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Opinion

Design for Deconstruction: Benefits, Challenges, and Outlook for Timber–Concrete Composite Floors

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Abstract: Design for deconstruction (DfD) considers the end-of-life scenario of buildings at an early design stage to ensure that these buildings (or parts of the buildings) can be deconstructed without unproportional effort and material loss. After deconstruction, the elements or materials can be used for future purposes such as reusing (preferably), remanufacturing, or recycling. This opinion paper is aimed to advocate for DfD in timber–concrete composite (TCC) floors as it represents an important contribution toward circular economy design and creates a more sustainable built environment. Different end-of-life scenarios for TCC floors according to their original design and connection type were initially explored. Existing deconstructable connection systems that could enable DfD in TCC floors were reviewed. Furthermore, potential challenges relating to the implementation of DfD in TCC floors are briefly highlighted. Finally, a discussion around the outlook and actions that might be needed to address some of the identified challenges is provided. This paper proposes directions for future developments and contributes to the understanding and promotion of DfD in TCC floors with an emphasis on deconstructable connectors that can enable material recovery and reuse as the preferred end-of-life scenario.

Keywords: timber–concrete composite; design for deconstruction; deconstructable connectors; reuse; circular economy

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1. Introduction

Buildings have a significant environmental impact and consume a large amount of raw materials. In order to reduce their environmental impact, the design for deconstruction (DfD) has recently received more attention. DfD considers the end-of-life scenario of buildings at the (early) design stage so that they can be fully or partially deconstructed without unproportional effort and material loss [1]. This allows for the elements or materials to be reused in new applications or to be further processed. However, especially for regular hybrid structures, deconstruction is often challenging as the individual materials are typically permanently connected. Therefore, this paper focuses on the implementation of DfD in one specific application in a hybrid structural system: timber–concrete composite (TCC) floors.

TCC floors are a type of structure that takes advantage of the superior properties of both timber and concrete. TCC floors require less concrete and typically less reinforcement compared to traditional concrete floors, which reduces the carbon footprint of the structure. Furthermore, TCC floors are characterized by a lower mass than concrete floors. Compared to timber floors, they offer higher mechanical properties, better fire performance, increased thermal mass, improved vibration properties, and better acoustic separation. With such characteristics, TCC systems offer a solution to reduce challenges related to the serviceability limit state design of timber buildings and long-span timber floors. Comprehensive reviews of the literature on TCC structures can be found in [2,3], and exemplar applications in residential and non-residential buildings can be seen in [4–8]. Despite the structural advantages of regular TCC floors, their end-of-life situation is typically not considered at

the design stage. As a composite system that contains a combination of materials with different life-cycle scenarios, TCC floors can lead to significant waste generation if the employed materials cannot be effectively separated. Therefore, it would be beneficial to implement DfD practices in the design to facilitate the full potential of these materials at the end of the building's life, including possible reuse scenarios.

In the context of this paper, DfD is defined as a design method that can allow for building components to be easily dismantled to aid in the recovery of materials for reuse (preferably), remanufacturing, and recycling [9]. The benefits of DfD in timber structures have been generally discussed in the literature [10,11]. Case studies on the subject can also be found in some research works [12,13]. In terms of TCC floors, a potential benefit of DfD is that it can help reduce the amount of waste that would otherwise be created during the demolition of these structures. Furthermore, by streamlining the segregation process of salvaged materials, issues relating to waste management and disposal can be minimized. Another benefit of DfD is related to the reusability of materials; in regular TCC floors, it can be time-consuming, labor-intensive, and extremely difficult to separate the timber, concrete, and connectors without causing significant damage to them. Therefore, the direct reuse of these materials might not be easy. With DfD, however, the direct reuse could be streamlined as it allows for easy separation and offers the potential to profit from the salvaged materials that are recovered from the deconstruction phase. In addition, buildings in which DfD principles have been considered in the design may offer higher adaptability for any future change in use or repair that might be needed.

The implementation of DfD is especially important in modern forms of TCC structures in which a high volume of laminated timber products with large cross-sections are used. To put this into perspective, as an example, in the Olver Design Building [4], around 2052 m^3 of the building elements are made with various types of timber products, including glulam (GLT) and cross-laminated timber (CLT); a large portion of this is used in the form of five-layer CLT–concrete composite floors. If future structures use DfD, such a high volume of timber materials could still provide a valuable, reusable resource that might be suitable for new structural or non-structural applications at the end of the building's service life. Nevertheless, despite its benefits, DfD is not yet a common practice, especially in TCC structures.

This opinion paper contributes to the understanding and promotion of DfD in TCC floors. The overarching aim is to encourage the timber construction industry, policymakers, and researchers to consider DfD as a mainstream approach in construction, especially for hybrid structures, to achieve sustainability goals in the built environment. This paper provides insights into the importance of implementing DfD in TCC floors and its role in achieving the principles of a circular economy. For this, end-of-life scenarios for TCC floors based on the design and connection type are initially explored, and some of the existing deconstructable connection systems that enable the implementation of DfD in TCC floors are introduced. The implementation challenges of DfD in TCC floors are then briefly highlighted. Finally, a list of required actions to address these challenges is proposed.

2. End-of-Life Scenarios for TCC Floors Based on the Design and Connector Type

The preferred end-of-life scenario in DfD is to be able to reuse the recovered materials in their original form, as this does not require a considerable energy input [13]. In this case, at least two reuse options could be considered for TCC floors as follows:

- Reusing the TCC slab elements: one option could be to reuse the entire TCC floor slabs in new applications, provided that the floor slabs are easy to separate from the building frames. This might be an especially good option in structures where several TCC slabs are prefabricated and then transported to the construction site and installed side-by-side to form a larger floor, see, e.g., [5]. If this option is chosen for a TCC floor, then it is not important if the TCC shear connectors are deconstructable or not; however, the slab to post/column connectors should be deconstructable in order to ease the deconstruction process. If the slab to post/column connectors are not deconstructable (such as those in most existing TCC floors that are designed using

traditional methods), the TCC slab can theoretically also be (partly) reused. However, additional time and effort are required in order to separate the TCC slab from the building frame.

– Reusing the individual parts: this option considers the reuse of individual parts of the TCC slab (e.g., concrete slab, GLT beams, CLT plates) in new applications. Direct reuse of the concrete slab in a similar floor application could be challenging (i.e., reusing the concrete slab as-is) because the concrete slabs in TCC floors are typically relatively thin and have a small amount of reinforcement. However, reusing these concrete slabs in alternative applications, e.g., with lower load capacity requirements, could be possible. Several examples of practical reuse cases for concrete slabs in different types of structures can be seen in [14]. Timber components, however, offer a higher flexibility for reuse in general [15]. A recent life cycle analysis on TCC floors [16] has also highlighted the potential of reusing the entire timber components. However, in this case, some challenges also exist in terms of, e.g., uncertainty in the mechanical properties, e.g., [17,18], which justifies in-depth research and development projects. Anyhow, in order to fully achieve the benefits of reusing individual parts of the TCC slab, deconstructable shear connectors are required. Furthermore, a deconstructable slab to post/column connector could be beneficial, as described previously, for reusing entire TCC slabs.

In addition to reusing, the recycling of materials (or part of them) might also be suitable. This could include, e.g., the timber offcuts and the individual materials in the concrete slab (e.g., steel bars, metallic connectors). However, even if conventional demolition is applied rather than the proposed reuse options, deconstructable connections would be beneficial when recycling and partially reusing these materials, which should be considered in order to minimize material waste.

3. Existing Deconstructable TCC Connections Suitable for DfD

To achieve the full potential of material recovery for reuse in TCC floors, deconstructable connectors are essentially important. In this case, although some practical deconstructable slab-to-post/column connectors exist, e.g., see [5], the availability of deconstructable TCC shear connectors on the market is currently quite limited. A few solutions have been proposed in recent research works, which have been classified in the following section based on their target construction method. The review of the literature in this section aims for a general overview of the existing solutions; for more details, refer to [19,20] and the cited papers.

3.1. Solutions for the Dry–Dry System

The dry–dry system refers to a construction method in which the concrete slab is prefabricated separately and then connected to the timber component, either offsite or onsite. Previous research works on the development of deconstructable solutions have mostly focused on the dry–dry system. In one of the early studies on the subject, Lukaszewska [21] developed and evaluated the mechanical properties of a prefabricated TCC system in which several connection systems were applied. One of their proposed connection systems, made with a steel tube and a coach screw, had the ability to be deconstructed. This connector could be used in combination with a notch as well. Some connection systems were also tested by Crocetti et al. [22], which have the potential to be used in DfD, including one connection made with a steel tube and screws. Khorsandnia et al. [23,24] specifically considered DfD principles as one of their justifications for developing new deconstructable connectors in TCC floors. They examined several different solutions, which were made using either bolts or screws in combination with other elements made with steel, wood, or plastic materials.

3.2. Solutions for the Wet–Dry System

The wet–dry system refers to a construction method in which the connectors are mounted on the timber component, and then concrete is cast on top. This can be performed either offsite, in the case of prefabrication, or onsite in the conventional cast-in situ approach. The wet–dry system is the most common method for fabricating TCC floors; however, only a few studies have considered applying deconstructable solutions in this system. One of the early studies was conducted by Natterer [25], whose applied solution was later extensively tested for further adoption in construction by other researchers [26–31]. Their proposed solution was a notch combined with a threaded steel bar. The steel bar had a plastic sleeve around it and a plastic cap in the concrete section and was glued in the timber section with an epoxy adhesive. However, DfD was not the focus of either of these studies, and therefore, the ease of deconstruction was not evaluated. Some of the solutions investigated by Boccadoro et al. [32] using steel rods combined with a notch connector may also allow for deconstruction; however, this was not tested in their study as DfD was not their focus either. Thai et al. [33] investigated a TCC connection fabricated in the wet–dry system that could be deconstructed as well. The connection was made with a rectangular notch and reinforced with two self-tapping screws. They demonstrated that their proposed system could be deconstructed even after exposure to large loads. Pang et al. [34] proposed a deconstructable connector for the wet–dry system as well using round notch connections, however, without the use of screws.

3.3. Solutions for Both Wet–Dry and Dry–Dry Systems

A commercially available connector, named FT connector [35], was designed to facilitate the prefabrication of TCC floors, especially in the dry–dry system. This connector has already been used in practical applications [36]. It comprises an inclined plastic tube (fixed at 30° angle) with a steel washer in the concrete section through which a screw can be inserted in the timber section. Gerber and Tannert [37] tested the connector in the wet-dry system as well, although it showed less stiffness and higher residual slip than a regular screw. A recent research project performed by the authors of this paper specifically focused on developing solutions that could allow for the use of DfD in TCC floors for both construction methods and a wide range of floor configurations. The mechanical performance and the ease of application and disassembly of the connector were demonstrated both at the connection level and at the floor level [19,20,38].

4. Challenges of DfD in TCC Floors

The application of DfD in TCC floors is currently limited. Identifying the actual reasons for this requires a comprehensive survey across the supply chain and the construction sector. However, some of the potential reasons that are relevant to TCC floors, in the opinion of the authors of this paper, are highlighted as follows:

4.1. Technical Challenges

An important technical challenge in implementing DfD in TCC floors is the lack of versatile deconstructable connection systems on the market. Most of the existing solutions in the literature have been designed only for a certain type of construction or for a certain floor configuration. In addition, often considerably stiff connectors are needed to meet the structural design requirements, especially for long-span TCC floors. Nevertheless, most existing deconstructable connections are less stiff than regular connections of the same configuration. Therefore, a lack of versatile and stiff deconstructable connection systems could become a driver for the designers to use a regular connection system that cannot be disassembled.

4.2. Higher Initial Cost Compared to Regular Design Methods

DfD is, in general, more expensive than regular design approaches [39]. In the case of TCC floors, this could be due to the higher price of deconstructable connection systems

compared to the regular counterparts and the extra effort needed in the design and/or the construction process. The additional cost might be offset to some extent at the end of service life, considering the reduced waste and easier reuse of the materials. However, the initial increase in the cost and related future uncertainties could still be discouraging for construction companies, especially when they can achieve similar or even better mechanical properties with lower costs using regular design approaches.

4.3. Lack of Representation in Regulations

Necessary incentives and motivations do not exist for the construction sector to implement DfD in composite systems, partially because DfD principles are not included in building codes and other relevant regulations. Currently, an overview of the design for disassembly and adaptability principles is available in ISO 20887:2020 [40], and its relevance to timber buildings has been recently examined with case studies in [41]. However, although it is a commendable guideline, ISO 20887:2020 [40] is still quite general and does not provide any specific standards regarding the expected performance levels.

4.4. Lack of Awareness and Resistance to Change

A lack of awareness is an important barrier to the implementation of circular economy practices in the construction sector [42–45]. This can also affect the adoption of DfD in TCC structures. In this regard, DfD principles are currently not represented extensively, even in higher education. Therefore, future decision makers, including designers or engineers, might graduate with limited knowledge of DfD and its relevance to different structures. This might contribute to increased resistance to change in the construction sector, where designers typically prefer to use traditional design approaches.

5. Relevance to Practical Implementation

The discussions provided in this opinion paper should promote and raise awareness about the importance of applying circular economy practices in the construction sector, with emphasis on the use of DfD in composite systems such as TCC floors to prevent major waste management issues at the end of service life. Despite representing the authors' viewpoints, the stated challenges against DfD in TCC floors and various end-of-life reuse scenarios discussed here could serve as a catalyst for future research and development programs on the subject.

6. Outlook

Overall, applying DfD practices in TCC floors offers several potentials to contribute to a more sustainable built environment through material reuse and increased carbon storage capacities. Finding solutions to the challenges raised in this paper requires a multidisciplinary approach toward the design, construction, and deconstruction of TCC floors. For this, some of the actions that might be needed are listed below:

- The potential benefits of DfD in TCC floors that are listed in this paper should be investigated to see whether these benefits are achievable in practice. Future studies on this subject should consider both the cost and environmental benefits of the deconstruction approaches discussed in this paper and compare them to the conventional demolition approach.
- Versatile deconstructable TCC connectors should be developed that can be used for various construction methods and floor configurations. Although previous research works on deconstructable TCC connectors have focused on the use of screws, such connectors should be integrated into a system that can deliver higher stiffness and higher strength, e.g., by combining them with a notch connector.
- Commercialization should be considered for deconstructable TCC connectors developed in the scientific literature to increase market accessibility. Furthermore, future research should try to minimize the additional cost associated with the use of deconstructable connectors, e.g., by reducing the complexity of the proposed connection systems.

- To create the required incentives and confidence amongst builders, integrating the DfD principles into building codes and/or relevant legislation should be considered. Establishing legislation, grading standards, and product certifications for salvaged timber materials could also promote DfD in TCC floors.
- In addition to the above aspects, it is important to raise further awareness amongst the next generation of designers and engineers in relation to the implementation of DfD.

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