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Publication date
2018

Document Version
Final published version

Published in
Proceedings of the Scientific Conference on Planning, Design, Construction and Building Renewal (iNDiS 2018)

Citation (APA)
Nijgh, M., Gîrbacea, A., & Veljkovic, M. (2018). Optimization of a composite (steel-concrete) floor system for fast execution and easy demolition. In *Proceedings of the Scientific Conference on Planning, Design, Construction and Building Renewal (iNDiS 2018)* (pp. 45-52)

SCIENTIFIC CONFERENCE
PLANNING, DESIGN, CONSTRUCTION AND BUILDING RENEWAL

iNDiS 2018
NOVI SAD, 21-23 NOVEMBER, 2018

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OPTIMIZATION OF A COMPOSITE (STEEL-CONCRETE) FLOOR SYSTEM FOR FAST EXECUTION AND EASY DEMOLITION

Abstract: One of the increasingly important parameters in the construction sector is the time required for the execution and easy demounting of a structure. The goal of this paper is to provide insight into an on-going research focusing on structural performance of large prefabricated concrete decks connected by a demountable shear connectors. A large bolt-to-hole clearance is used to accomplish both requirements. The holes are injected by an epoxy resin to ensure composite action. The demountability and reusability of the composite beam system was successfully tested.

Key words: Composite beams, demountable shear connectors, execution tolerances, experiments.

OPTIMIZICIJA SPREGNUTE (BETON-ČELIK) PREFABRIKOVANE MEĐUSPRATNE KONSTRUKCIJE ZA BRZO IZVOĐENJE I LAKU DEMONTAŽU

Rezime: Jedan od faktora u modernom zgradarstvu koji sve više dobija na značaju je skraćivanje vremena potrebnog, kako za izvođenje, tako i za laku demontažu konstrukcije. U ovom radu dat je prikaz istraživanja ponašanja velikih prefabrikovanih betonskih ploča spregnutih sa demontažnim mozdanicima za vezu sa čeličnim nosačima. Laka demontaža i ponovno korišćenje postignuto je pomoću velikog zazora između ankernog zavrtnja i rupe, pri čemu je sprezanje obezbeđeno zapunjavanjem zazora primenom epoksidnih smola.. Efikasnost ovakvog sistema je dokazana eksperimentalnim ispitivanjem prefabrikovane ploče u punoj razmeri.

Ključne reči: Spregnuti nosači/ploce, demontažni moždanici, tolerancije izvršenja, eksperimentalno ispitivanje.

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1. INTRODUCTION

The construction sector is generally recognized as very inert industry, with relatively small number of innovations and slow improvement of competiveness. It is rather difficult to improve this position because the majority of the constructions are unique, with lot of in-situ work and relatively low margins of profit. This calls for very careful introduction of any (disruptive) changes compared to what was done traditionally.

Environmental concerns steer the construction towards more sustainable designs. Smaller amount of CO_2-equivalent emission and less waste during process construction, shorter execution time and lower total costs are relatively simple sustainability characteristics of a construction product. Steel-concrete composite beams are a popular solution in current design practice due to their efficient material use and competitive construction. However, commonly used welded connectors obstruct the non-destructive demountability or require time consuming and labour intensive processes to separate the two components.

The circular economy in the case of buildings is best illustrated by Addis [1] through the virtuous circle of design for deconstruction and reuse (see Figure 1). A circular economy applied to a building system means an ability to closely couple the recovery and reuse of products from end-of-life buildings to stock replacement and maintenance [2]. The design process should focus on the future reuse by integrating the building in a closed-loop cycle. To allow for reuse of a building, the building and its components should not be worn-out or outdated and still able to interact with other structural components [3]. To ensure the economic viability of reusable structures in their first lifecycle, the cost-effectiveness and speed of execution and demounting of the structure should be at a similar or (at least) acceptable level compared to that of a traditional, non-reusable and non-demountable, solution.

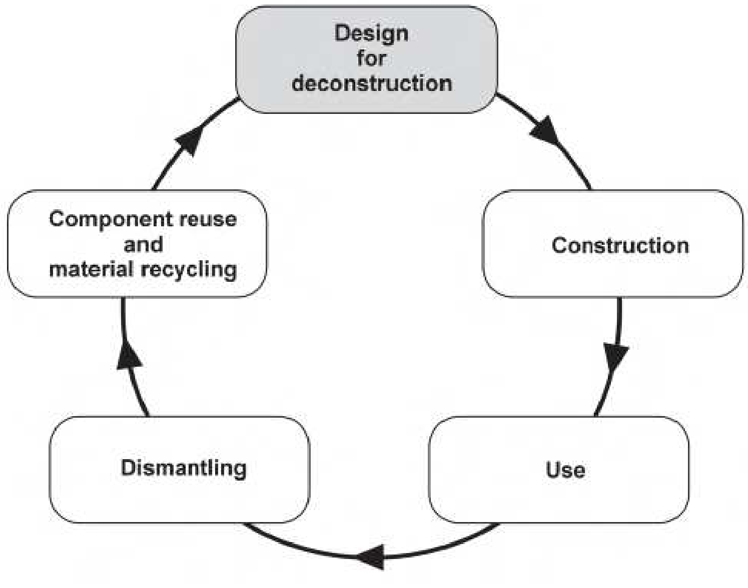


Figure 1 - The virtuous circle: Design for deconstruction and reuse [1]

In past 2 years, Delft University of Technology has collaborated with SCI (UK), University of Bradford (UK), University of Luxembourg (LUX), Tata Steel (NL), AEC3 (UK), Bouwen met Staal (NL), and Astron (LUX) within the RFCS project REDUCE. One of the main project goals was to develop technical solutions which will enable design for more than on life time cycle. It is known from the literature e.g. [4] [5], that demountable shear connectors can establish the possibility of reuse in composite floor systems.

The main objective of this paper is to show how composite action in a demountable steel-concrete composite structure can be achieved, whilst allowing for fast execution as well as demountability and reusability of the components. Large prefabricated decks are considered to save execution and demounting time, which has brought about a new set of engineering questions related to execution and fabrication tolerances.

2. GENERAL APPROACH TO DEMOUNTABLE AND REUSABLE COMPOSITE STRUCTURES

2.1. Demountable shear connector for a large prefabricated deck

The bolt-coupler system illustrated through Figure 2 is a demountable alternative to the welded headed stud. A benefit of the bolt-coupler system is that all of the connecting components are internal during transportation and assembly, hereby reducing the risk of any damage.

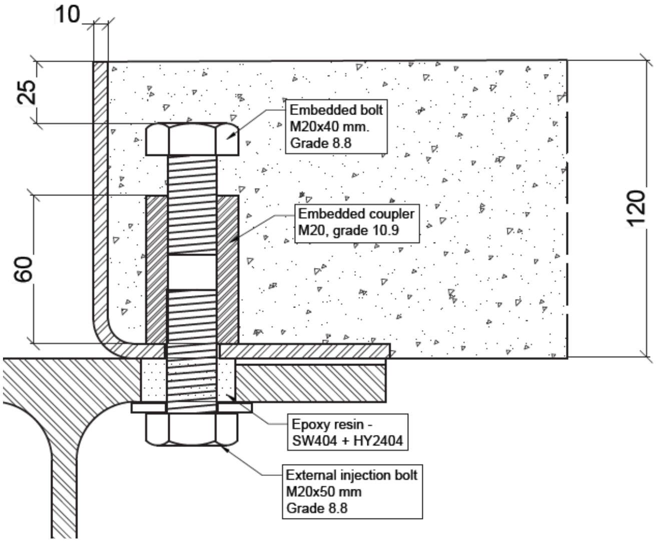


Figure 2 - Resin injected bolt coupler system [6]

The shear connector consists of an embedded bolt and coupler which are connected to an injection bolt from below. By injecting epoxy resin into the bolt-to-hole clearance, instantaneous and simultaneous composite action is achieved for all of the shear connectors [6]. The injection bolt allows for great executional and fabrication tolerances without sacrificing on structural efficiency of the composite beam. The coupler is of a higher grade (10.9) than the external bolt (8.8) in order to prevent any damage in case of overloading, ensuring the deck can be reused. Angle profiles are placed all around the bottom side of the deck to protect the concrete edges during transportation and installation,. The width of the decks is limited by typical transportation demands of 2.4-2.6 m, if transported horizontally.

The feasibility of the execution process of demountable and reusable composite structures has recently been demonstrated in [6]. By using demountable shear connectors in combination with oversize holes and resin-injected bolts the concept has been proven in full-scale. In addition, investigations are on-going which address the demounting time and additional costs related to demountable and reusable composite structures. Also, an improved version of resin is developed which consists of a conventional resin enhanced by steel shots (spherical particles) [7]. The mechanical behaviour of the most commonly used resin and steel-reinforced resin can be found in [8] [9].

The design of composite beams is either governed by serviceability criteria or by its resistance in the ultimate limit state. In both design cases, a composite beam can be designed to be demountable and reusable. The serviceability criteria of statically loaded composite beams for reuse is typically governing, i.e. the deflection under design working loads and the first eigenfrequency are critical. In particular, the first eigenfrequency should be sufficiently high to satisfy requirements related to the human perception of comfort.

Steel-concrete composite beams are generally prismatic, i.e. their cross-section does not vary along the beam length. However, tapered composite beams offer both structural and functional advantages compared to prismatic composite beams. Recently, experiments were conducted in [6] to determine the elastic mechanical behaviour of tapered composite beams with various arrangements of demountable shear connectors. It was found that the elastic behaviour of simply-supported composite beams can be optimised by concentrating the shear connectors near the supports. This finding is in line with the theoretical predictions by Roberts (1985) [10] and Lin *et al.* (2017) [11].

2.2. Feasibility study of a "multi-storey car park building"

Based on design of a multi-storey car park building presented by [12], an experimental setup was fabricated taking the space constraints of Stevin 2 laboratory at Delft University of Technology into account. Therefore the beam length was shorter by 10% than the typical span for a multi-storey car park building (16 m), i.e. the free span was 14,4 m.

The setup consists of three tapered beams and four concrete decks. The dimensions of the tapered beam are shown in Figure 3.

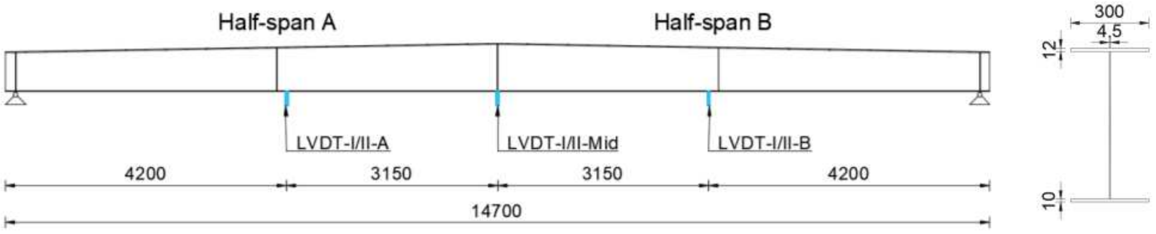


Figure 3 – Dimension of the main beam used in the feasibility test, height of the web 570mm and 725mm at the support and in the mid span respectively.

The four decks were 7.2 m by 2.6 m and the deck thickness was 120 mm. In transversal direction a gap was considered to account for any imperfections, see Figure 4. Longitudinally, at mid-span, the decks were designed to be in direct contact, without taking account of any tolerances. Oversize holes of Ø32 mm for an M20 injection bolts were spaced at 300 mm c.t.c. in the longitudinal direction of the beam.

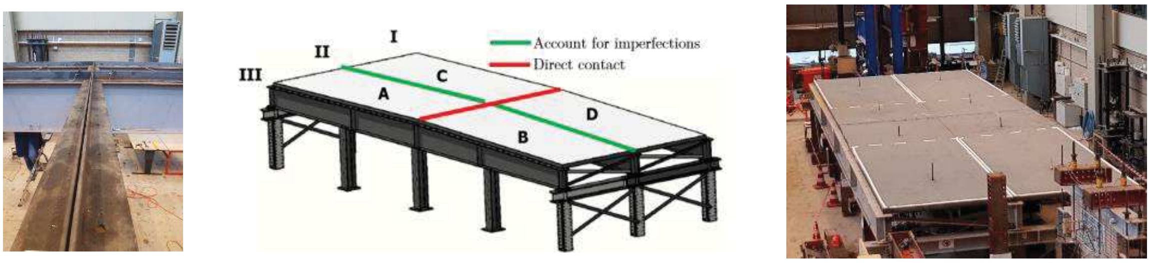


Figure 4 – Lay-out of the specimen

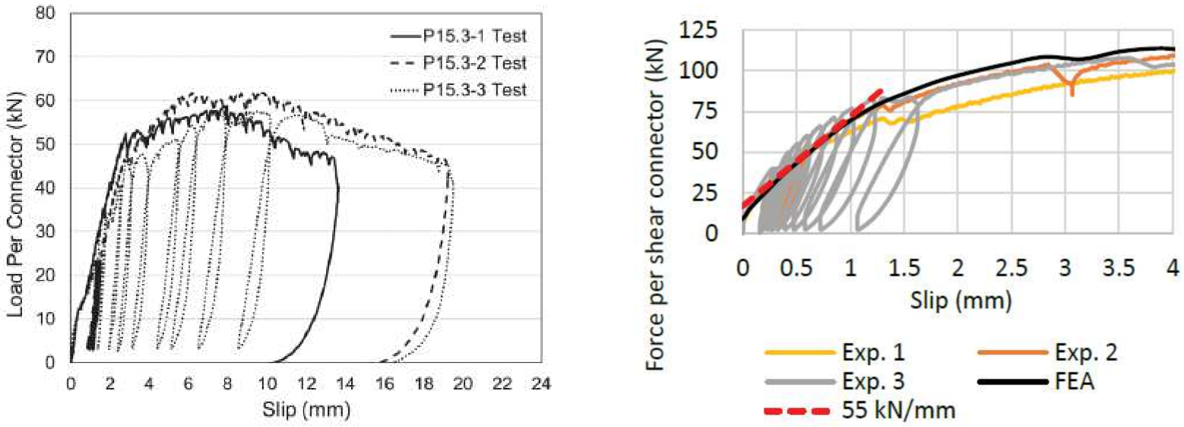
Execution of the specimens and findings from the feasibility test are shown in [12], where justification for the 12mm clearance is documented to allow assembly of the large concrete decks. The influence of the edge side beam is taken into account by adding three facade columns which creates a differential vertical displacement between the beams.

2.3. Shears characteristics of the resin injected bolts in the bolt-coupler connector

The bolt-coupler connector, shown in Figure 2, consists of the coupler made of higher grade (10.9) compared to the external bolt (8.8) to avoid possible damages to ensure that the decks can be reused. The concrete deck edges are “reinforced” by a L-profile prevent damages during handling of the decks. It has been experimentally proved that larger hole clearance can be allowed without compromising the load-bearing capacity and resistance [13] by injecting the hole clearance or by pretensioning. .

Push-out tests are shown in [13] for solid slabs with 150mm height. The failure mode was shearing-off of the lower bolt at an average load level of 131kN per the connector. The initial stiffness is 100kN/mm until the load level of 50kN, after which the stiffness decreases to 30kN/mm, see Figure 5a.

The push-out tests results depends on the deck thickness. In case of 120mm deck thickness the initial stiffness is 55 kN/mm and the resistance 110 kN, shown in [6] and in Figure 5b.



a/ 150mm solid slab results [53]

b/ 120mm solid slab results

Figure 5 – Load-slip curve, push out tests on injected bolt coupler connector, hole clearance 12 mm

2.4. Four point bending tests

The bolt shank will not be in direct contact with the flange, after installation, due the oversized holes. This causes an additional deflection of the steel beam. The initial composite interaction would be accomplished when the external bolts would reach the beam flange. Injecting resin into the hole clearance is a possible solution to achieve composite action without any additional initial slip. Mechanical behaviour of the composite beam was studied using the set-up shown in Figure 6. Two solid concrete decks are supported by two tapered steel beams. The 14.4 m composite beam is subjected to four-point bending at 4.05 m from the supports. The transverse connection between the decks at mid-span is only capable of transferring normal forces due to bending. The c.t.c. distance between the steel beams is 2.6 m. The 28-day concrete strength was determined as 39 MPa, and it was assumed that $E_{\text{deck}} = 33\text{ GPa}$.

The main purpose of the testing was investigate difference between uniform and non-uniform distribution of connectors along the length of the beam in achieving the composite action. From the slip distribution analysis it was expected that the efficiency of the arrangement could be improved by concentrating connectors closer to the supports.

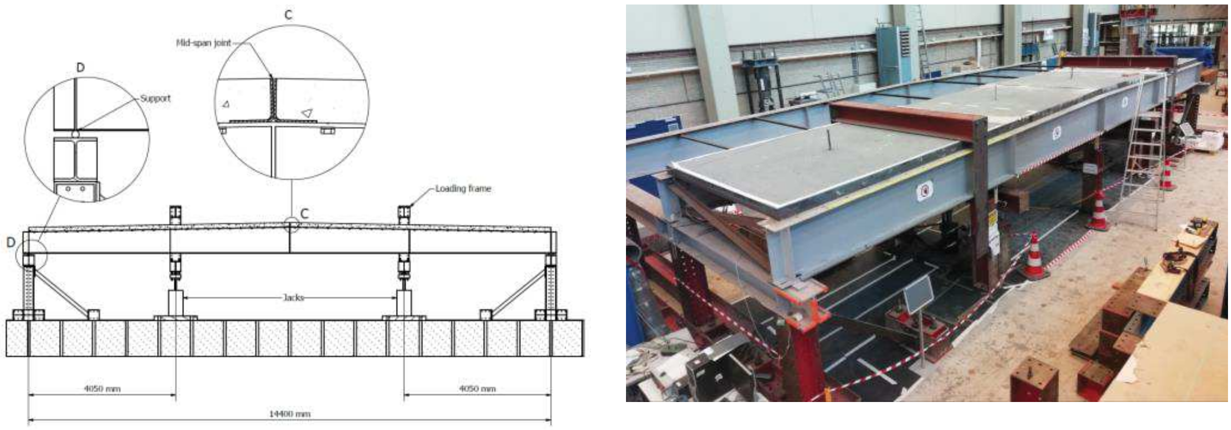
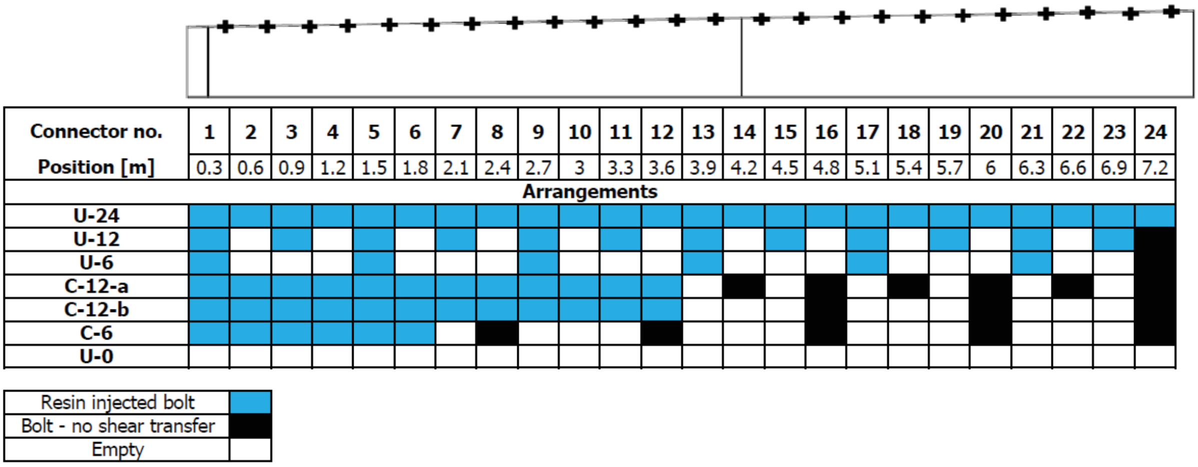


Figure 6 – Four-point floor system testing

The different shear connector arrangements that have been studied are shown in Figure 7. Each blue coloured box indicates an active pair of connectors for longitudinal shear transfer (one connector per steel beam). Bolts with no shear transfer are non-injected bolts used only to prevent vertical separation of the deck and beam. "U" denotes uniform connector spacing, whereas "C" indicates concentrated connector spacing near the supports. The composite beam is symmetric in the plane at x = L/2.



Connector no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Position [m]	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.4	2.7	3	3.3	3.6	3.9	4.2	4.5	4.8	5.1	5.4	5.7	6	6.3	6.6	6.9	7.2
Arrangements																								
U-24	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
U-12	🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦		🟦	■
U-6	🟦				🟦				🟦				🟦				🟦				🟦			■
C-12-a	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦		■		■		■		■		■		■
C-12-b	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦				■				■				■
C-6	🟦	🟦	🟦	🟦	🟦	🟦		■				■				■				■				■
U-0																								

Resin injected bolt	🟦
Bolt - no shear transfer	■
Empty	

Figure 7 – Experimentally tested connector arrangments, beam is symmetric w.r.t. midspan

Seven elastic tests were performed to study the load-deflection behaviour of the composite beam, with the arrangements presented in Figure 7.

Starting with uniform distribution of U-24 the number of connectors is reduced to U-12 and U-6. The uniform distributions U-12 and U-6 can be directly compared to non-uniform arrangements C-12 and C-6, respectively. Two options were tested for C-12-a and C-12-b to study the influence of increasing the spacing between non-active shear connectors which have the role to prevent the vertical separation. No significant differences were observed between the two arrangements in terms of deflection, end-slip and stresses.

A final test was conducted in which the composite beam was loaded to failure. For this test the connector arrangement C-6 was chosen with a spacing of the non-active connectors of 600mm. Even after reaching failure, the composite beam could be demounted easily.

The results obtained for different connector arrangements using an analytical method, proposed in [14] are shown in Figure 8 together with the experimental and finite-element results obtained by Nijgh et al in [6]. The results are expressed in terms of the effective bending stiffness of the composite beam:

$$k_{\mathrm{b,eff}} = \frac{\Delta F}{\Delta w(x = L/2)}.$$

The analytical and numerical model closely match in terms of effective bending stiffness, but also in predicted end-slip. However, the predicted end-slip deviates up to 54% compared to the results obtained in the experimental work of Nijgh et al. [6]. Discussion of reasons for such scattering is left out of the scope of this work and is subject to future investigations.

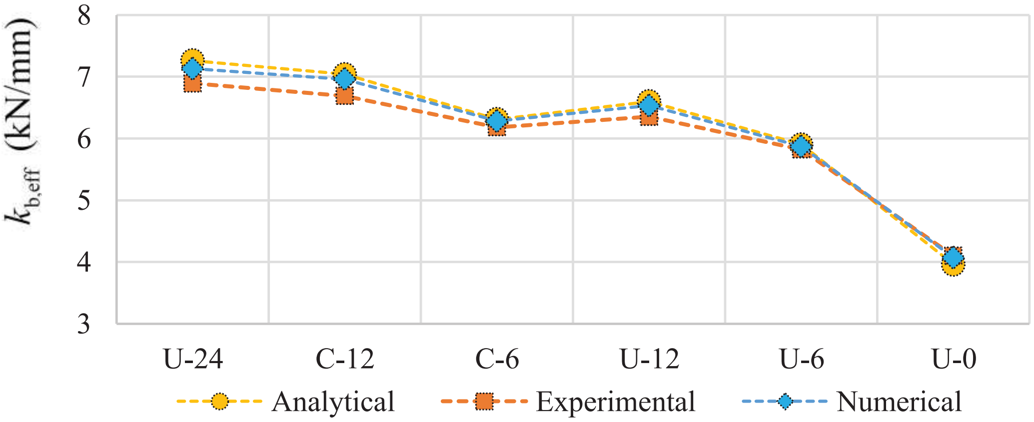


Figure 8 - The effective bending stiffness parameter obtained using the proposed analytical method [14], compared to the experimentally and numerically obtained results [6],

3. CONCLUSIONS

The possibility of disassembly and reuse of the demountable composite floor system consisting of large prefabricated concrete decks and tapered beams connected by injected bolt coupler connectors is successfully demonstrated through full-scale experiments. The composite beam was demountable even after the steel beam has been plastically deformed.

It is shown within the REDUCE project that the resin injected connectors allows for larger fabrication tolerances which reduced construction time while effectively enables composite action of all the connectors simultaneously and instantaneously under live loads. The application of the resin and steel-reinforced resin [7] in combination with injection bolts has the potential to be applied in demountable and reusable composite structures, but also in steel-intensive steel structures.

Analytical and finite element analysis of demountable and reusable tapered composite beams shows very good agreement. The proposed analytical method proposed in [14] accurately predicts the deflection of tapered composite beams. On average, the deviation of the proposed analytical method regarding midspan deflection is 2.4 % compared to the experimental results and 0.4% compared to the finite element results [6]. Predictions regarding end slip obtained using the analytical method proposed in [14] are consistent with FEA, with an average deviation of 6%. The analytical and numerical model do not predict the end slip obtained in the experimental work of Nijgh et al. [6], the deviations are up to 54%. Discussion of reasons for such scattering is left out of the scope of this work.

4. ACKNOLWEDGMENTS

This research was carried out with financial support of the Research Fund for Coal and Steel (RFCS), within the research project ”Reuse and Demountability using Steel Structures and the Circular Economy” REDUCE (RFCS-02-2015). Cooperation of the project partners (SCI, University of Luxembourg, University of Bradford, Lindab A/S, Tata Steel, Bouwen met Staal and AEC3) is gratefully acknowledged

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