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Economic viability of demountable steel-concrete composite beams

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ABSTRACT

Composite beams are commonly used in current design practice due to their efficient material use and competitive execution. The shear connection is mainly achieved by means of headed studs welded on the top flange. However, the welded connectors obstruct the possibility of a non-destructive disassembly required to reuse the steel beams and concrete slabs. Raised concern regarding sustainability aspects drive the construction sector to introduce a shear connector which enables the demountability of the flooring. Composite action can be enabled by a bolted connection consisting of an embedded bolt and coupler connected by an external injection bolt through the top flange of the steel beam. This paper aims to assess the initial investment costs and economic viability of two demountable steel-concrete composite beam solutions. The investigated systems comprise of two different concrete flanges: a prefabricated solid deck and an in-situ casted profiled sheeting slab. The cost inputs of the analysis were defined by industry experts based on assumed labour and material requirements. The unit price of the novel connector is significantly higher (approx. 15 times) compared to the regular headed welded stud. This justifies the need to optimize the connector arrangement in order to keep the cost per square meter as low as possible. Non-uniform connector arrangements can be used to reduce construction time and costs with minor decrease in beam stiffness. A tool was developed to generate a batch of 13500 composite beam designs which were later analysed in terms of costs.

Keywords: demountable composite beams, cost assessment, cost breakdown

1 INTRODUCTION

Environmental concerns drive the construction industry to innovate in order to reduce harmful emissions and waste. According to Huang et. al. (1) roughly a quarter of the global CO_2 emissions are attributed to the construction industry. Until recently the second life of a structure was not specifically considered in design. This led to waste generation, downcycling or recycling of the structural components instead of reusing them. Eurostat (2) indicates that the construction industry is responsible for 36.4% of the waste generated in the European Union. Reusing the building components will reduce the waste, the need for raw materials and maintain their economic value.

The widespread use of steel-concrete composite beams in multi-story buildings is justified by the competitive construction and efficient material use. The shear connection at the steel concrete interface is mainly established by welded connectors. The headed stud welded to the top flange of the steel section is at the moment commonly used to enable the composite action. Welding the connectors demands energy and time consuming operations to separate the steel section from the concrete slab. From an economic point of view the costs of disconnecting the two parts will outweigh any environmental concerns, leading to the structure being reduced to waste. Nevertheless, even if the connection between the steel beam and concrete slab is removed the composite action between the two parts would be no longer possible in a second life cycle

A connector which facilitate the non-destructive demountability and reusability of the composite beams can take the form of a bolted connection. This paper focuses on the bolt coupler connector as means to enable the composite action between the concrete slab and steel beam. The bolt coupler connector consists of an embedded bolt and coupler connected by an external injection bolt. Resin injection is used as measure to mitigate the initial slip rising from the need of oversized holes. The increased hole clearance is required to accommodate fabrication and construction tolerances as demonstrated by Gîrbacea (3) through extensive imperfection measurements and finite element analysis. The economic aspects of two demountable flooring systems (see *Fig. 1b* and *c*) are quantified and compared to the traditional non-demountable profiled sheeting slab connected by mean of welded headed studs (see *Fig. 1a*).

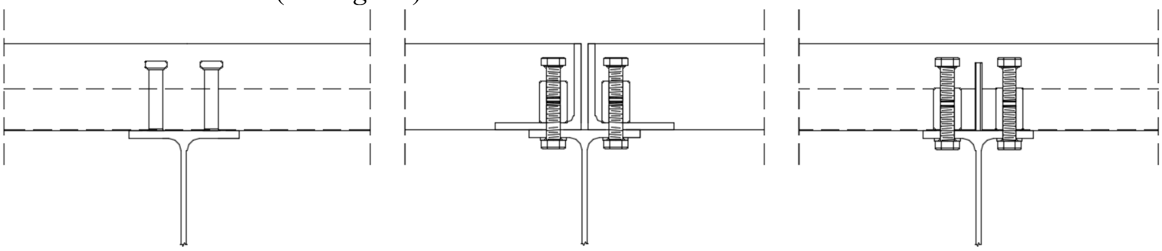

Fig. 1. a) Traditional profiled sheeting slab, b) Demountable prefabricated solid deck, c) Demountable in-situ casted profiled sheeting slab

Prefabricated solid decks are manufactured prior to construction and transported on-site to be installed. The prefabricated decks are protected all around its edges by angle profiles from damage during transportation and construction. Experimental research performed Gîrbacea (3) confirms the possibility of assembly of the flooring through full scale experiments. The demountable profiled sheeting slab system is a in-situ casted solution that can be demounted to be reused in a second life cycle. The concrete slab is partially interrupted between the connectors to facilitate cutting it in smaller parts. The flooring system was studied by Gritcenko (4) through extensive experimental research.

Due to the novelty of the connector their unit price is significantly higher compared to regular studs. Four point bending tests performed by Nijgh et. al. (5) on composite beams, constructed from tapered beams and prefabricated decks connected by means of bolt coupler connectors, confirm that non-uniform connector arrangements are more efficient compared to traditional uniformly spaced connectors. To reduce construction time and costs the connectors are concentrated towards the supports where they are most effective.

2 CASE STUDY METHODOLOGY

Composite beam design is generally governed by stiffness requirements at the serviceability limit state. The load-deflection behaviour of composite beams can be described by numerous analytical expressions included in design guidelines or structural engineering literature. However, the application of such formulas is limited to uniform connector arrangements, prismatic steel sections and the initial stiffness of headed stud connectors. An analytical model was developed and validated by Nijgh et. al. (6) to account for any connector distribution, initial stiffness and steel beam sections.

2.1 Design tool

A design tool was developed to perform the case study using the proposed analytical model. The tool is structured in two modules. The first module generates the input parameters required by the second one to determine the elastic load-deflection behaviour and resistance of the composite beam. The analytical model requires the discretization of the composite beam into segments in order to account for non-uniform connector arrangements and non-prismatic steel beams. Each segment is described by a sixth order differential equation previously developed by Newmark et. al. (7). The segment length is determined by the connector spacing and the steel beam depth is equal with its average along the segment. The model closely matches experimental and finite element results.

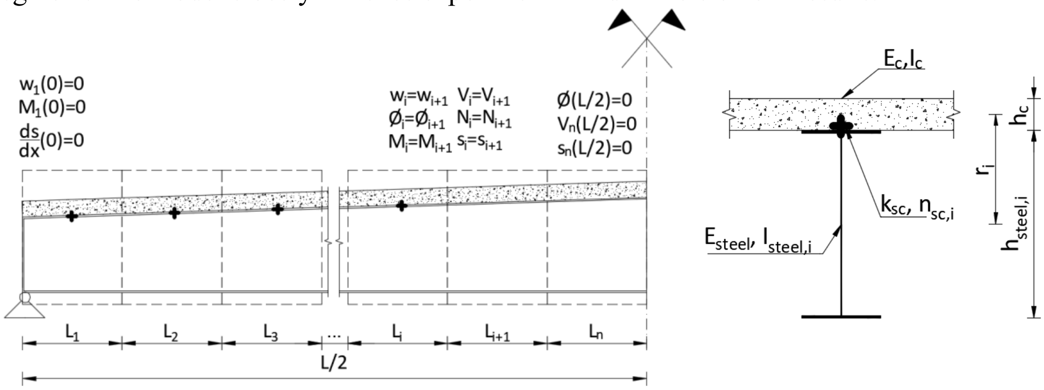

Fig. 2. Composite beam discretization and cross-section (tapered beam example)

For a number of *n* segments it will correspond a set of *n* sixth order differential equations with 6 x *n* unknowns. To reduce computation time the simply supported beam is model taking advantage of its symmetry. In order to solve the system of unknowns 3 boundary conditions will be applied at each end of the beam and 6 x (*n*-1) interface conditions will describe the continuity between the segments as shown in *Fig. 2*. Computation time increases exponentially with the number of segments. For this reason the first module is optimized in order to reduce the number of iterations.

A set of input parameters for the second module is defined by the cross-section properties and the number of shear connectors. For each cross-section the tool will first solve the case of maximum interaction defined by the beam length and connector spacing. If design requirements are met at the extreme case the tool will start searching for the minimum number of connectors required. To further reduce computation demand the incrementation of the shear connection was calibrated based on the relationship between the number of connectors and beam bending stiffness illustrated in *Fig. 3a*. The connectors found in the first quarter span are most effective, summing up to 77% of the cumulative connector force (see *Fig. 3b*). Consequently, the iteration is slow for the connectors in the first quarter span and progressively increases towards mid-span. Implementing these criterions in the first module of the tool reduced computation time for this case study by a factor of 16.

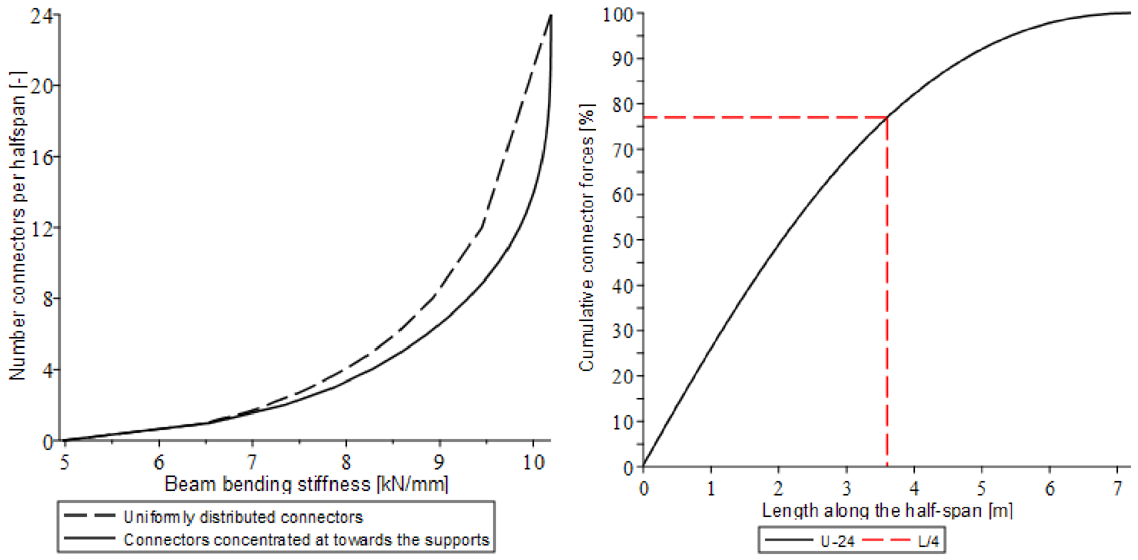

Fig. 3. a) Example of relations bending stiffness and number of connectors for uniform and non-uniform arrangements; b) Cumulative connector force along the length of the half-span for maximum iteration (24 connector rows)

The tool generates a large batch of beam designs which can be multiplied by their corresponding cost inputs. The results can be then used to perform a sensitivity study by varying different costs inputs to analyse the influence of different prices on the beam design.

2.2 Design verifications

Variable loads are assumed equal to q_k=3.3kN/m^2 for office spaces. The self-weight of the steel beam and concrete slab is determined based on the cross-section inputs and the following assumed densities: $\gamma_{concrete}$=25kN/m^3 and γ_{steel}=78.5kN/m^3.

The resistance of the composite beam is verified according to Eurocode guidelines at ultimate limit state. The total beam deflection is limited at serviceability limit state as follows:

$$\delta_{tot} \leq L/250$$

$$\delta_{tot} = \delta_{self-weight}(E_{steel}I_{steel}, g_k) + \delta_{live}(EI_{t=28}, \psi_1 q_k) + \delta_{creep}(EI_{t=\infty}, \psi_2 q_k)$$

To reduce computation time to half, δ_{creep} was assumed in a conservative way equal to 15% of δ_{live}.

Reusable structures require to behave elastic throughout their life time in order to be fit for reuse. As pointed out by Nijgh. et. al. (5) the end-slip elastic limit obtained from push-out tests is 1 mm.

2.3 Cost inputs

So far, no demountable steel-concrete composite structure using the bolt coupler connector was built. Consequently the cost inputs used in this case study are defined by industry experts based on assumed material and labour use. The cost assessment focuses only on the first life cycle of the structure.

Table 1.	**Materials**	
Steel	/kg	2 €
Hot dip galvanizing	/kg	0.25 €
Angle profile (L120x120x10)	/m	10 €
Hole (beam, angle or sheeting)	/unit	1 €
Concrete	/m^2	15 €
Reinforcement mesh	/m^2	10 €
Fire protection	/m^2	25 €
Profiled sheeting	/m^2	20 €

Table 2.	**Connectors**	
M20 Injection bolt 8.8	/unit	3 €
M20 Coupler 10.8	/unit	3.1 €
M20 Bolt 8.8	/unit	0.75 €
Washer	/unit	0.75 €
Stud and ceramic ferules	/unit	0.5 €
Total connector price		
Injectable connector	/unit	7.6 €

Table 3.	**Manufacturing**	
Casting and reinforcement installation	/m^2	15 €
Decking for profiled sheeting slabs	/m^2	10 €
Formwork and angle-profile installation for prefabricated decks	/m^2	60 €
Connector installation	/unit	1 €
Stud welding	/unit	2 €

Table 4.	**In-situ work**	
Resin injection (resin, labour, consumables, release agent)	/unit	2.50 €
Prefabricated deck installation (crane, operator, fuel, 2 workers)	/deck	185 €

Table 5.	**Transport**	
Transport 3.6m wide deck	/unit	750 €
Transport less than 3m wide deck	/unit	500 €

The unit price of the bolt coupler connector is higher by a factor of 15. This explains the need to reduce the number of connectors by using an optimized longitudinal shear connection. The durable design of the deck increases manufacturing cost but will ensure the reuse is economically justified in a second life cycle. The length of the deck was limited to 10 m to meet transportation demands. The complete documentation of the cost inputs can be found in (3).

3 ECONOMIC VIABILITY OF DEMOUNTABLE FLOORINGS

The economic viability of the two demountable steel-concrete composite beams illustrated in *Fig. 3* is investigated by comparing them to the traditional solution. The input parameters of the case study are defined in *Table 6.*

Table 6.	Parameters	Range
1. **Traditional profiled sheeting slab** k_{sc}=80kN/mm, spacing=300mm	Materials	C30/37, S355
2. **Demountable**	Slab thickness	120 mm
• **solid slab** k_{sc}=55kN/mm, spacing=200mm	Steel section	IPE, HEA, HEB
• **profiled sheeting slab** k_{sc}=30kN/mm, spacing=300mm	Slab width	2.0 m, 2.6 m, 3.0 m, 3.6 m,
	Span	From 6 to 20m

Fig. 4 illustrates the cost breakdown for the two demountable beams at a span of 10.8 m. In this case both solutions are more economic as composite beams. Even though the novel connector has a high unit price, the contribution of the connectors to the overall costs is limited. The most influential contribution to the final price of flooring is the concrete work including materials and labour summing up to roughly 45% followed by the steel beam roughly 25%.

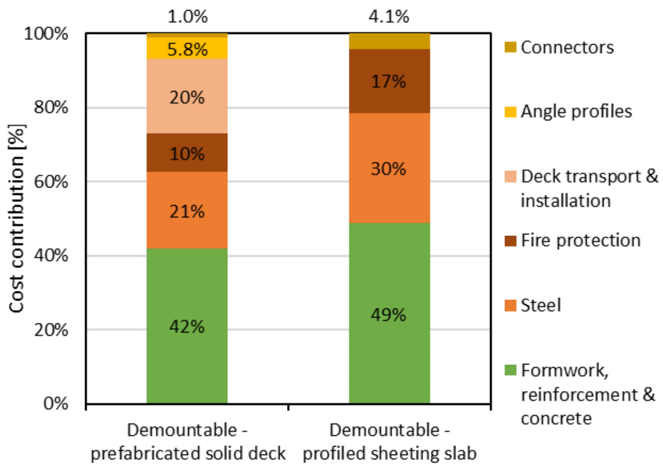

Fig. 4. Cost breakdown

For all three flooring solutions the price per m^2 decreases with increasing slab widths and it rises with span length. The significantly higher cost of demountable flooring constructed with prefabricated slabs (seen in *Fig. 5 a*) is explained by the labour intensive manufacturing and need for additional transportation and installation. Even though the initial investment is higher the robust design of the prefabricated decks ensures that the concrete slabs will not be reduced to waste or downcycled. For spans ranging from 6 to 12 m the average cost increase compared to non-demountable floorings is 70% and reduces to 45% for spans between 12 and 20 m. Prefabricated solid decks connected by means of bolt coupler connectors are more economically as composite beams in 86% of the cases. (see *Fig. 5 b)*

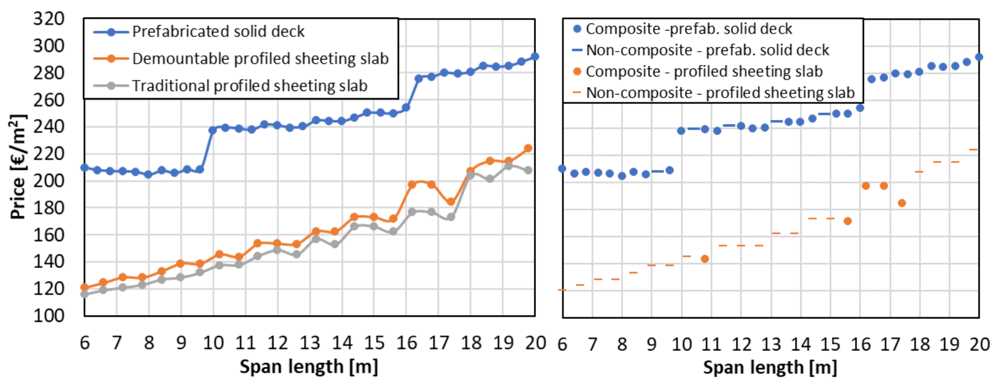

Fig. 5. a) Price per m^2 against span length for 3.6m wide slabs b) Price per m^2 against span length for 3.6m wide slabs with differentiation of composite action

The cost increase for demountable profile sheeting slabs compared to the traditional solution is roughly 5%. Due to the high cost per unit and low initial stiffness only 26% of the beam designs for spans between 6 and 20 m are more economical having composite action. The economic viability of the system is studied by reducing the connector cost inputs by half. For the reduced connector costs, 42% of the cases will yield a lower price per m^2 as composite beams. Bending tests performed by Gritcenko (4) show that in the second life cycle the connector stiffness reduces by 40%. Consequently, the bolt coupler connector in combination with profiled sheeting slabs is not economically viable.

4 CONCLUSIONS

An extensive case study based on cost inputs assumed by industry experts was performed on a batch of 13500 beam designs to study the economic viability of two demountable steel-concrete composite flooring systems. The extensive case study was performed using a design tool developed to determine in a computational efficient manner the load deflection behaviour of composite beams using non-uniform connector arrangements.

The most influential contribution to the final price of flooring is the concrete work including materials and labour roughly 45% followed by the steel beam roughly 25%. Even though the connector unit price is significantly higher compared to a common headed stud the cost contribution to the overall costs is less than 2% for the prefabricated solid deck solution.

The price of the demountable flooring constructed from large prefabricated decks increases compared to a non-demountable solution by 70% for spans ranging from 6m to 12m. For longer spans up to 20m the cost increase is 45%. The case study indicates that the flooring constructed from large prefabricated solid concrete decks connected by means of bolt coupler connectors is economically viable as a composite beam. The robust design of the decks results in a higher initial investment but ensures the economic value will be maintained in a second life cycle.

Demountable profiled sheeting slabs yield a minor average cost increase of roughly 5%. However, the case study and previous experimental research indicate that the system is not economically viable to be used as a composite beam due to the low initial stiffness of the connector.

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