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Design of composite flooring systems for reuse

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Abstract. Composite floor systems are frequently used for high-rise buildings and multi-storey car park buildings, mainly because of the competitive combination of the steel beam and the concrete deck. Traditionally, composite beams are cast in-situ and shear interaction between the concrete and steel beam is provided by welded headed studs. The application of welded headed studs prevents the non-destructive separation of the composite beam, which leads to a very low scoring in the sustainable assessment in terms of the reuse of structural components. An alternative to welded headed studs are bolted shear connectors, which allow for demountability and reusability of a (prefabricated) composite floor system. A key challenge for demountable and reusable composite beams consisting of prefabricated elements is to provide sufficient tolerances to allow for easy execution and demounting, but also to achieve a stiff and strong shear connection under live loads. The required tolerances can, for instance, be obtained by using large bolt-to-hole clearances. The, at first glance, contradictory requirement of a large hole clearance in the execution phase and high stiffness under live loading conditions was solved by using injection bolts. The goal of this paper is to demonstrate how the demountable and composite structures fit in the circular economy framework, and to show that such a demountable and reusable structure was successfully erected and demounted under laboratory conditions. In addition, a cost assessment will be addressed using a simple methodology based on estimated service life (ESL) factors to estimate the annual environmental costs of a composite floor system.

Keywords: Composite structure; reusability; demountability; sustainability, shear connector; resin-injected bolted connection

1. Introduction

The Dutch construction sector is responsible for 50% of annual resource consumption, 40% of the total energy consumption and 40% of the construction and demolition waste [1]. The Dutch government has initiated the vision that in 2050 all newly built structures are to be sustainably built, maintained, reused and demounted [1]. In particular, demountability is a key focus area since it allows for value retention of the structural members, the potential for the cost reduction in extended life cycles, and a smaller environmental impact. The Dutch government includes the life cycle costs in own construction projects, hereby boosting field of sustainable construction. Generally, sustainable buildings require a higher investment costs, but may lead to a lower total cost of ownership (TCO) in the long-term [2].The actual service life of a building is generally governed by cultural, social and aesthetic considerations, rather than by its technical and/or structural condition [3]. Obsolescence can be resisted by designing for durability, postponed by designing for maintenance and upgrading, and reversed by designing for repair, refurbishment and remanufacture [4]. To extend the service lifetime and prevent demolition, it will generally be necessary to adapt the building to new functional requirements or to reassemble the structure at a new location. For both operations, the demountability of parts of the structure or the structure as a whole is a very important characteristic for future structures.

A decrease of the societal and environmental risks related to natural resource use and environmental degradation can be achieved by decoupling these causes from economic growth [5]. Decoupling is either relative, meaning that the resource use increases at a slower rate than the economy, or absolute, meaning that the environmental impact decreases although the economy grows [5]. Clearly, demountability and reusability of structures aids in the decoupling process, as less new materials are necessary and the environmental degradation is minimized. Designing out waste and pollution, and keeping products and materials in use, are the key principles of the circular economy model.

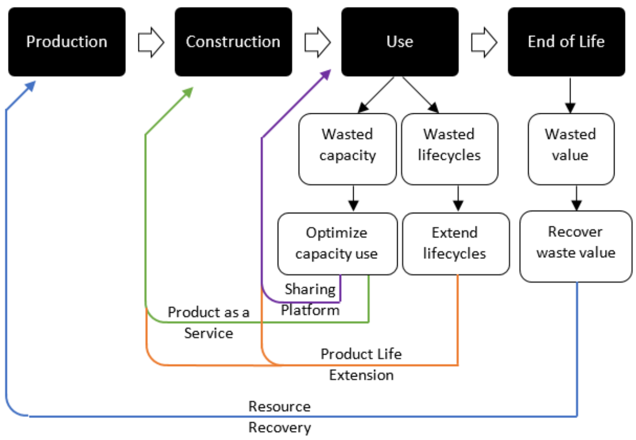

Figure 1 – The application of circular business models and their relation to the lifecycles stages of a structure.

There are generally five main models within the circular economy framework that can be used to generate sustainable business [6]:

- Circular Supplies: providing renewable energy in the fabrication stage,
- Resource Recovery: recovering useful resources or energy of disposed products,
- Product Life Extension: extending the service lifetime of a structure,
- Sharing Platforms: increasing the utilization rate of an asset,
- Product as a Service: offering product access but retaining ownership

Figure 1 illustrates how the circular business models could be applied to the construction sector. Clearly, demountability and reusability of a structure is necessary for the Product as a Service and Product Life Extension models. The Sharing Platform and Resource Recovery models solely rely on adaptability and demountability, respectively, of the structure.

2. Demountability and reusability of composite structures

Traditional composite structures consist of a steel beam and concrete deck, connected by welded headed studs. Such traditional composite structures cannot be demounted, but only be demolished due to the permanent connection between steel beam and concrete deck. This permanent connection impairs the opportunity for composite structures to be reused, as the structure cannot be easily demounted and reconstructed at another location, nor can the floor plan of the structure be adopted to fulfil the new functional needs. When the structure is no longer fulfilling any function, it is regarded as obsolete [7] and demolition is often imminent. With the demolition of an obsolete but technologically sound structure, the economic value of the structure is lost. Demolishing the old structure and rebuilding a completely new structure has a great impact on the environment, which would not have been necessary if the structure was saved from demolition by reusing it.

Demounting a (composite) structure is potentially faster and cheaper than demolishing it, as the steps in the demounting process are better defined and can be planned more precisely compared to a traditional demolishing process. Savings regarding costs and time can be especially pronounced in the case of urban environments and high-rise buildings. Clearly, the aforementioned is mostly valid if the structure consists entirely of prefabricated elements, as this eliminates the need for any in-situ cutting of the concrete deck before the demounting process can start.

To allow for demountability and reusability of composite structures, the traditional welded headed studs, used to obtain shear interaction, must be replaced by demountable shear connectors. Various types of demountable shear connectors exist, but the focus of this paper is on bolted shear connectors as shown in Figure 2. This type of shear connector consists of a bolt and coupler embedded in the concrete deck, connected to the steel beam with an external bolt. The benefit of using the coupler as an intermediary member is that during transportation and handling no part of the connector can be damaged, as would be the case with conventional bolted shear connectors.

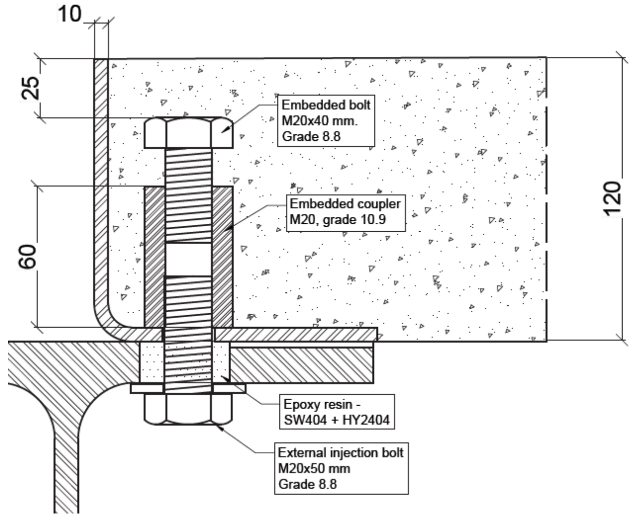

Figure 2 - Cross-section of demountable shear connector, concrete strength class C30/37. Dimensions are in mm.

A key condition for easy demounting and reusing a structure at another location is that assembling the structural members should be without any issues related to alignment. A prerequisite for successful alignment is to allow for all foreseeable geometrical deviations (tolerances) related to the fabrication and assembly of the structural elements. As the fabrication tolerances are larger for concrete than for steel, the bolt-to-hole clearance for the bolted shear connectors needs to be larger than in case of a steel-to-steel connection. Apart from fabrication tolerances, additional bolt-to-hole clearances are required to allow for in-situ deviations (e.g. due to inclination of columns) and to increase the execution speed.

To achieve the desired level of shear interaction, it is imperative that all bolted shear connectors are (simultaneously) in contact with the steel beam. However, due to the large bolt-to-hole clearances that are necessary, the bolted shear connectors cannot immediately contribute to shear interaction under the live load, rendering the shear connection useless. Obviously, there is a contradiction between the need for bolt-to-hole clearances and the need for shear interaction. This contradiction can be solved by connecting the steel beam to the concrete deck by using injection bolts instead of conventional bolts. The remaining bolt-to-hole clearance in the beam flange is injected with a stiff and durable epoxy resin, hereby ensuring instantaneous shear interaction under live loads. As all of the shear connectors are active

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instantaneously and thus simultaneously, the structural effectiveness is fully optimized and reliable predictions of the actual mechanical behaviour of the composite beam can be made.

Two bays of a nearly full-scale composite multi-storey car park building were constructed in the laboratory to investigate the structural feasibility of demountable and reusable composite structures. The composite beam consists of a tapered steel beam with a span of 14.4m, and prefabricated concrete decks of 7.2m by 2.6m, with a thickness of 120mm. An overview of the mock-up of the building is provided in Figure 3.

a) b)

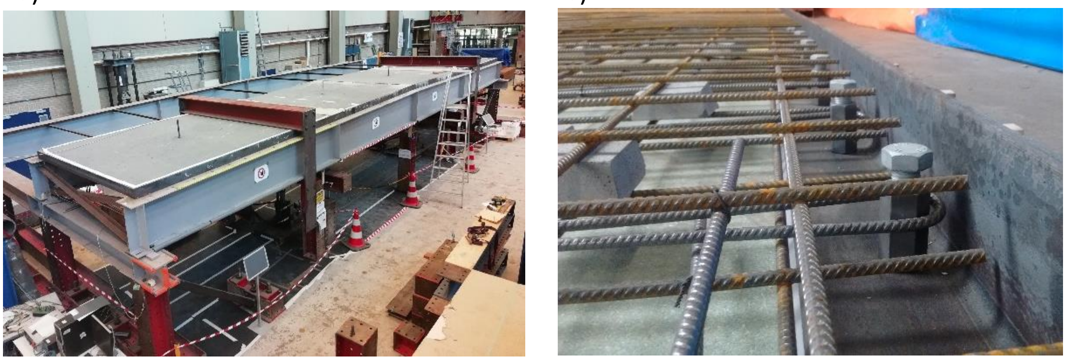

Figure 3 - a) Experimental set-up, b) Prefabricated deck prior to casting, indicating the reinforcement and embedded couplers and bolts.

Angle profiles (120x120x10mm) form the perimeter of the solid concrete decks, acting as formwork during concrete casting and protecting the edges of the decks against damage, hereby increasing the possibility of future reuse.

Shear interaction is obtained by the shear connectors illustrated in Figure 2. Initially, it was assumed that a Ø26mm hole would provide sufficient clearance to install the M20 external bolt into the coupler embedded in the prefabricated deck, taking into account the fabrication and execution tolerances. Based on actual measurements of the fabrication tolerances of the steel beam and concrete decks, the Ø26mm holes were enlarged to Ø32mm. After installation of the decks, the remaining bolt-to-hole clearances were injected using RenGel SW404+HY2404/5109 epoxy resin.

The experimental composite beam could be assembled and demounted without any problems. All of the structural elements (e.g. steel beam, concrete deck, and external bolts) could be reused when rebuilding the structure, except for the epoxy resin. During subsequent tests, the composite beam was subjected to two point loads at 4.05m from the supports, using various arrangements of shear connectors (see Figure 4). It was found that the number of shear connectors necessary to fulfil serviceability criteria (deflection) can be reduced if the connectors are concentrated near the supports, as theoretically predicted by Roberts [8] and Lin et al. [9]. Optimization of the number of shear connectors increases the economic viability of reusable composite structures, since fewer in-situ labour is necessary to fully demount and re-erect a given structure. Further details on the experimental programme and the obtained results can be found in the work of Nijgh *et al.* [10].

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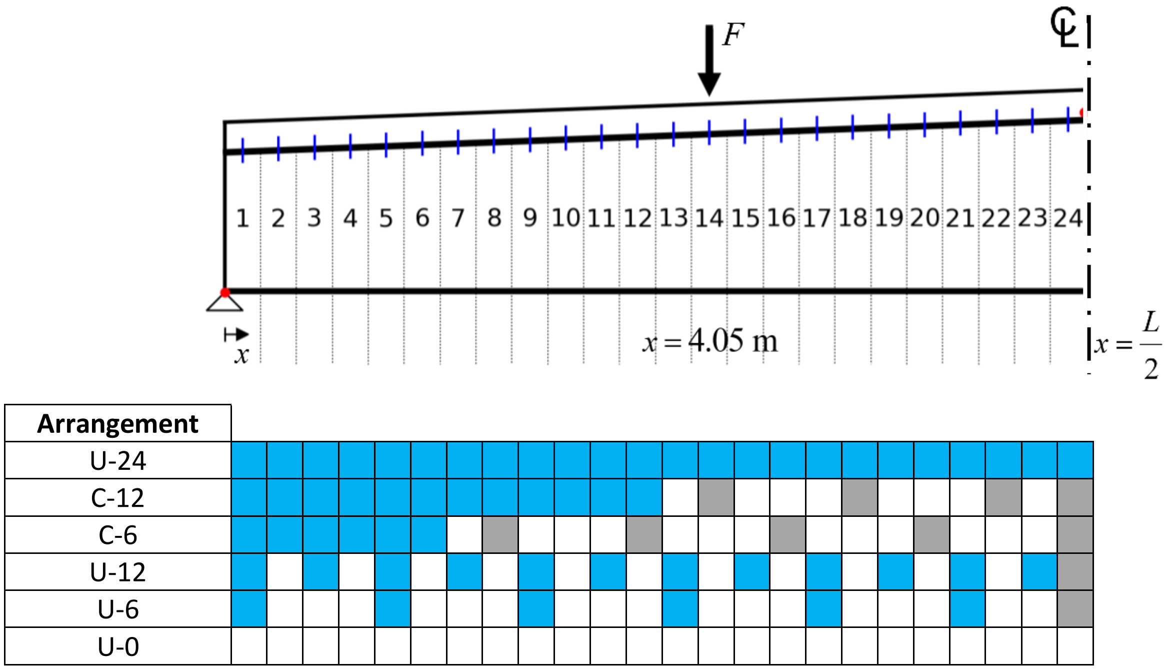

Figure 4 - Shear connector arrangements in the experimental study. Each coloured box indicates a pair of fasteners (one per steel beam). Resin-injected bolts provide shear connection; normal bolts are placed only to prevent vertical separation of the deck and the beam. "U" denotes uniform connector spacing, "C" denotes concentrated connector spacing near the supports. The beam is symmetric in the plane at x = L/2.

3. Environmental benefits

The environmental benefits of demountable and reusable composite structures can be quantified using different methods. For example, the benefits of demountability and reusability can be included in the lifecycle analysis (LCA) of the structure. In a cradle-to-grave LCA, the following four stages in the lifecycle of the structure are to be considered:

- Production (fabrication) and construction (execution),
- Use stage,
- End of life.

The production and construction stage includes the raw material supply, the manufacturing (fabrication), the transportation, and the assembly (execution) process. During the use stage, the maintenance, repair, replacement and refurbishment should be taken into account. Finally, in the end of life stage, the deconstruction, transport, and waste processing and disposal are included. In addition to the traditional three stages in the LCA, a fourth stage may be included to account for benefits beyond the boundaries of the three traditional stages, resulting from recycling or reuse. Two main approaches exist to take account of the environmental benefits of recycling and/or reuse:

- End of life (EOL) recycling approach, in which environmental benefits are granted for a fraction of materials that are recoverable and recyclable or reusable after the first use phase.
- Recycled content (RC) recycling approach, in which environmental benefits are granted only for the actual fraction of secondary material in a product.

The EOL approach allows taking benefits in an earlier stage than the RC approach. It could be argued that taking benefits in the present for something that may or may not happen in the future is disputable. However, for steel (and metal) parts, the EOL approach is reasonable because of negligible quality loss and high actual rates of recycling. For concrete elements, the recycling of coarse aggregate is rather established in practice as well, whereas this is not yet the case for the fine sand and cement. The latter component has a very pronounced impact on the environmental footprint of concrete. At Delft University of Technology, a new technology called HAS (Heating Air classification System) was developed that can separate the fine sand and cement, so that both can be reused in a new concrete [11]. In addition, the International Energy Association (IEA) indicates four major strategies to reduce the environmental footprint of concrete [12]:

- Increasing of thermal and electric efficiency in the cement production process
- Using less carbon-intensive fuels in the cement production process
- Substituting clinker with cementitious materials with lower CO_2 emissions
- Capturing and storing CO_2, to prevent CO_2 from being released into the atmosphere

The aforementioned technological advancements and challenges provide a good basis to assume that the actual recycling rates of concrete will increase in the future, and thus that the implementation of the EOL approach may be justified assuming the current recycling rates.

The annual environmental costs of a structure can be calculated as

$$e = b + \frac{A + C + \sum_{i=1}^{n} R_i + D}{T_{\text{ref}}}, \tag{1}$$

in which b is the annual environmental impact resulting from the use, A is the environmental impact resulting from construction, and C is the environmental impact at the end of life. The environmental impact associated with the i-th cycle of reuse by R_i, and the service life of the building by T_{ref}. The benefits of recycling are accounted for by D.

The environmental impact resulting from the building use (b**)** is expressed on an annual basis to take note of the fact that the level of maintenance of the structure has a clear influence on the environmental performance. If the building is well-maintained, the environmental impact as a result of its use (e.g. heating, water demand) does not vary significantly in time.

Clearly, A is a constant of which the magnitude has been defined at the moment the structure was initially built. It can be assumed that b, C, and D are constant in time, as the impacts related to these stages do not fluctuate significantly in time. The total annual environmental impact can then be minimized by increasing the service life. To estimate the actual service life of a given structure, Dobbelsteen (2004) has suggested to modify the estimated service life (ESL) approach currently used for construction products, components or systems, to be suitable for buildings as a whole. The original ESL approach is laid down in ISO 51686-1:2000 [13], and is used to determine the ESL based on a RSL and actual in-use conditions, such as component quality, design level, execution level, environment and maintenance conditions. The ESL is calculated as:

$$ESL = RSL \times A \times B \times C \times D \times E \times F \times G, \tag{2}$$

in which A-G are factors relating to the aforementioned actual in-use conditions. Van den Dobbelsteen [3] noted that it is extremely complicated to determine the preceding factors for buildings as a whole. Instead, van den Dobbelsteen [3] suggests to define the ESL for buildings based on considerations related to the flexibility of the building, as this offers great opportunities to prevent obsolescence by allowing for other types of future use. Types of flexibility and the technical measures to achieve a certain type of flexibility are listed in Table 3.

Table 1. Types of flexibility and potential technical measures to be taken to increase flexibility [3]

Type of flexibility	**Technical measures**
Multi-functionality (without technical flexibility)	- Use standards - Floor structure bearing capacity
Sub-dividability (without technical flexibility)	- Entrances - Staircases and elevator shafts - Facility groups and shafts
Excess	- Capacity - Floor height - Passages size
Extendibility (horizontal)	- Building plot size - Façade openability and demountability
Extendibility (vertical)	- Column/foundation bearing capacity - Cellar floor usability
Re-dividability	- Bearing structure openness - Obstacles - Compartmentation - Partition removability

Based on Table 3, alternative factors can be derived to replace the original factors *A*-*G* to make the ESL framework suitable for buildings as a whole For multi-storey buildings, Tool [14] suggests to base the alternative ESL factors on (1) storey height, (2) floor area, (3) column grid size and (4) load bearing capacity. Increasing the storey height compared to the specified minimum storey height increases the possibility for other uses, and so does increasing the floor area. Obviously, the larger the column grid size, the fewer obstacles and hence the more suitable the structure can be for other purposes. The magnitudes of the preceding factors have to be established more or less subjectively, whereas the factor relating to the load bearing capacity could be established more objectively based on codified variable loads. An estimation for the magnitudes of the aforementioned ESL factors was established by Tool [14] based on a case study of 11 renovation and transformation projects.

The case study and the ESL framework clearly indicate that functionality of a structure is paramount to maintain its (economic) value during its technical service life. From this perspective, buildings 'as functionality banks' may be superior to buildings 'as material banks' as the annual environmental impact of the former may be lower due to its higher actual service life.

4. Conclusion

The sustainability awareness is constantly increasing in the construction sector, leading to investigations in the field of demountable and reusable structures. Demountability and reusability of a composite flooring system consisting of steel beams and prefabricated concrete decks was successfully demonstrated experimentally. Composite action was achieved by resin-injected bolted shear connectors rather than conventional welded headed studs. The advantage of resin-injected shear connectors is that composite action is obtained instantaneously under live loading. Concentrating the shear connectors near the supports of a simply-supported beam was proven to increase the composite beam stiffness. Demountable and reusable structures provide value retention during the structure's entire technical lifetime, by allowing for a change in functionality or a change in the location of the building. The annual environmental impact of a demountable and reusable structure decreases as the asset has the potential to last during its entire technical lifetime rather than its functional lifetime.

5. References

[1] Ministerie van Infrastructuur en Milieu, Ministerie van Economische Zaken 2016 *Nederland circulair in 2050* Den Haag

[2] TNO 2018 *Circulair bouwen in perspectief*

[3] Dobbelsteen A van 2004 *The Sustainable Office - An exploration of the potential for factor 20 environmental improvement of office accommodation* Delft, Delft University of Technology

[4] Hollander M den, Bakker C and Hultink E 2017 Product design in a circular economy: development of a typology of key concept and terms *Journal of Industrial Ecology* **21** 517-525

[5] UNEP 2011 *Decoupling natural resource use and environmental impacts from economic growth*

[6] Accenture 2014 *Circular Advantage: Innovative business models and technologies to create value in a world without limits to grow*

[7] Burns B 2010 Re-evaluating obsolescence and planning for it *Longer lasting products - Alternatives to the throwaway society* Cooper T Farnham (UK) Gower 39-60.

[8] Roberts T 1985 Finite difference analysis of composite beams with partial interaction *Computers & Structures* **21** 469-473

[9] Lin J, Wang G, Bao G and Xu R 2017 Stiffness matrix for the analysis and design of partial-interaction composite beams *Construction and Building Materials* **156** 761-772

[10] Nijgh M, Girbacea I and Veljkovic M (under review) Elastic behaviour of a reusable tapered composite beam *Engineering Structures*

[11] Lotfi S and Rem P 2016 Recycling of End of Life Concrete Fines into Hardened Cement and Clean Sand *Journal of Environmental Protection,* **7**

[12] IEA 2018 *Technology Roadmap: Low-Carbon Transition in the Cement Industry*

[13] ISO 2011 *ISO 51686-1:2000 Buildings and Constructed Assets - Service Life Planning - Part 1: General Principles* Geneva

[14] Tool F 2010 *Ontwerptool voor de beoordeling van constructieve alternatieven op duurzaamheid* Delft, Delft University of Technology

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