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Structural Performance of Demountable Hybrid Floor Systems Under Monotonic and Cyclic Loading

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Abstract

The building sector is actively researching and reviewing technical solutions for deconstruction, driven by the increasing importance of sustainability requirements, as outlined in the EU Commission's 'Green Deal,' which aims to achieve net-zero greenhouse gas emissions by 2050. Two key research areas in efficient structural design strategies are the performance of hybrid structures, which combine mechanical properties and architectural appearance of different materials, and the techniques and mechanical properties of connections between structural components that enable deconstruction and reuse. However, there is a scarcity of studies and methods focused on demountable and hybrid structural systems, limiting the understanding of their overall structural performance at a real-structure floor level. In this paper, a finite element model is presented to conduct a comparative study between the traditional floor system with welded stud connections and the demountable floor system with coupler-embedded bolted connectors. The numerical results showed that the serviceability loading capacity of the demountable floor system was 8% lower, and the difference in ultimate resistance was further enlarged. Reusing a demountable floor system, analysed in the case study, had little effect on the ultimate resistance, but it is difficult to exclude local plastic deformation after the first life cycles.

Keywords

Reusable floor system, Demountable connectors, Headed stud, Numerical modeling, Hybrid floor systems

1 Introduction

In light of the global commitment to carbon neutrality the adoption of structural design for deconstruction, leading to the reuse of structural components, is expected to significantly contribute to the sustainable development of the built environment [1]. As of 2021, the buildings and construction sector accounted for 36% of global final energy use and 37% of the global carbon dioxide emissions at 3.6 $GtCO_2$, 10% of which is a result of manufacturing important building materials such as steel and cement [2]. To achieve a sustainable built environment, the preferred strategy is to prioritize design for demounting and the reuse of structural components, following Cramer's [3] circular economy framework for sustainable construction. Demountability and reuse are key focal points in the construction sector as they enable value retention of structural members, potential cost reductions in extended life cycles, reduced environmental impact, and overall enhancement of sustainable construction practices.

The current developments in steel and steel-dominating hybrid structures highlight their advantages, including faster construction, optimized material use, reduced floor weight, and increased span compared to other structural systems like reinforced concrete and timber [4]. These structures predominantly utilize steel components that are nearly 100% recycled or reused, and they can be easily assembled, disassembled, and reused through bolted connections. Hybrid structures, as presented in this paper, involve floor systems with hybrid beams (combinations of steel and concrete) that exhibit excellent structural characteristics in terms of stiffness and strength, surpassing steel or reinforced concrete beams [4]. This is due to their ability to combine the mechanical properties of different construction materials, such as concrete in compression and steel in tension. When it comes to the connections between the floor systems and steel beams, demountable shear connectors have shown significant potential in facilitating the deconstruction of these systems [5-7].

Therefore, with the remarkable progress in demountable connectors, this paper presents a numerical case study that compares the structural performances of demountable and non-demountable floor systems. The recent developments on demountable connectors are summarized and

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then, an advanced finite element model where connectors are explicitly modeled has been developed to investigate the mechanical properties of the two designs. Finally, concluding remarks and future research prospects have been provided.

2 Technical practices on the design for deconstruction and reuse

2.1 Demountable connectors

Figure 1 presents a summary of the most commonly utilized demountable connectors. One of the most straightforward methods to achieve demountability involves the use of bolted shear connectors shown in Figure 1(a), in which the bolts pass through the upper flange of the steel beam and are fixed by nuts [8-10]. Considering the lower stiffness compared to welded studs, researchers have used pre-embedded nuts in the concrete slab to increase the stiffness [11, 12]. As reported by Pavlović et al. [5], although bolted shear connectors with a single embedded nut could reach 95% shear resistance of welded studs, the stiffness in the serviceability range is 50% lower than that of welded studs.

An alternative to the bolted shear connectors is the high-tension friction-grip bolts shown in Figure 1(b), in which bolts are preloaded to improve friction resistance [13-15]. However, once the shear resistance is exceeded, the stiffness becomes unexpectedly low until the bolts act against the holes [16]. Besides, the gradual loss of pretension force would also cause additional slip and reduced composite action. Therefore, Kozma et al. [17] modified the connectors by casting pre-tensioned bolts in steel tubes to prevent pretension loss.

Demountable blind bolts are normally post-installed from the bottom surface of the top flange after drilling, which has often been used for rehabilitation to strengthen the composite action. Various types of blind bolts have been proposed, such as hollow-bolt [18] and ajax bolts [19], as shown in Figure 1(c). However, it showed that although the ultimate resistance of some bolts was comparable to welded studs [20], almost all types of blind bolts connection possessed lower initial stiffness due to the bolt-hole clearance [21].

Consequently, in order to control the initial slip caused by bolt-hole clearance, Suwad et al. [22,23] proposed the locking nut shear connectors (LNSC) and friction-based shear connectors (FBSC) shown in Figure 1(d). Both demountable connectors have been proven to have comparable and even better mechanical properties than the welded studs connection [24]. However, the fixed bolt position due to grouting may hinder the installation process in the subsequent life cycles.

To benefit from the replaceable bolts and make installation more flexible, researchers have proposed the bolted connector with an embedded coupler shown in Figure 1(e) [25, 26]. Kozma et al. [17] injected epoxy resin in the bolt-hole clearance to limit the slip, and they reported that this can make the larger bolt-hole clearance possible favoring the execution process. Subsequently, Nijgh and Veljkovic [27] utilized the steel-reinforced epoxy resin injection and found that the initial slip can be successfully limited without compromising the ultimate shearing resistance. Most recently, Kavoura et al. [6] found that the confined condition has a significant influence on the failure modes of the proposed shear connector focusing on the applications to concrete slabs for buildings and FRP decks for bridges.

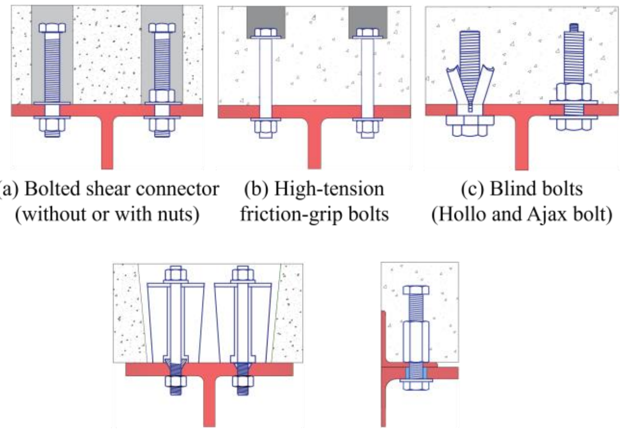

Figure 1 Schematic diagram of main demountable connectors a) [8-10], b) [13-15], c) [19], d) [22,23], e) [25,26].

2.2 Reuse of steel-dominated hybrid structures

The concept of reusing steel structural elements is strongly supported by various approaches focusing on the reusability of buildings, such as the "Donorskelet" [28], initiatives like the "Nationale Bruggenbank" for bridges [29], and platforms like "Circulair Bouwen in 2023" [30] that establish digital databases for reclaimed steel structural elements. Furthermore, numerous projects have demonstrated that reusing existing steel structures is often more feasible than designing and constructing new steel structures of the same size and functionality. Detailed case studies in the RFCS project Progress [31] showcase the use of reclaimed steel structures in various EU countries, highlighting successful technical solutions to overcome challenges. However, it is acknowledged that significant barriers, including time/program constraints and costs, exist across the supply chain.

The assessment of the sustainability potential of demountable and reusable structures has been conducted in numerous studies using Life Cycle Assessment (LCA). LCA is an internationally recognized methodology that examines and evaluates the environmental aspects and impacts of a product throughout its entire life cycle, encompassing activities such as raw material extraction, manufacturing, use, and end-of-life options such as reuse, recycling, or disposal [30]. By considering various emissions and aggregating them into environmental impact categories, LCA offers a holistic understanding of the overall environmental impact. This impact can be quantified in a functional unit, such as monetary value (€), which represents the societal cost associated with measures aimed at achieving emission reduction targets. In the Netherlands, this value is called the MKI-value or shadow cost. LCA assessments have consistently demonstrated that demountable steel-dominated hybrid structures have the potential to significantly reduce the environmental footprint [1, 33, 34].

3 Numerical study on hybrid floor systems

3.1 Geometry and boundary conditions

In this case study, two steel-concrete hybrid floor systems have been simulated. The reusable hybrid floor system utilizes a demountable injected bolted connector with a coupler to connect the steel beam and concrete deck. The performance of this demountable floor system was compared with a traditional one with welded-headed studs which achieves the composite action in the non-demountable floor system. The size and configurations of the floor system are shown in Figure 2. The distance of the end connector to the beam end is 150 mm, the center-to-center distance is set to 300 mm, and a 6 mm bolt-hole clearance is considered for ease of on-site installation accounting for the tolerances.

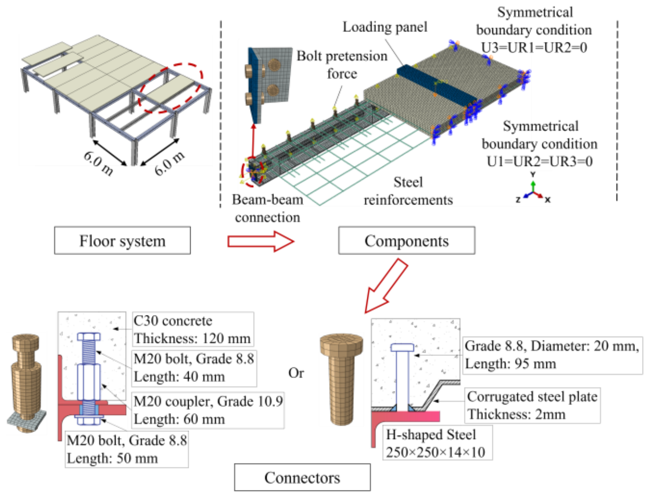

Figure 2 Schematic diagram of the demountable floor system and the floor system with welded shear studs under various scales.

The commercial FE platform Abaqus/Standard is used for the simulation, and a quarter model is established based on symmetry. Taking the demountable floor system as an illustrative example, the element meshing scheme, boundary, and loading conditions are displayed in Figure 2. Except for truss elements (T3D2) for steel reinforcement with a radius of 8 mm, the eight-node linear hexahedron element with reduced integration (C3D8R) is applied for steel beams, concrete slab, L-section profile, corrugated steel plate, and connectors through assigned partitions. With regard to the boundary conditions, the right end of the steel beam and concrete slab is set as Z-plane symmetry (U3=UR1=UR2=0) to represent the mid-span. Besides, X-plane symmetry (U1=UR2=UR3=0) is also set on the side surface of the suspended concrete slab. In addition to the symmetry condition, the left beam end is assumed to be connected to the primary beam by an L-section steel profile with bolted connection, and a rigid plate with fixed boundary condition (U1=U2=U3=UR1=UR2=UR3=0) representing the web of the primary beam. The loading process includes one step corresponding to displacement in the y-direction. In addition to the monotonic loading up to 300 mm, the cyclic loading protocol is also adopted, and the amplitude increased from ±10 mm to ±100 mm in 10 cycles.

3.2 Material properties

The concrete damage plasticity model is used to characterize the material properties of concrete. The uniaxial stress-strain curves for C30 grade concrete elements are determined following the method in EC 2 [35]. The elastic modulus, peak stress, peak strain, and damage variable are depicted in the literature [5]. In terms of material properties of steel elements, ductile damage is considered for bolts, studs, and steel beam sections. The equivalent plastic strain for ductile damage with the variation of stress triaxiality is depicted by the literature [5].

3.3 Interactions and constraints

The concept of soft contact between the external bolt and hole, to mimic the role of the injected epoxy resin on the demountable connector is adopted. In parallel, the coupler and bolt are embedded into the concrete deck. As for the welded studs, the bottom surface is tied to the top flange to model the welding, and the main body is embedded into the concrete. The steel bars and L-shaped steel profile are embedded in the deck, and steel stiffeners are tied on the beam web. The contact of other steel components followed the surface-to-surface contact with normal hard contact and tangential behavior of friction coefficient as 0.2 [37].

4 Discussion and results of the numerical study

4.1 Monotonic loading

The load mid-span deflection curves for both demountable and traditional floor systems are compared in Figure 3. Generally, the curves can be divided into (1) the elastic range where load linearly increases with deflection, (2) the elastic-plastic range where non-linearity appears due to steel yielding and concrete damage, and (3) the hardening stage where the slow increase in load is accompanied by a rapid increase in deflection due to the hardening effect of the steel elements. In this study, the deflection limit of L/250 = 24 mm is the serviceability limit state, which also roughly coincides with the elastic range. It can be found that the serviceability load P_{ser} of the demountable floor system is 8% (19.8 kN) lower than that of the traditional one with welded headed studs, which can be mainly attributed to the additional deflection induced by the bolt-hole clearance of demountable connectors. However, when comparing the ultimate resistance, the scatter between the two designs is changed to a difference of 8% (28.4 kN).

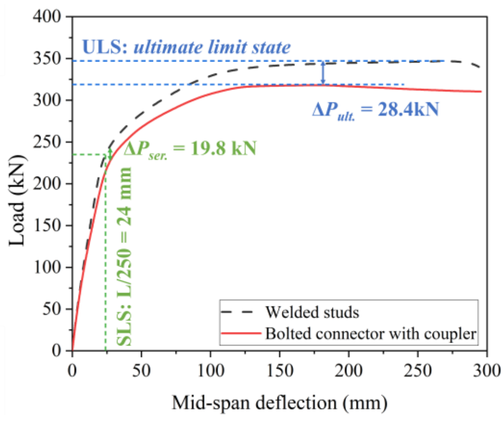

Figure 3 Load-deflection curves.

In addition, the relationship between load and end slip has also been plotted in Figure 4. The slip corresponding to the ultimate limit state at the end of the floor system is 1.6 mm when using welded studs and 1.9 mm when using a bolted connector with a coupler. The demountable floor system would slip at a load of 112 kN. The onset of the slip for the welded-headed studs floor system corresponds to the load of 152 kN, which is 36% larger than that of the demountable floor system. As for ultimate failure patterns of the demountable connector and welded studs, it can be observed that ductile damage appeared at the interface where bolts contact against the L-shaped steel profile, while the damaged zone for welded studs was mainly concentrated at the welding surface, suggesting a high strength concentration in this area.

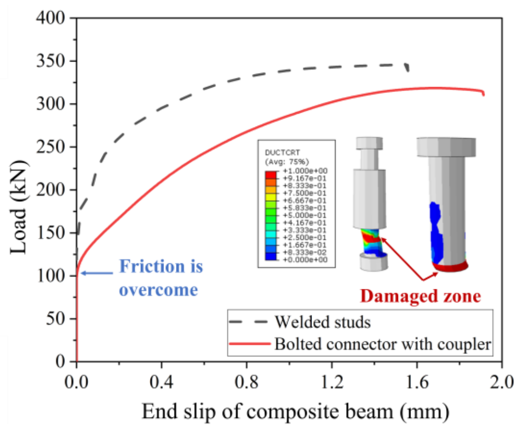

Figure 4 Load-slip curves of the demountable connector and the welded shear stud at the end of the composite beam.

4.2 Cyclic loading

In order to further investigate the mechanical properties of the demountable floor system in the subsequent life cycles, the loading scheme is set as 10 cycles in the elastic range and then loading to the resistance. Reversed cyclic loading scheme where displacement is controlled by gradually increasing from +10mm to -100 mm in 10 cycles as shown in Figure 5. It can be noticed that there is no obvious pinching phenomenon in both hysteric curves. However, compared to the monotonic loading, the hysteretic peak load for the demountable floor system is 8% lower on average. As for energy dissipation capacity, the maximum equivalent viscous coefficient [35] is 0.352 which is slightly higher than 0.339 for the traditional floor system with welded studs.

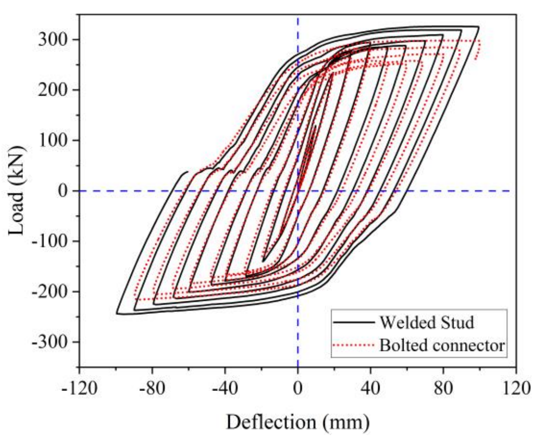

Figure 5 Hysteretic curves under cyclic loading.

5 Conclusions

This paper presents a numerical case study to compare the mechanical properties of the bolt with coupler connector and headed stud connector in floor systems. In the used numerical model, the injected epoxy resin was characterized by soft contact. The structural responses under both monotonic loading and cyclic loading schemes have been evaluated regarding serviceability limit and ultimate limit states. Results showed that the ultimate slip is less than 2.0 mm. The serviceability load capacity of the demountable floor system is 8% lower when compared with the welded shear stud floor system. Moreover, although the energy dissipation capacity is slightly higher than the floor system with headed studs, plastic deformations have been observed during subsequent cycles, This highlights the possible need for reinforcing techniques in the end concrete deck or its replacement in the next life cycle.

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