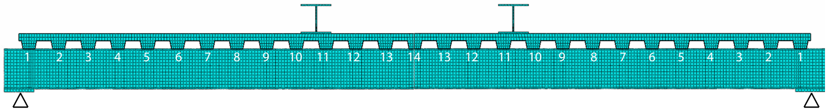


Fig. 3. a) Cross-sectional view; *b)* Test layout (dimensions in mm)

The specimen was tested in 2 life cycles. In first cycle the composite beam was loaded at various load levels not exceeding the linear-elastic limit. Afterwards, the concrete deck was cut longitudinally in the middle over the timber joist, creating a discontinuous reinforcement. The composite beam was then lifted by an additional steel beam, the resin was removed from the bolt holes, the timber piece was replaced and the composite beam was re-assembled and tested again elastically at different load levels and up to the failure. A visualization of the experimental program was developed in order to demonstrate in detail the testing procedure. The animated program can be found via the link https://youtu.be/FQMLcSBU6Kk.

The shear connector with coupler provides a possibility to remove the external bolt and, hence, vary the degree of shear connection after the specimen is cast. Therefore, various shear connector arrangements were tested. *Fig. 4* demonstrates the investigated arrangements. The U-26 configuration stands for 'uniform 26 shear connectors per half span'; NonU-14 for 'non-uniform 14 shear connectors per half span' and S-08 for 'supports 8 connectors per half span'.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	13	12	11	10	9	8	7	6	5	4	3	2	1
U-26	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X
NonU-14	X	X	X	X			X			X			X		X			X			X			X	X	X	X
S-08*	X	X	X	X																				X	X	X	X
* Configuration tested only in 1st life cycle																											

Fig. 4. Testing program

3 FINITE ELEMENT MODELING

3.1 Geometry and boundary conditions

Finite element analysis was performed using Abaqus/Standard. A model of the composite beam was built up using 4 elements: the steel beam, the metal decking, the concrete slab and the load application beam. To simplify the problem only half span was modelled with a symmetry boundary condition, as indicated in *Fig. 5*.

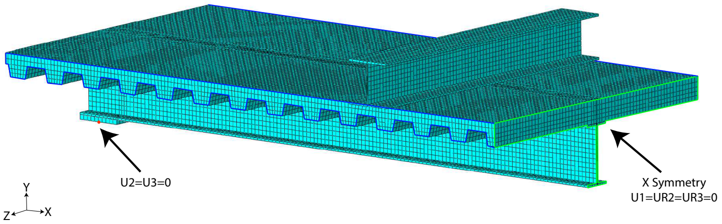


Fig. 5. FE model of 4 point bending test. Boundary conditions

3.2 Element type and finite element mesh

The three dimensional eight-node solid brick element C3D8R with reduced integration was used to mesh the concrete slab and steel beams. The profiled metal decking is very thin material; therefore shell element with reduced integration (S4R) was used. The element size for all elements was chosen as 30mm.

3.3 Interaction contact and constraint

The general contact interaction was chosen for all surfaces in the model. The normal behavior is described by "Hard" contact, whereas for tangential behavior the Penalty friction formulation is adopted with a friction coefficient of 0.14. For the contact between profiled sheeting and concrete slab a tie constraint was assumed. Shear connectors between concrete slab and the beam were modeled as non-linear springs in x (along the beam) and z and in y direction the spring is assumed to behave rigidly. The springs were defined between the surface of profiled sheeting and the top flange of the steel beam. The load-slip behavior of the shear connectors was obtained previously from push-out experiments conducted by (9).

4 RESULTS

The results of experiments are evaluated in terms of effective bending stiffness and the effective shear stiffness parameters, which were defined as:

$$k_{b,eff} = \frac{\Delta F}{\Delta u} \tag{1}$$

$$k_{s,eff} = \frac{\Delta F}{\Delta s} \tag{2}$$

where $k_{b,eff}$ is the effective bending stiffness,
$k_{s,eff}$ is the effective shear stiffness,
F is the point load,
u is the deflection of the composite beam at the mid span,
s is the relative slippage between the concrete deck and the steel beam.

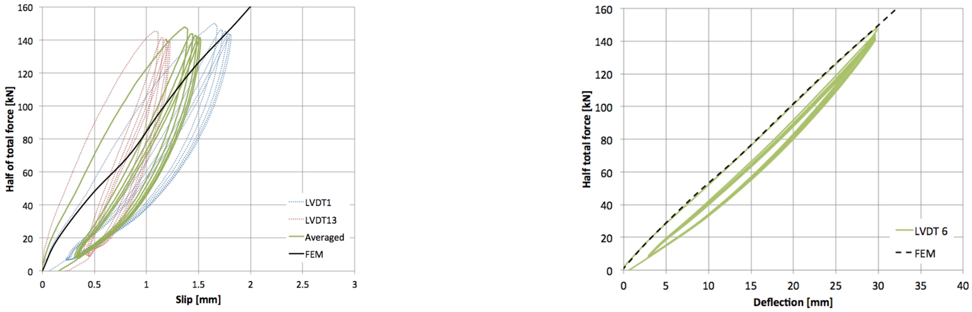
These parameters were defined for two force intervals between 40kN-70kN (force applied by one point load) and 70kN-100kN, which corresponds to an equivalent uniformly distributed load between 2.5kN/m^2–4.4kN/m^2 and 4.4kN/m^2 – 6.25kN/m^2, respectively.

The results of first and second life cycles experiments are given in *Table 1* and *Table 2*, respectively, together with the predictions based on finite element model.

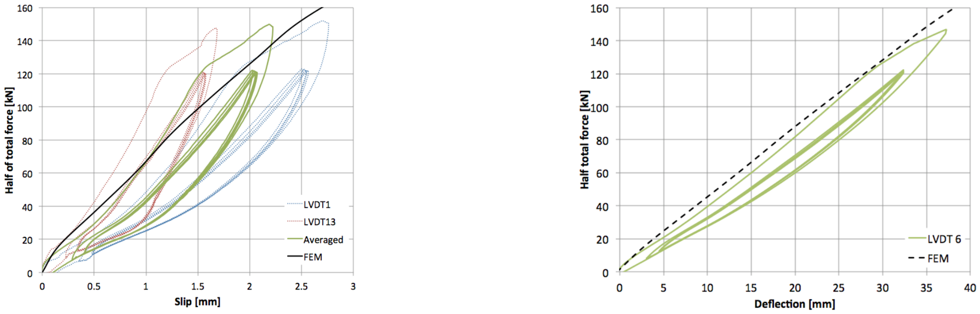
Table 1. Effective bending stiffness and effective shear stiffness for the various shear connector arrangements in first life cycle, based on the experimental results and the numerical model.

Arrangement	$k_{b,eff}$ [kN/mm]				$k_{s,eff}$ [kN/mm]			
	40-70kN		70-100kN		40-70kN		70-100kN	
	Exp.	FE	Exp.	FE	Exp.	FE	Exp.	FE
U-26	4.69	4.69 (0.0%)	5.08	5.00 (-1.6%)	103.45	68.18 (-34.1%)	125.00	88.24 (-29.4%)
NonU-14	3.75	4.22 (+12.5%)	4.11	4.23 (+2.9%)	63.83	61.86 (-3.1%)	76.92	63.16 (-17.9%)

Figures 6 a),b) demonstrate the end slip on both sides of the beam (LVDT1 and LVDT 13), averaged end slip and finite element prediction. *Figure 6 c)* and *d)* present the mid span deflection (LVDT6) as a function of applied load and the numerical prediction. It is clearly observed that one side of the beam behaved stiffer compared to other, although the beam was manufactured symmetrically and applied point loads were identical.



a) c)



b) *d)*

Fig. 6. *a)* End slip development for U-26; *b)* End slip development for NonU-14; *c)* Mid-span deflection for U-26; *d)* Mid span deflection for NonU-14

Table 2. Effective bending stiffness and effective shear stiffness for the various shear connector arrangements in second life cycle, based on the experimental results and the numerical model.

Arrangement	$k_{b,eff}$ [kN/mm]				$k_{s,eff}$ [kN/mm]			
	40-70kN		70-100kN		40-70kN		70-100kN	
	Exp.	FE (60%)	Exp.	FE(60%)	Exp.	FE	Exp.	FE(60%)
U-26	4.10	4.29 (+4.6%)	4.48	4.17 (-6.9%)	54.07*	56.60 (+4.7%)	58.88*	52.60 (-10.7%)
NonU-14	3.46	3.77 (+9.0%)	3.79	3.57 (-5.8%)	42.25*	47.62 (+12.7%)	35.20*	42.35 (+20.0%)
* End slip only on one (less stiff) side of the composite beam is considered								

In the second life cycle tests the effective bending and shear stiffness demonstrated a decrease compared to the first life cycle tests. By applying analytical model for partial shear interaction described in (10) for U-26 arrangement, a hypothesis of reduced by 40% initial shear connector stiffness was adopted. Following this assumption the FE model was modified in order validate it against the experimental results.

A rather good agreement was found between the FE model and experimental results for both life cycles in terms of the effective bending stiffness with a maximum deviation of 12.5%. However, the experimentally obtained shear stiffness parameter, in general, demonstrated larger difference compared to numerical predictions (up to 34.1%).

5 SUMMARY

The main outcomes of the experimental and numerical assessment of the demountable slab floor system are as follows:

- It was demonstrated that dismantling and re-assembly of demountable composite flooring system is possible in laboratory conditions.
- The elastic beam behavior in the first life cycle is relatively well modeled by the FE analysis based on the push-out results of the demountable shear connector. The predicted bending stiffness is in a good agreement with test results with maximum difference of 12.5%. However, the development of the interface slip is predicted poorly by numerical model (maximum deviation 34.1%).
- In the second life cycle, composite beam demonstrated a decrease in both bending and shear stiffness compared to the first life cycle. It was shown that the numerical model with the reduced shear connector stiffness by 40% demonstrates a good agreement with the test results for bending stiffness (maximum deviation 9.0%).

- An application of edge trims along the longitudinal joint should be adopted. It has potential to facilitate the cutting procedure and ensure the confinement of shear connectors. When used in combination with a full height timer separation and discontinuous reinforcement the re-assembly process can be facilitated due to clearances provided by full height timber piece. Nevertheless, the concrete cracking over the timber joist and durability issues have to be addressed and further investigated.
- The 26mm hole clearance in the steel beam flange is sufficient to successfully demount and re-assemble the composite slab to its original position. However, to successfully re-use the composite slab in combination with an arbitrary steel beam, the hole clearance has to be increased in the second life cycle. Similar finding was confirmed in a feasibility study by (11) on a demountable composite flooring system with large prefabricated decks.

6 ACKNOWLEDGMENT

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