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Design strategies for reusable structural components in the built environment

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ABSTRACT: The technical solutions for deconstruction are reviewed and investigated in the building sector as this is an expected trend under the sustainability requirements set in the EU Commission´s "Green Deal" towards net zero greenhouse gas emissions by 2050. Two of the main research areas for efficient deconstruction strategies are; i) the behavior of multi-material structural components (hybrid structures) that combine the advantages of mechanical properties and architectural appearance of different construction materials, and ii) the techniques and mechanical properties of connections between structural components which allow deconstruction and reuse. However, there is a very limited number of studies and methods into specific demountable and hybrid structural systems, and even fewer focus on their practicability and feasibility. Since these systems have the potential to reduce construction waste, encourage resource efficiency and reduce embodied carbon impacts, it is expected that they will contribute immensely to a sustainable built environment. This paper focuses on technical solutions of the design strategies that currently have been developed for hybrid and steel reusable structural systems, and proposes an approach on implementing structural floor systems designed with the linear approach to a circular building environment.

1 INTRODUCTION

1.1 *Re-use of steel structural components*

In response to the sustainability requirements set in the EU Commission's "Green Deal" (European Commission, 2018) towards reduction of the greenhouse gas emissions, it is estimated that the structural design for deconstruction (leading to structural components' reuse) is going to contribute considerably to the sustainable development of the built environment (Brambilla et al., 2019). The construction sector is responsible for a big percentage of the annual resource consumption, of construction and demolition waste, and of total energy consumption. The preferred strategy in order to achieve a sustainably built environment is to design for demounting, and reuse of the structural components before thinking about repair, remanufacturing, or recycling following Cramer's (Cramer, 2015) scheme on how a circular economy can be incorporated for sustainable construction. Demountability and reuse are the main focus areas in the construction sector since they allow for value retention of the structural members, the potential for cost reduction in extended life cycles, a smaller environmental impact and consequently enhancing sustainable construction.

The idea of reusing steel structural elements is developing through the years. Even if it is still in primitive application in practice, it is highly supported by approaches addressing nowadays the reusability of buildings like "Donorskelet" (Terwel & Korthagen 2021), bridges like the "Nationale Bruggenbank" (2023) or platforms that create digital databases on reclaimed steel structural elements like the "Circulair Bouwen in 2023" (2023). Also, recommendations for the reuse of steel structures have been made stating that any sign of plastic deformation is a reason for rejection and presenting a strategy to support reuse (SCI 2019, Progress 2020). Even if broad concepts on the reusability of structures have been discussed and developed in the aforementioned concepts, very few have presented extended processes to successfully implement the concept in real-life structures. An overview of the reusability of steel and steel-concrete hybrid floor systems is discussed in the next Sections.

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1.2 *Steel-dominated hybrid demountable structures*

Current developments of the steel and steel-dominating hybrid structures underline their advantages with respect to their speed of construction, optimum material use, and consequently decrease in floor weight and the self-weight of the structure while achieving larger floor span when compared with other types of structural systems (e.g. reinforced concrete, timber) (Ahmed et al, 2019). The skeleton of these steel-dominating hybrid structures is made mainly of steel structural components where nearly one hundred percent of the steel is recycled or reused while they can be easily mounted, demounted, and reused with the use of bolted connections. So, as the demand for new structures and the need for reusing existing ones are increasing due to the growing pace of urbanization, there is no doubt that the selection of steel-dominating hybrid structures can have an immense contribution to the sustainable development of the built environment.

Hybrid structures as defined in this paper, consist of floor systems with hybrid beams (steel structural components and multi-material floor and deck systems) that exhibit excellent structural characteristics, in terms of their stiffness and strength, when compared with steel or reinforced concrete beams. The reason is that they combine the advantages of mechanical properties of different construction materials (e.g. concrete in compression and steel in tension). When it comes to the connections of their floor systems with the steel beams, the demountable shear connectors have shown that they can play a significant role in the deconstructability of these systems (Pavlovic et al. 2013, Nijgh et al. 2018).

So, through the transition from a linear economy to a circular one for steel-dominated hybrid structures, a few proposed solutions are summarized in Figure 1. Specifically, through research developments of the last few years the conventional constructional method of the steel-concrete composite floor systems, the steel beams are connected with welded headed studs which are encased within the concrete slab in order to achieve the necessary shear connection. Through developments, this construction method can be transformed into a demountable structure which could lead to a sustainable built environment. This could be achieved through the use of "green" concrete materials [e.g. geopolymer concrete (Liu et al. 2015, Ataei et al. 2016)] the reuse of the structures' components through the use of demountable connectors (Pavlovic et al. 2013, Nijgh et al. 2018, Odenbreit et al. 2019), and the optimum material use through the use of tapered and high strength steel beams (Nijgh et al. 2018) and composite slabs (Gritsenko et al. 2019).

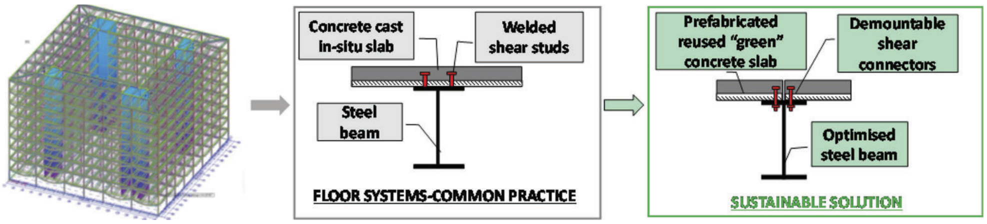

Figure 1. Development of a sustainable solution for a hybrid floor system through research developments focusing on optimum material utilization and floor system deconstruction and reuse (though demountable connectors).

2 REUSE OF STEEL-DOMINATED HYBRID STRUCTURES

2.1 *Reuse of steel structural systems*

Design for deconstruction of one-story steel buildings has been presented in detail in the RFCS project Progress (2020) where the in-situ and relocated reuse scenarios are examined thoroughly. The overall same approach for the reusability of reclaimed steel structural components is also adopted by SCI (2019). Accordingly, the process for the reuse of reclaimed steel structural elements is described in Figure 2. The three main phases for the reuse of a structural component and its implementation in the circular building environment include a) the pre-deconstruction audit and assessment for reuse, b) sampling and testing, and c) design for reuse.

The first phase of the pre-deconstruction audit and assessment for reuse includes the preliminary assessment for the evaluation of the feasibility of reclaiming and reusing the existing steelwork. A preliminary overall visual inspection (e.g. identifying problems such as excessive corrosion, excessive/plastic deformation of the structural elements, etc.) and quantitative/empirical evaluation and reporting (e.g. dimensions of joints and their connectors, etc.) of the existing steelwork are undertaken within this phase. The second phase of sampling and testing includes techniques that quantify the material properties and verify the structure. The testing programs include a range of destructive (DT) and non-destructive (NDT) tests. Non-destructive tests (NDT) do not damage the structure and can be useful to locate and/or measure the size of the defects. Some examples are hardness tests, positive metal identification (using X-ray Fluorescence and optical emission spectrometry), and small punch testing. Destructive testing (DT) techniques require extracting (by cutting or drilling) small samples from the existing structure following the EN 10025 (2004) standards. Destructive testing (DT) techniques include tensile testing, chemical composition analysis, charpy impact test, and metallography. Last, the design for reuse phase includes the design considerations for achieving a reliable structure with reclaimed steel elements and the structural analysis principles according to EN 1993 provisions.

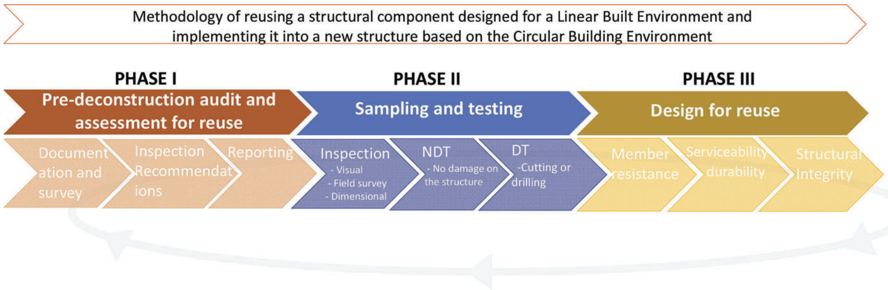

Figure 2. Methodology of reusing a structural component designed for a linear built environment and implementing it into a new structure based on the circular building environment according to the RFCS project Progress (2020).

2.2 *Case studies*

The idea of reusing steel structural elements is highly supported by approaches addressing nowadays the reusability of buildings like "Donorskelet" (Terwel et al. 2021) (see Figure 3), bridges like the "Nationale Bruggenbank" (2023), or platforms that create digital databases on reclaimed steel structural elements like the "Circulair Bouwen in 2023" (2023). Additionally, projects worldwide have proved that reuse of the old steel structure was more feasible than designing and erecting a new steel structure with the same dimensions and functionality (Wakefield 2017, Snyder 2022). Several case studies are presented in detail in the RFCS project Progress (2020) and illustrate the use of reclaimed steel structures in various EU countries and some of the technical issues that were overcome. It is underlined that the case studies and consultations with the supply chain, confirm the technical viability of the reuse of steel reclaimed elements. The additional time/program and cost of using reclaimed steel have been identified as significant barriers across the supply chain. However, the structural design using reclaimed steel elements has shown environmental and economic benefits. These benefits are discussed in Section 3.1.

Case studies using reclaimed steel elements taken from stocks and digital databases on truss bridges (van Lookeren Champagne 2022) and frame structures (Rademaker 2022) have been studied recently. These studies support the design by considering that not all profiles, lengths, and dimensions are available at all times when having such databases (Gorgolewski 2008, Bukauskas 2020). Also, reclaimed elements often lack information about material properties and the used standards when being manufactured. For this reason, the need for a standardized process for the reuse of steel elements is underlined. Countries like the Netherlands, are in the process to standardize the procedure to guarantee the material properties by

Figure 3. Construction of Biopartner 5, whereby steel elements are used from the neighboring Gorlaeus-building (Terwel et al. 2021).

NEN-EN 1993-1-1 for new structural steel for reclaimed steel profiles. The goal is then that the required information about the reclaimed steel element will be included in a material passport, which will be presented in the digital database.

3 DEMOUNTABLE STRUCTURES AND CONNECTORS

3.1 *Demountable and reused floor systems – environmental impact assessment*

The sustainability potential of demountable-reused structures has been assessed by several studies through a Life Cycle Assessment (LCA). The LCA is an internationally used technique that aims at the analysis and evaluation of the environmental aspects and impacts of a product from the procurement of raw materials to the end-of-life stage which can consist of reuse, recycling, or disposal (International Organization for Standardization, 2006). Then different types of emissions are unified into several environmental impact categories which all together determine the total impact. The total impact may be expressed in the functional unit €, which describes the cost society is willing to pay for measures to achieve each emission target. In the Netherlands, this value is called MKI-value or shadow cost. The information obtained from the LCA results concludes a more comprehensive decision process, including quantitative information about the total environmental impact of the structure (International Organization for Standardization, 2006).

Through LCA it has been evaluated that a demountable steel-dominated hybrid structure could reduce considerably the amount of environmental footprint (Brambilla et al. 2019, Bohen 2021, van Maastrigt 2019). The demountability and consequently the reusability of these systems are supported by the use of demountable shear connectors which allow for the assembly and disassembly of the systems. A detailed list and discussion about types and the structural performance of demountable connectors through the years are given in Section 3.2.

3.2 *Demountable connectors*

The key structural component for achieving a demountable and reusable structure is the type of shear connectors used for the connection between the steel beam and the floor system (for cast-in-situ and prefabricated slabs) (Kavoura et al. 2022a). One of the first types of demountable connectors introduced in the literature is the friction-grip bolt (see Figure 4a). These preloaded bolts have been tested in the late 1960s, through push-out and beam tests (Dallam 1968) in order to evaluate if full interaction occurs between the concrete slab and the steel beam within the serviceability limit states. It was reported that friction-grip bolts are demonstrating higher fatigue strength than conventional welded shear studs.

Another type of demountable connection that has been investigated experimentally and analytically in the literature is the bolted shear connectors with embedded nuts (see Figure 4b) (Kwon et al. 2010, Pavlovic et al. 2013). Push-out experiments and detailed FE models have been investigated on prefabricated concrete slabs with single-nut bolt shear connectors (Pavlovic et al. 2013).

They have demonstrated a reduced stiffness of 50% at service loads when compared with headed studs but they could achieve approximately 95% shear resistance (Pavlovic et al. 2013). Post-installed double-nut bolt connectors were used in an investigation of the strengthening of existing bridge girders (Kwon et al. 2010). Static experiments on post-installed double nut bolt connectors showed that they have lower shear strength and ductility when compared with post-installed friction-grip bolted shear connectors but they exhibit high stiffness in the elastic range.

The behavior of bolted shear connectors with a coupler system (see Figure 4b) has been recently studied experimentally on push-out and beam tests (Kozma et al. 2019, Nijgh et al. 2018, Nijgh et al. 2019, Gritsenko et al. 2019). This connector consists of a coupler welded on a steel L-shaped profile on top of the steel beam in which two bolts are connected. One bolt is embedded in the slab and a second removable bolt is placed from below the steel beam flange. In this concept of shear connectors, the coupler has higher strength than the bolts, so damage related to the overloading of the shear connector accumulates in the external bolt, rather than in the embedded coupler. In this way, in a subsequent life cycle, the external bolt can be replaced and the concrete deck is fit for use (Nijgh et al. 2019).

In subsequent studies, injected bolted shear connectors with a coupler system (see Figures 4 c and d) were tested in push out and beam tests on prefabricated slabs (Nijgh et al. 2018, Nijgh et al. 2019) and composite slabs with profiled steel sheeting (Gritsenko et al. 2019). After the injection and curing, the epoxy resin acts as a load-bearing element, and its resistance is substantially higher than its uniaxial compression strength due to the natural confinement provided by the bolt hole (Nijgh 2021). The injected bolted shear connectors allow for oversized holes which can account for the fabrication and execution tolerances and consequently improve the execution efficiency. Even if the increased bolt-to-hole clearance causes a decrease in the effective shear connector's stiffness (Yang et al. 2018), injecting the remaining bolt-to-hole clearance with an epoxy resin has the potential to mitigate this decrease in stiffness (Nijgh 2021). Last, these injected demountable connectors with a novel injected steel-reinforced resin have demonstrated high stiffness when compared to the conventional injectant bolted connections under different deck applications (e.g. concrete and FRP) and consequently confinement conditions (Kavoura et al. 2022b).

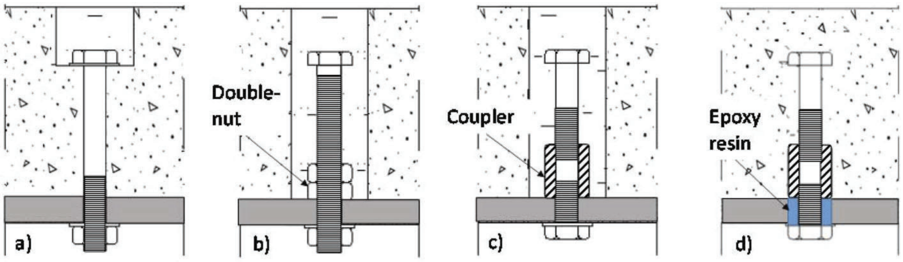

Figure 4. Types of demountable bolted connectors a) friction grip bolts, b) double-nut, c) coupler system connectors, d) injected bolted shear connectors with a coupler system.

3.3 *Demountable and reused floor systems – structural behavior*

In this paper, the developments on the reuse of steel reclaimed elements and the technical solutions for reusing a steel-nominated hybrid floor system are discussed. Several research has been contacted on these two thematic areas but up to now there is a research gap on how these could be combined. In the general theoretical framework of reusing a structural component designed for a linear built environment and implementing it into a new structure based on the circular building environment, the reuse of steel structural components is well-investigated and implementations are attempted through standardization processes (Progress, 2020). However, when it comes to the reuse of hybrid floor systems research and real-life applications still need to be developed.

A first attempt at the analysis of floor systems designed with the linear approach is realized in this paper through a case study. A conventional floor system with continuous beams and a corresponding demountable solution are analyzed in the program Midas (2011) for comparing their structural performances. The two structural systems are explained in Figure 5 along with their dimensions.

The main concept of this short case study is to evaluate modeling techniques and results by implementing demountable connections between composite beams and slabs created with the linear built approach. These connections are modeled as spring elements between the two structural components with the shear and tensile mechanical characteristics of a bolt connected at the locations of zero bending moments of the continuous beam. The vertical displacement and bending moment contour maps are shown in Figures 6 and Figure 7 respectively. It is observed that in the case of the demountable floor system, the maximum deformations occur close to the end supports. This behavior is caused by the semi-rigid connection between the hybrid beam and the concrete slab implemented as spring elements. The alternation of the bolted demountable connector which is commonly used as a shear connector in hybrid beams (presented in Section 3.2) to another type of connector more suitable for these applications or the implementation of more rigid connectors, could result in a slab behavior closer to the conventional one. Even if technical solutions for connecting hybrid beams with a slab have not yet been developed, this is a research area with great potential and contribution to the sustainable building environment.

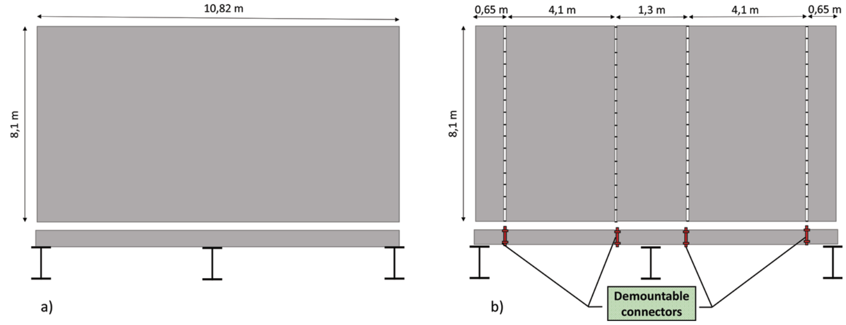

Figure 5. a) Conventional and b) demountable steel-concrete hybrid floor systems (not in scale).

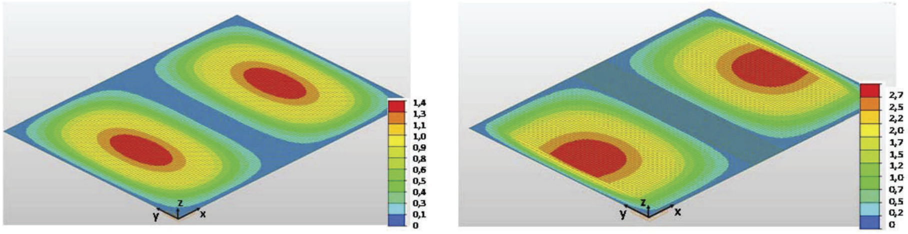

Figure 6. Vertical displacements in mm of a) conventional and b) demountable steel-concrete hybrid floor systems.

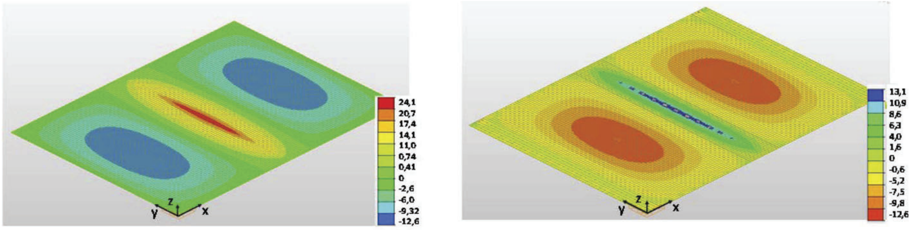

Figure 7. Moment around y-axis in kN*m/m for a) conventional and b) demountable steel-concrete hybrid floor systems.

4 CONCLUSIONS

This paper presents an overview of the most recent developments regarding the efficient strategies for the reuse of reclaimed steel elements and multi-material structural components (hybrid structures), and the types and properties of connections between structural components which allow deconstruction and reuse. The main conclusions of this paper are summarized below:

- The idea of reusing composite structural elements has been developing through the years. Even if it is still at the initial stage of application in practice, it is highly supported by guidelines and recommendations in addressing the reusability of buildings.
- The three main phases for the reuse of a structural component and its implementation in the circular building environment include a) the pre-deconstruction audit and assessment for re-use, b) sampling (in terms of grouping) and certification of structural components, and c) design for reuse as instructed by well-developed guidelines (SCI 2019, Progress 2020).
- Through LCA it has been evaluated that a demountable steel-dominated hybrid structure could considerably reduce the amount of environmental footprint.
- The reuse of hybrid floor systems and their implementation into a circular building environment, even if they were created with the linear execution approach, has not been developed and needs further investigation. A first attempt at implementing the connection between the hybrid beams and the concrete slabs shows that maximum deformations occur close to the end supports rather than at the midspan of the slab. This behavior will eventually require more sophisticated modeling and implementation of connections between the two systems, in order to capture the real behavior of the system in the vertical and horizontal directions.

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