

Keynote Paper

Development of composite floor system for a circular economy

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ABSTRACT

Circular economy is an economic system aimed at minimizing wastes and making the most of the current resources. This regenerative approach is in contrast to the traditional linear economy, which has been adopted by the construction industry. Developing new construction technologies for sustainable built environment is a top priority for the construction industry throughout the world. Much of the environmental impact from the construction industry is associated with the consumption of resources and generation of waste. The construction industry in Europe consumes over 70,000 million tonnes of materials each year and generates over 250 million tonnes of waste. Composite flooring formed by connecting the concrete slabs to the supporting steel beams has been widely used for many years and is well established as one of the most efficient floor systems in multi-storey steel frame building structures. However, shear connectors are welded through the steel decking to the steel beams and cast into the concrete; this made deconstruction and reuse of these components almost impossible. A new composite flooring system which allows for the reuse of the steel beams and composite floor slabs is developed and tested to assess its potential and suitability for reuse. This paper presents the results of a series of full-scale beam tests and demonstrates the reusability of this new form of composite flooring systems.

1. INTRODUCTION

Steel manufacturing consumed a large amount of energy when comparing with the production of concrete. However, steel is 100% recyclable whilst concrete can only be down cycle or sent to landfill. Steel and concrete contribute to the most embedded energy in construction due to their huge usage. In building structures, flooring

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contributes to a large volume of concrete being used. If both steel and concrete components can be reused without remanufacturing at the end life of the structure, this could save significant resources and reduces carbon emissions, and move up the waste hierarchy from recycling to reuse.

To achieve a circular economy, it is essential to create reusable components for a sustainable built environment. Allowing us to use structural components longer by repeated use. Creating high quality systems to avoid recycling or downcycling.

Composite structure consists of steel beams connected to metal profiled deck concrete slabs is the most popular flooring system for steel framed building structures around the world. Composite action between the steel beams and the floor slabs led to increases in member stiffness and bending moment resistance, which in turn, enable the increases in beam span. However, the current composite flooring system achieved its composite action by use of through deck stud welding that has made the deconstruction of the composite floor system impossible.

Recently, researchers have been searching for innovative connection systems to overcome the weakness of the welded shear connectors to make the deconstruction of the composite system possible, bolts used as demountable shear connectors might be a solution, however, so far bolts have not been extensively adopted in construction practice to fulfil the deconstruction aim. (Pavlovic et al. 2013) studied the M16 Gr8.8 bolted shear connector through push tests in solid slabs and compared the experimental results with welded headed shear studs in solid slabs. It was found that the Gr8.8 bolted shear connectors with a single embedded nut achieved about 95% of the shear resistance under static loads, but the stiffness was reduced by 50% compared to the welded headed stud. A full-scale composite beam test with profiled metal decking was reported by (Moynihan and Allwood 2014) using M20 Gr 8.8 bolts as shear connectors in a composite beam. Their research showed that these bolts may be used as demountable connectors and they behaved in a similar way to welded connectors and the slabs can be taken off easily from the steel beam. (Dai et al. 2015) investigated the load slip behaviour of modified demountable shear connectors through push tests and finite element modelling. (Rehman et al. 2016, 2017) and (Lam et al. 2017) studied the modified demountable shear connectors in composite slabs by push tests and full-scale composite beam systems. It was found that the demountable shear connectors completely fulfilled the aim of deconstruction of the composite system.

This paper presents recent research by the authors on the use of demountable bolted shear connectors using cast in-situ composite construction with profiled decking, the aim is trying to keep the first-cycle of use as close as possible to the current construction practices. The behaviour and failure modes were analysed through a series of push tests and numerical simulations, which led to a better understanding to the behaviour of this form of shear connectors.

The three main characteristics for re-use are: it is not worn, yielded or corroded, it is not a superseded technology, and it can be interfaced with new components. The

aims and objectives of the research is to develop an innovative composite floor system which is demountable and allow the reuse of both the steel beams and the concrete slabs. The composite system presented in this paper is closely mimicked the currently commonly used composite flooring system to encourage uptake by the construction industry. This paper investigates the reusability of the system by comparing its performance of first-use vs. re-use. The demountability and re-assemblability of the system is highlighted.

A sequence of experiments on a long-span asymmetric composite cellular beam with conventional welded shear connectors were previously performed at the Heavy Structures Laboratory, University of Bradford (Sheehan et al. 2016). The degree of shear connection used was less than half of the required number for such beams specified in EN 1994-1-1 (CEN 2004). The beam failed at an applied uniform load of 3.4 times of the design working load and shear resistance was 45% higher than predicted. Overall, the tests demonstrated the potential of unpropped composite beams with low degrees of shear connection. To explore the potential of demountable shear connectors, the composite beams tested and presented in this paper, were cast unpropped and were designed for a 27% nominal degree of shear connection (actual 21.6%) which was much smaller than the minimum value of 40% required for welded studs specified in BS EN1994-1-1 (CEN 2004).

2. BEAM TEST

Composite beams using demountable shear connectors in profiled composite slabs with transverse ribs to the longitudinal axis of the beam were designed to investigate the structural behavior and composite action of the beams at two scenarios:

- cast in-situ slabs, i.e. no cutting, and
- reassembled slabs with transverse grout joints (Fig. 1).

Two identical composite beam specimens, namely B1a and B1b, were constructed unpropped and tested at the Heavy Structures Laboratory, University of Bradford. Temporary props were attached to the beams (Fig. 2) to support the decking during concreting to simulate unpropped construction and were removed after concrete was hardened. The use of unpropped construction is not explicitly covered in BS EN1994-1-1 (CEN 2004). One of the advantages of unpropped construction of composite beam is that there is zero stress to the shear connectors caused by dead loads after the concrete has hardened, resulting in less slip requirement compared to propped construction.

To facilitate reuse of the beam and slabs, pairs of 150mm deep edge trims were embedded in concrete (Fig. 3) along the centreline (longitudinal) of the beam. The slabs were separated and thus no cut is needed at the beam centreline during deconstruction.

Demountability of the structure and reusability of both the composite slabs and the steel beam was highlighted. Load vs. deflection, load vs. slip, strains and mode of failures obtained from the tests were compared and presented in this section.



Fig. 1 Reassembled/reused slab segments with grout joints (specimen B1a REUSE)



Fig. 2 Temporary supports attached to the beam



Fig. 3 Embedded edge trims shown after transverse cutting

2.1 Fabrication and details of specimens

The two full-scale composite beam specimens were cast at the same time with the same concrete mixture. The concrete used was in grade C30/37, with an average 14-day cube strength of 45.7 N/mm², 28-day strength of 51.2 N/mm² and test-date strength of 54.7 N/mm². The average tested compressive strength of grout was 19.4 N/mm² after 24hrs, 38.8 N/mm² after 48hrs and 53.5 N/mm² on test day. Setup of B1a and B1b before concreting and specimens after cast are shown in **Fig. 4** and **Fig. 5**. Each specimen comprised of a steel beam and two separate composite slabs. The composite slabs were formed by pairs of 150mm depth edge trims placed at the center line of the beams. A pair of 19 mm demountable shear connectors were bolted to the

beam section at each trough of the profiled decking with 100 mm transverse spacing. The studs were placed at either side of the central edge trims. Torque of 120 N·m was used to tighten the demountable shear connectors, equivalent to the torque applied by the impact driver commonly used on site for steel frame erection. Embedment height of the connectors was 120 mm which was approximately 6 times of the diameter. Shear resistance of the studs was approximately 50 kN/connector which was obtained from standard push test designed in accordance with BS EN1994-1-1 (CEN2004). There were 14 shear connectors to the first load point. Pre-drilled holes in the beams and profiled decking were 18 mm and 17 mm in diameter, respectively. Bended rebars were embedded in specimen B1a for lifting purpose as shown in Fig. 5. The used reinforcing mesh was resting on the metal decking (60mm height). To prevent longitudinal spilling of the concrete slabs, standard U-bars were used in accordance to the BS EN1994-1-1 (CEN2004).

Summarized details of the composite beams are given as follows:

Clear span:	6 m
Steel beam:	UB 356 × 171 × 57 kg/m, 6.3m, S355, $f_y=448$ N/mm ²
Slab size:	150mm × 750mm × 6.1m
Overall width:	1500mm
Profiled sheeting:	TR60+ (0.9mm thickness, SMD Ltd)
Shear connectors:	19mm shank, 16mm threads 120mm embedment height, 50kN shear resistance (push tests)
Edge trim:	150mm depth, 0.9mm thickness
Reinforcing mesh:	A193, mesh size 200m × 200mm
U-bar:	φ10mm
Concrete:	C30/37

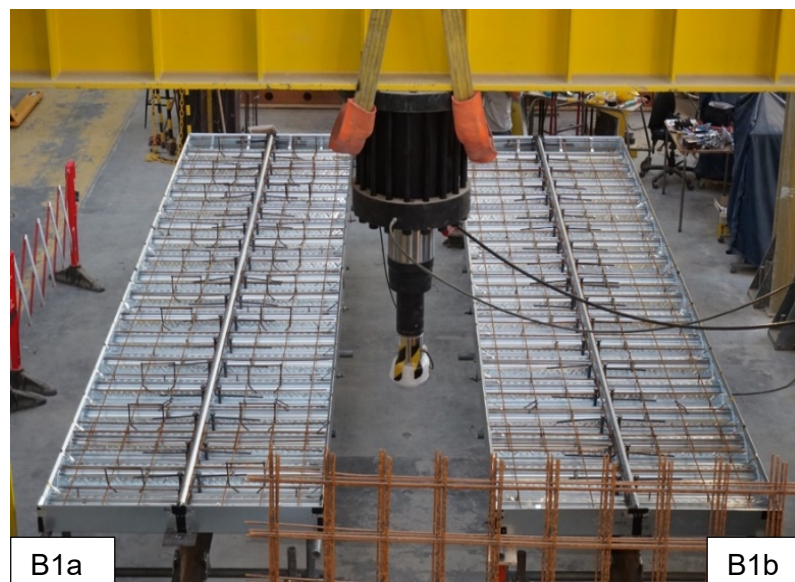


Fig. 4 Setup of B1a & B1b before concreting



Fig. 5 Specimens after the concrete was cast

2.2 Test setup and instrumentation

A 250-tonne actuator was employed to exert the compressive load at the mid-span of the beam. Loading setup and instrumentation are illustrated in **Fig. 6**. Rollers were placed underneath the composite beam ends and the spreader beam ends. LVDTs and/or dial gauges were employed to measure the deflections of the beam at mid-span and loading points, and slips between the beam and the slabs. Strain gauges were used to capture the longitudinal strains at beam sections (**Fig. 6**) and slab (at mid-span).

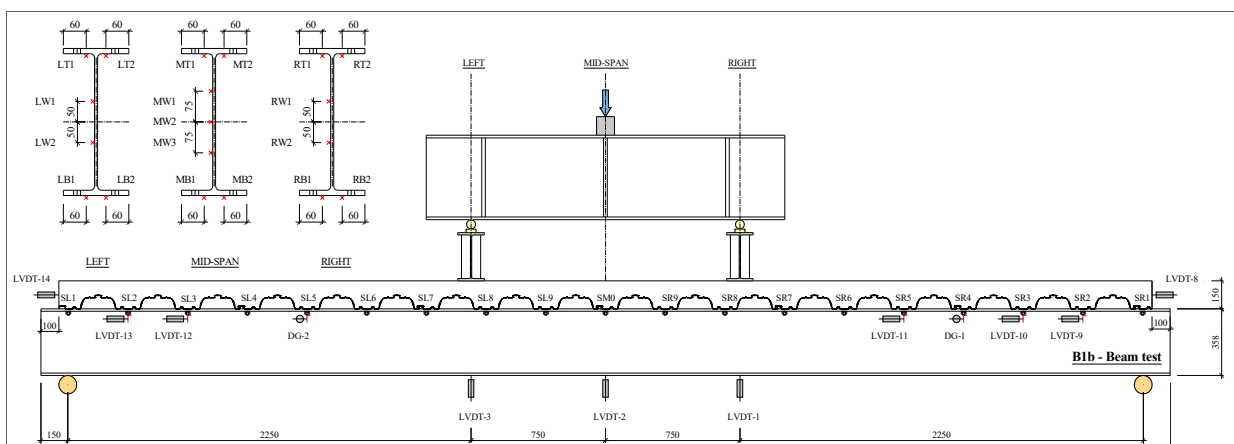


Fig. 6 Loading setup and instrumentation

2.3 Loading protocol

The beams were subjected to 2-point loads so that a defined zone of the beam was subjected to constant shear (2250 mm). The specimens were subjected a sequence of loading cycles, excluding the self-weight of the specimens (composite slab 2.67 kN/m², steel beam 0.19 kN/m²) and loading system (3.1kN, 0.17 kN/m²). Specimen B1b was tested to failure after a few cycle loadings up to the design working load (5 kN/m²), 40% of estimated failure load and serviceability state limit (span/300). Specimen B1a experienced cycle loadings up to 40% of tested failure load (from B1b) and serviceability limit before unloading. Afterwards, the continuous slab (B1a) was cut into segments, detached and reconnected to the beam for a second use /test (test for reuse). The tests on specimen B1b and reused specimen B1a were terminated after the maximum load was reached and the steel beam fully yielded.

Loading protocols for B1a and B1b is given as follows:

Specimen B1b:

- loading to 90 kN (design working load of 5 kN/m²), 5 cycles between 25 kN (5% of estimated failure load) to 90 kN
- loading to 200 kN (40% of estimated failure load / 2.2 times design working load), 5 cycles between 25 kN to 200 kN
- loading to 20 mm of mid-span deflection (serviceability state limit, span/300), (287 kN – 280 kN, approximately 3.1 times design working load), 2 cycles between 25 kN to 20 mm of mid-span deflection
- loading to failure
- unloading

Specimen B1a before dismantling:

- loading to 200 kN (40% of failure load), 5 cycles between 25 kN to 200 kN
- loading to 275 kN (20 mm of mid-span deflection, serviceability limit), 10 cycles between 25 kN to 275 kN, wait for 5 mins each time at 275 kN
- unloading

Specimen B1a after reassembling with grouting:

- loading to 275 kN (20 mm of mid-span deflection, serviceability limit), 1 cycle between 25 kN to 275 kN, wait for 5 mins at 275 kN
- loading to failure
- unloading

2.4 Experimental results

Load vs. mid-span deflection Load vs. mid-span deflection curves of the beams are compared in [Fig. 7](#). Total load was excluded of self-weight of beam and slab. Both composite beam experience large mid-span deflection which demonstrated superior ductility. Summarized failure load, failure moment and maximum mid-span deflections from the failure tests of specimens B1a reuse and B1b were listed in [Table 1](#). The

difference in resistance of the two tested specimens was approximately 2% which demonstrated good reusability of the beam and composite slabs and a similar composite action. Measured maximum deflections and residual deflections at the end of each load cycle is given in Table 2. The residual deflections at the end of each load cycle grew slightly with the increasing of the load, but was relatively small (up to 7.49 mm at 25 kN, span/800). The mid-span deflections of both specimens reached the serviceability limit of span/300 at a load level of approximated 3.1 times of the design working load. The residual deflection of specimen B1a after the first test was 3.33 mm, and was decreased to be negligible after the composite slab was cut into segments and detached from the steel beam.

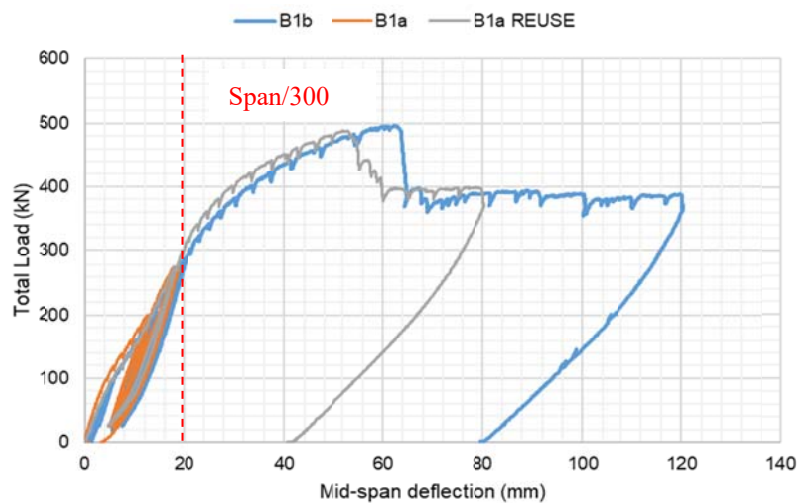


Fig. 7 Total load vs. mid-span deflection

Table 1 Failure load, moment and corresponding deflection of the beams (mm)

Specimen	Failure load kN	Failure moment kN·m	Max. mid-span deflection mm
B1a REUSE	487.9	548.9	52.2 (span/115)
B1b	496.0	558.0	62.4 (span/96)
Difference in resistance = 1.7%			

Table 2 Measured mid-span deflections at the end of each loading cycle excluding self-weight (mm)

Specimen	5 kN/m ²		2.2 × 5 kN/m ²		3.1 × 5 kN/m ²		
	At max.	At 25 kN	At max.	At 25 kN	At max.	At 25 kN	At 0 kN
B1a	/	/	13.20	5.41	18.77	6.45	3.33
B1a REUSE	/	/	/	/	17.95	4.76	/
B1b	5.46	2.85	13.90	6	19.95	7.49	/

Note: deflections listed included initial displacement caused by loading beams – 3.1 kN

End slips The mean slip capacity at 90% of the composite beam resistance was 6.17 mm which suggested a ductile manner of the beams, as shown in Fig. 8 and Table 3. The measured maximum end slips and residual slips at the end of each load cycle was up to 2 mm at the maximum load, 1.22 mm at 25 kN and 0.79 mm after unloading, respectively.

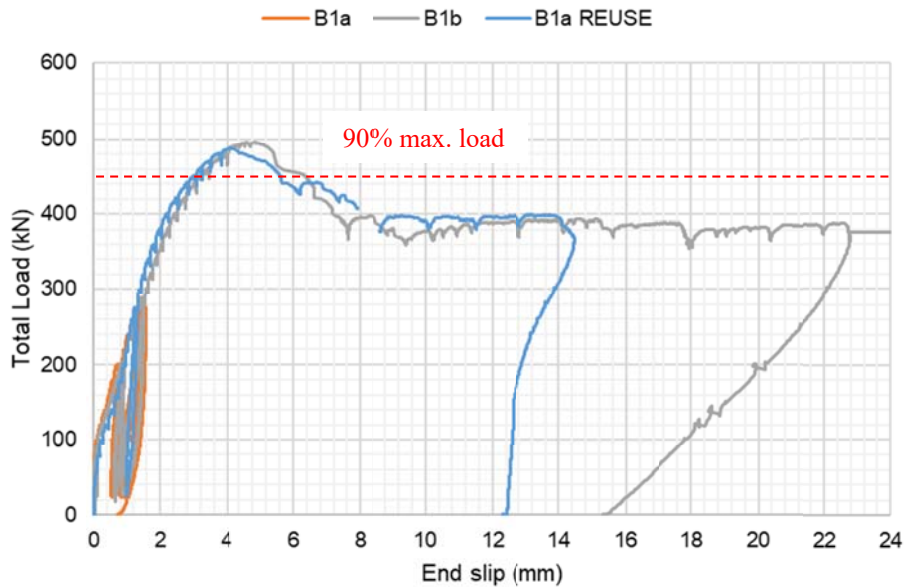


Fig. 8 Total load vs. end slip

Table 3 Measured end slips after the loading cycles and after tests (mm)

Specimen	5 kN/m ²		2.2 × 5 kN/m ²		3.1 × 5 kN/m ²			End slip at 90% max. load
	At max.	At 25 kN	At max.	At 25 kN	At max.	At 25 kN	At 0 kN	
B1a	/	/	1.50	1.06	2.04	1.22	0.79	/
B1a REUSE	/	/	/	/	1.25	0.99	/	5.90
B1b	0.14	0.12	0.92	0.68	1.46	0.86	/	6.43
Average								6.17

Strains Strains measured at the bottom beam flange and concrete surface for specimen B1a during the first use/ test (Fig. 9 and Fig. 10) showed that the beam section and composite slab did not yield before the reuse test. Negative and positive values indicate compressive strain and tensile strain, respectively.

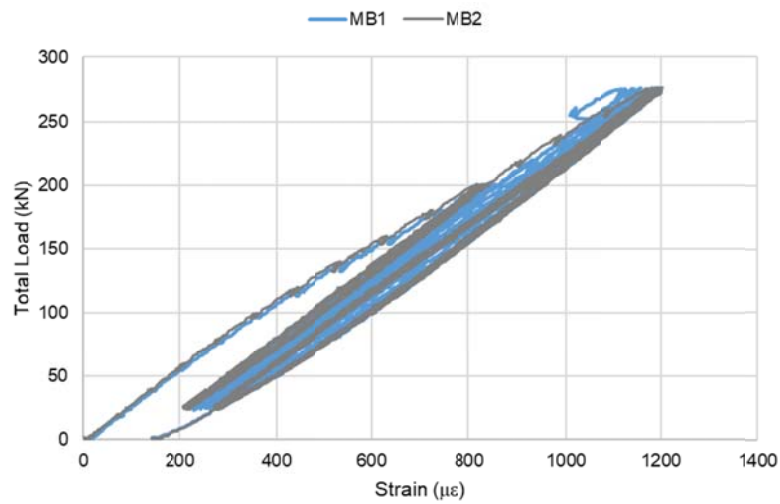


Fig. 9 Total load vs. strain at the bottom beam flange (Mid-span; B1a)

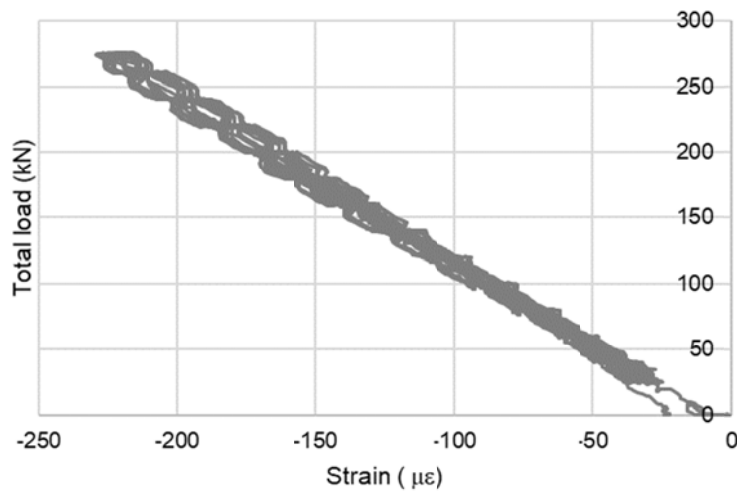


Fig. 10 Total load vs. strain at concrete (B1a at mid-span,)

Total load vs. strains measured at the mid-span of the beam bottom flange for specimens B1a reuse and B1b are plotted in **Fig. 11**, which shows that the beam yielded before the fracture of the demountable shear connectors. This demonstrates that the demountable shear connectors used have sufficient slip capacity and that their shear resistance can be achieved.

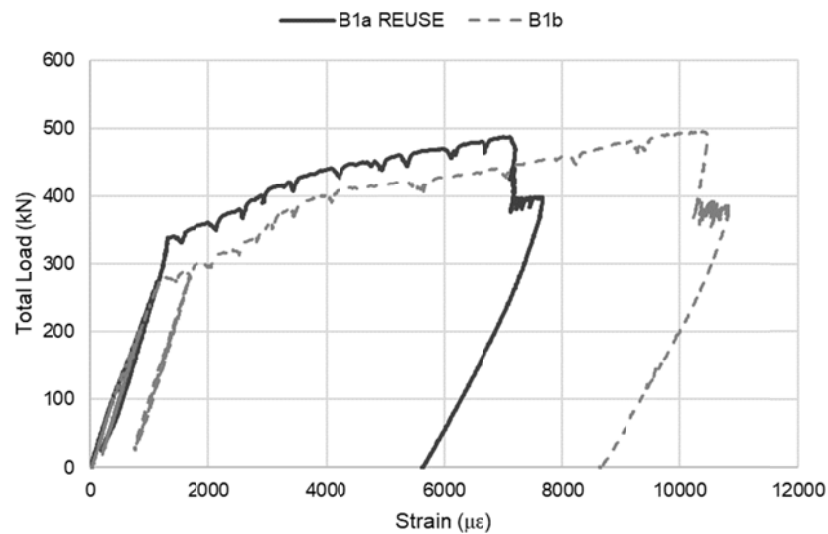


Fig. 11 Total load vs. strain at the bottom beam flange (mid-span; B1a-REUSE and B1b)

Observed failures The final failure of the composite beams was fracture of the shear connectors from beam end up to the first loading point at one shear span, as shown in **Fig. 12**. No concrete crushing was observed. For the first test of specimen B1a, cracks in concrete slab at loading points were observed at high load e.g. 275 kN; (**Fig. 13**) nearly half way of the slab depth with measured crack width of 0.01mm. After the 10th cycle between 25 and 275 kN; the specimen was unloading to 0 load. Cracks were prorogated to full depth. This could be the other reason that caused 2% lower resistance of specimen B1a at the 2nd test (reuse) compared to specimen B1b.



Fig. 12 Stud fracture at one shear span (B1b)



Fig. 13 Concrete cracking at and between loading points (B1b)

Deflection of the composite beam is presented in **Fig. 14** in which plastic deformation of the beam at loading points can also be observed. Although the composite beam experienced large deflection, e.g. up to 120 mm for specimen B1b, the composite slab can still be easily detached after cutting, which can be seen from **Fig. 15**. This figure also shows intact shear connectors after the test at the one shear span, in contrast to the stud fracture occurred at the other shear span (**Fig. 12**).



Fig. 14 Deflection of beam and slab and yielding of beam section (B1b)



Fig. 15 Studs at the other shear span (no fracture during testing and dismantling; B1b)

3. REMARKS ON DEMOUNTABILITY AND REUSABILITY

After the first round of tests, the composite beams were easily dismantled with the slabs cut into segments. For specimen B1a, the beam and composite slab segments were reassembled after the first test/use. Segment sizes were planned based on the following concerns: 1) minimum cuts, 2) manageable weight, 3) storage space, and 4) width for future transportation. A total of 4×2 cuts was made (10 slab segments) for each specimen. The segment size was approximately 1000 mm \times 750 mm for the two mid-span segments, 1210 mm \times 750 mm for the four end segments and 1340 mm \times 750 mm for the other four segments. The blade of the diamond saw used for cutting was 5 mm in thickness. The gap between adjacent slab segments after cutting was between 5 mm to 7 mm, which is enough for grouting when reconstructed the specimen.

Beam specimen B1a was loaded to serviceability limit and unloaded after 10 cycles between the limit to 5% of failure load. The mid-span deflection of the beam was measured before concreting, and after the slab was cut into segments, and detached from the beam. It was found from the measurements that the beam had no residual deformation, which was align with the stain readings that showed the beam did not yield. The difference in resistance of specimen B1b and reused specimen B1a was approximately 2%, demonstrated a similar composite action between first use and reuse. From the test observations, the grout could transfer in-plane forces and there was no problem to easy separation of the floor units.

For composite structures, it is possible to re-use both the steel section and the composite slabs. The beams could also be re-used individually. For re-use of salvaged composite floor slabs, the slab segments can be cut to the required length and re-used as precast floor elements with similar composite action (2nd use) or with no (3rd use) composite action. Grout will be used to fill the gap between the slab segments.

4. CONCLUSIONS

A series of beam tests were carried out to investigate the behaviour of composite beam with demountable shear connectors. Comparable results were obtained from the first-use beam and the re-use beam. The less than 5% differences in load resistance could due to the effect of cast in-situ vs. precast, further analysis is currently on-going. Testing of the demountability and re-assemblability showed that the flooring system can be easily reused without additional erection tolerances. The degree of shear connection of the tested beams with demountable shear connectors was 21.6 %, much smaller than the lower bound of 40% specified in EN 1994-1-1 (CEN2004) for welded shear studs, the slip capacity at 90% of beam resistance was 6 mm in average and fulfilled the ductility requirement. This finding demonstrates the benefits of unpropped composite construction, in terms of reduce slip requirement and lower degree of shear connection.

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