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Aleksandra Simović [1], Ana Francisca Santos [2], Hélder D. Craveiro[2], Aldina Santiago[2]

DEMOUNTABLE COMPOSITE FLOOR SYSTEMS: A STATE-OF-THE-ART REVIEW

Summary: Demountable and reusable construction systems are increasingly recognized for supporting sustainability and circular economy principles by enabling disassembly, reuse, and reduced waste compared to conventional monolithic solutions. This paper presents a state-of-the-art review of demountable and reusable steel-concrete composite structures, summarizing recent experimental and numerical studies on structural behavior, including serviceability and load-bearing performance. Particular attention is given to the fire performance of demountable and reusable systems, as research remains limited despite its importance. These systems are particularly susceptible to reduced load-bearing capacity, compromised connection integrity, and fire and smoke propagation. Existing research, design approaches, and ongoing developments are discussed.

Keywords: steel-concrete composite structures, demountable systems, sustainability, fire resistance

DEMONTAŽNI SPREGNUTI PODNI SISTEMI: PREGLED LITERATURE

Rezime: Demontažni i ponovo upotrebljivi konstrukcijski sistemi sve više se prepoznaju kao rešenja koja doprinose održivosti i principima cirkularne ekonomije, omogućavajući demontažu, ponovnu upotrebu i smanjenje otpada u poređenju sa konvencionalnim monolitnim rešenjima. U ovom radu prikazan je pregled savremenog stanja istraživanja demontažnih i ponovo upotrebljivih spregnutih konstrukcija od čelika i betona, uz sistematizaciju novijih eksperimentalnih i numeričkih studija koje se odnose na njihovo konstrukcijsko ponašanje, uključujući granična stanja upotrebljivosti i nosivosti. Posebna pažnja posvećena je ponašanju demontažnih i ponovo upotrebljivih sistema u uslovima požara, budući da su istraživanja u ovoj oblasti i dalje ograničena, uprkos njenom značaju. Ovi sistemi su posebno osetljivi na smanjenje nosivosti, narušavanje integriteta veza, kao i na širenje požara i dima. U radu su razmatrana postojeća istraživanja, projektantski pristupi i aktuelni pravci razvoja.

Ključne reči: spregnute konstrukcije od čelika i betona, demontažni sistemi, održivost, otpornost na požar

[1] University of Coimbra, ISISE, ARISE, Department of Civil Engineering, Portugal, aleksandra.simovic@uc.pt
[2] University of Coimbra, ISISE, ARISE, Department of Civil Engineering, Portugal

1. INTRODUCTION

Steel-concrete composite floor systems are among the most widely used structural solutions in multi-storey buildings, owing to their high stiffness, load-bearing capacity, and construction efficiency. In conventional practice, composite action is typically achieved by means of welded headed stud connectors embedded in the concrete slab. However, this monolithic configuration makes disassembly difficult and generally prevents the direct reuse of both the steel beam and the slab at the end of the structure's service life. Demountable composite construction addresses this limitation by replacing welded studs with mechanical connectors capable of providing shear transfer during service while allowing non-destructive separation of the slab and beam. In this way, demountable systems support design for deconstruction, component recovery, and reuse. Life-cycle assessment studies have further shown that their environmental benefits become significant provided that reuse is effectively implemented. This paper summarizes recent developments in demountable steel-concrete composite floor systems, with particular emphasis on proposed shear connector types and their experimentally and numerically observed behavior at both connector and structural levels. In addition, available studies on fire performance and diaphragm behavior are also discussed, highlighting the main research gaps that need to be addressed before wider practical application.

2. CONNECTORS FOR DEMOUNTABLE STEEL-CONCRETE COMPOSITE SYSTEMS

High-strength friction-grip bolts (HSFGBs) have been widely investigated as demountable shear connector solutions for reusable composite beams [1-5]. Their response is initially governed by pretension-induced friction behavior, which provides high initial stiffness, but slip develops once this friction is overcome because of the bolt-hole clearance. The studies indicate that HSFGBs can achieve ultimate shear resistance and ductility comparable to welded studs, while beam tests confirm satisfactory flexural behavior, although the response remains strongly dependent on pretension level, clearance, and slab material. HSFGB is shown in Figure 1a).

The T-shaped embedded-nut bolted connector (T-ENBC), presented in Figure 1b) was developed by *Chen et al.* [6] to improve upon HSFGB behavior. Relative to HSFGB, it achieved about 9.7% higher ultimate shear resistance and about 143% higher shear stiffness in push-out testing. These improvements result from replacing oversized bolt holes with tight-clearance holes and a T-shaped embedded nut, which increases bearing and friction forces but limits slip and plastic deformation, thereby reducing ductility. The available evidence is still limited to connector-level push-out tests, and no beam-level or fire validation has yet been established.

The T-shaped bolt shear connector (Figure 1c)) is a friction-based non-embedded connector with a mainly bilinear load-slip response. *Li et al*. [7] reported that its failure mode is mainly governed by wear of the bridge-shaped gasket, while the load-transfer mechanism is primarily controlled by friction generated through bolt pretension. The connector also shows excellent anti-lifting capacity, and its shear performance is significantly influenced by bolt pretension, friction coefficient, bolt diameter, and channel spacing.

Clamping connectors (Figure 1d)) are friction-based demountable systems validated at both the connector and beam scale by *Wang et al.* [8-11]. For the studied Lindapter C-clamp configuration, the baseline M24 specimen reached a peak shear resistance which is comparable to the resistance of a 19 mm welded stud, while its initial tangent stiffness substantially exceeded the reported value for stud behavior. Their performance has been investigated through push-out testing and further supported by four full-scale beam tests, which confirmed ductile global behavior and flexural strengths close to AISC predictions. Fire performance, however, remains unresolved, since this connector type has not yet been studied under elevated temperatures, and pretension loss due to elevated temperatures could directly compromise its friction-based load-transfer mechanism.

Within the REDUCE family [12-15], the fully demountable **cylinder system (P3)** (Figure 1e) typically develops shear resistance of about 141 to 168 kN per connector, with slip capacities of roughly 7 to 10 mm. Its governing failure mode is bolt shear, while the connected members remain largely undamaged, which is favorable for deconstruction and reuse because the failed bolts can be replaced and the system can be reassembled with similar resistance, stiffness, and slip capacity.

The related **coupler system P15.1** (Figure 1f)) is also a demountable solution and, in the *FIREDUCE* push-out tests, reached an ultimate load of 159.2 kN per bolt at room temperature. Under elevated temperature push-out tests, P15.1 retained a shear resistance of 156.68 kN per bolt at 300 °C, compared with 132.84 kN for P3.1. However, both systems experienced reduction in shear resistance of approximately 50% above 500 °C owing to the degradation of bolt strength. [12-14]. This distinction is important at the system level: P3 is more attractive where full demountability and deformation capacity are prioritized, whereas P15.1 is advantageous where thermal performance and protection of the threaded region are critical.

The resin-injected variant P15.2 (Figure 1g)) modifies the coupler concept of P15.1 by filling the hole clearance around the bolt with epoxy resin, which prevents early bolt slip and allows larger construction tolerances without compromising load-bearing capacity. Its average resistance is approximately 131 kN per connector, with an initial stiffness of 100 kN/mm, compared with 142 kN per connector and 70 kN/mm for P15.1. Accordingly, P15.2 exhibits about 7.7% lower resistance but about 42.9% higher initial stiffness. Its main limitation is the reduced slip capacity, as this series fails to meet the EC4 ductility requirement of 6 mm [12-15].

The **tapered iron bolt (TIB)**, shown in Figure 1h)), is intended to reduce initial interfacial slip and provide high shear stiffness. In push-out tests carried out by *Song et al.* [16], the average experimental resistance reached 49.3 kN for M12 connectors and 82.2 kN for M16 connectors. However, the connector exhibited limited slip capacity, with all newly assembled specimens failing below 6 mm, which is below the EC4 ductility threshold.

The locking nut shear connector (LNSC) (Figure 1i)) was developed to eliminate the early slip associated with bolt-hole clearance in conventional bolted systems. Push-out tests showed about 25% higher shear resistance and about 600% greater shear stiffness than comparable HSFG connectors, while review evidence indicates approximately 20% higher resistance than welded headed studs of equivalent diameter [17].

Karakus et al.[18], [19] investigated **bolted angle connectors**, which consist of a standard steel angle section bolted to the beam flange with a high-strength bolt, with a smaller hat section welded to the vertical leg to provide tension resistance, as illustrated in Figure 1j). Push-out tests reported for the front-loaded specimens' shear resistance at 6 mm slip in the range of about 149 to 292 kN, depending mainly on angle size and concrete strength. Initial stiffness was approximately 61 to 173 kN/mm, and most configurations satisfied the EN 1994-1-1 [20] ductility requirement [19]. Full-scale beam tests further confirmed global flexural behavior comparable to conventional composite beams with welded headed studs [18].

Steel-yielding pocket connectors (Figure 1k)) intentionally shift the inelastic mechanism into a deformable steel pocket, promoting a ductile force-slip response. *Feidaki et al.* [21] reported that the shear resistance is about 170 to 320 kN. The initial stiffness is comparable to that of welded shear studs, and ductility is very high, with specimens designed for ductile response achieving at least 30 mm of slip capacity. This concept is particularly attractive for precast hollow-core floor units because it enables demountability through operations performed only from the top of the floor.

Pathirana et al. [22] and *Hosseini et al.* [23], [24] concluded that **blind bolts** generally provide shear resistance comparable to that of welded studs. However, their initial stiffness can be lower and remains sensitive to connector configuration and bolt-hole clearance [22], [24-26]. In direct shear tests, blind bolts reached an average ultimate resistance slightly higher than headed studs, while their average stiffness was about 68% lower [23]. Distinct differences were also observed between the two variants, with BB1 (Figure 1l)) showing higher stiffness but lower ductility, and BB2 (Figure 1m)) showing higher strength and ductility, together with greater sensitivity to initial slip caused by hole clearance [22], [25], [26].

Chen et al. [26] reported that **through-bolt connectors** can provide peak load and ductility comparable to conventional welded studs, but they are typically characterised by a low initial slip load, which remains their main mechanical limitation.

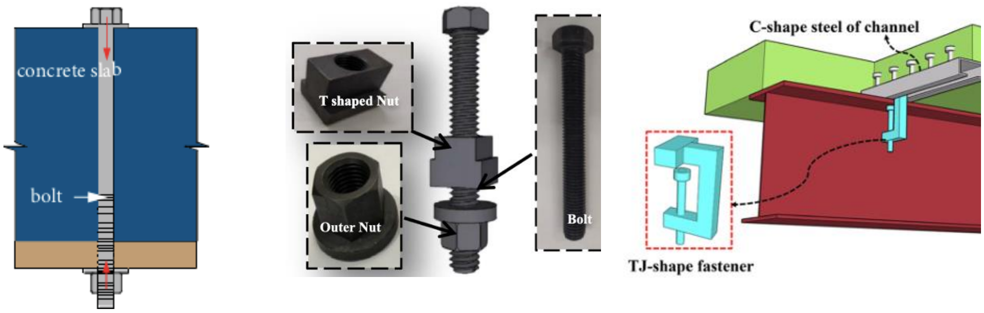
Threaded headed studs and non-embedded nut bolts (NENB) connectors have been shown to provide adequate shear resistance and ductile/slip capacity, making them attractive for reusable composite construction [27-29]. However, clearance in pre-drilled or oversized holes can lead to initial connector slip before bearing is fully mobilised, which may reduce the early-stage stiffness and temporarily weaken composite action between the steel and concrete/UHPC components [28-30]. The connector is shown in Figure 1n).

Single embedded nut bolts (SENB) improve on earlier bolted solutions by using a single embedded nut, as presented in Figure 1o), to mitigate slip and rotational effects within the hole and thereby enhance the initial elastic response. Even so, their behavior still includes clearance-induced slip before full bearing develops, and reported performance is approximately 95% of the shear resistance of comparable welded headed studs, but only about 50% of their stiffness at serviceability load levels [31], [32].

To further improve the behavior of embedded bolted shear connectors, **double-embedded-nut connectors (DENB),** shown in Figure 1p), have also been investigated by *Pavlović* [33], *Wang et al.* [34] and *Zhang et al.* [31]. The additional embedded nut increases the local bearing area, improves the initial stiffness, and can help delay local concrete crushing around the connector; it may also contribute to improved ductility depending on the concrete type, reinforcement details, and failure mode. However, the available evidence suggests that the clearest advantage of the double-embedded-nut arrangement is related to stiffness and local bearing behavior, while any increase in ultimate shear resistance relative to well-detailed SENB connectors is not consistently proportional to the added fabrication complexity.

Ren et al. [35] investigated an innovative **demountable H-section steel shear connector (DHSSC)** for steel girders and precast concrete slabs, in which an H-section steel element is connected through bolts and nuts, as shown in Figure 1r). Reported shear capacities ranged from about 953 to 1438 kN, and in the ductile failure mode, the characteristic slip capacity ranged from 13.86 to 28.94 mm. Satisfactory deformation capacity was achieved when yielding of the H-section steel connector, rather than bolt shearing, governed the response.

In addition to the connector types discussed above, several other demountable solutions have been proposed in recent years, including lock-bolt connectors [36-39], double-bolt coupler shear connectors [40-42], concrete-plug demountable shear connectors [43], and steel-yielding demountable bolt connectors (SYDBCs) [44].



a) HSFG [34] b) T-ENBC [6] c) T-shaped bolt [7]

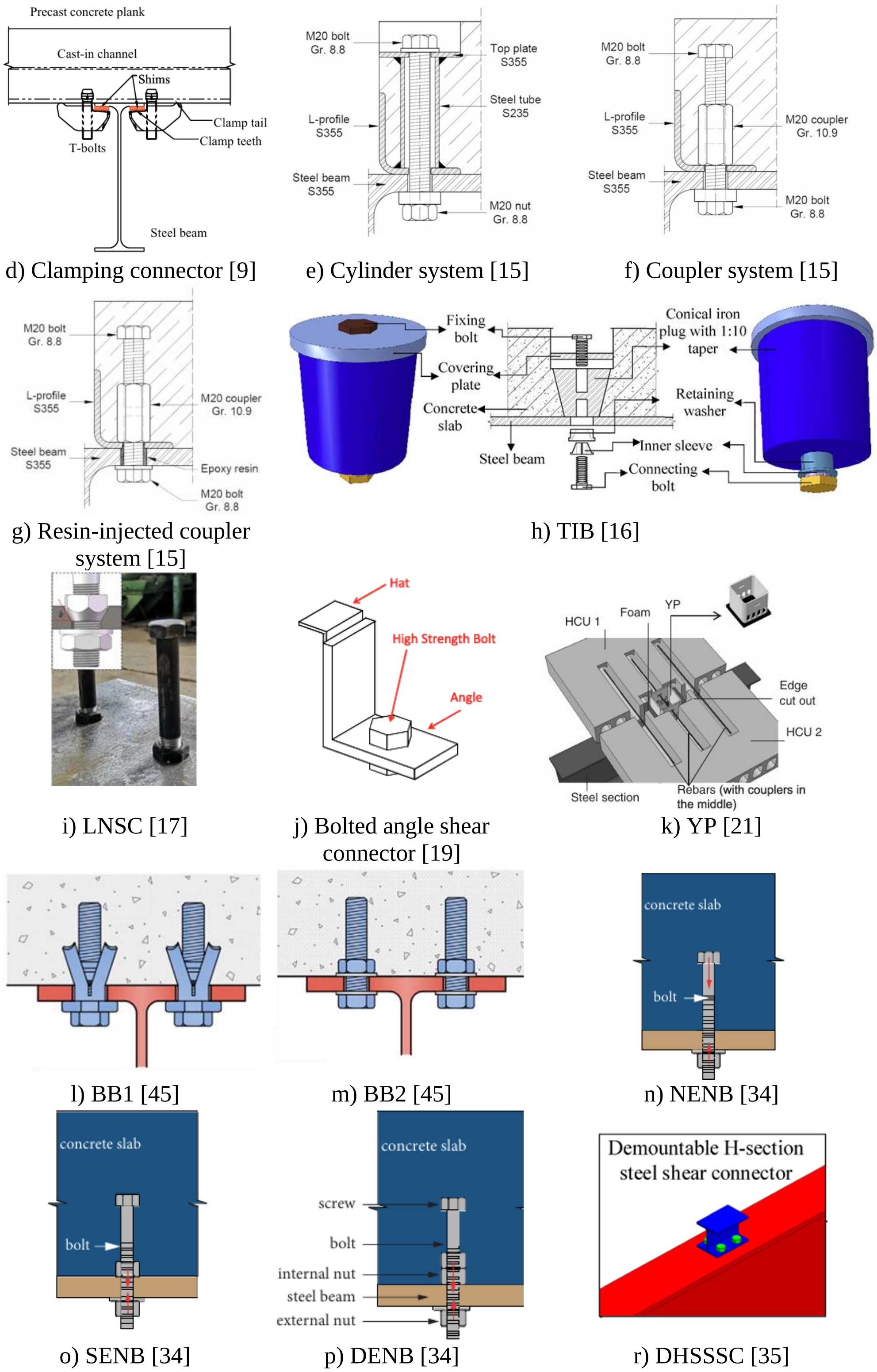


Figure 1: Demountable shear connectors for steel-concrete composite floor systems

3. BEHAVIOR OF DEMOUNTABLE STEEL-CONCRETE COMPOSITE FLOOR SYSTEMS AT ELEVATED TEMPERATURES

Research on the fire behavior of demountable steel-concrete composite beams has only very recently emerged, driven by the need to validate these systems for real-world application in the context of circular construction. *Long et al.* [46] conducted the first experimental fire tests on prefabricated demountable composite beams with profiled steel decking, demonstrating that unprotected beams reach failure rapidly, while beams with appropriate passive fire protection can achieve a nominal fire resistance rating. In parallel, *Mansilla et al.* [14] performed push-out tests at elevated temperatures on two types of demountable connectors (cylinder and coupler systems), showing that the shear resistance degrades progressively with temperature, with the most significant loss occurring above 500 °C. Within the *FIREDUCE* project, *Mora et al.* [13] carried out full-scale beam bending tests under fire exposure, confirming that demountable composite beams equipped with a timber and mineral wool protection system can sustain their load-bearing capacity well beyond 90 minutes of standard fire exposure. Building on these experimental campaigns, the same authors developed a numerical model and subsequently an analytical method based on *EN 1994-1-2* [47] for evaluating the plastic bending moment capacity of demountable composite beams in fire, achieving good agreement with test results. Collectively, these studies indicate that existing Eurocode design provisions can be extended, with appropriate modifications, to demountable shear connection systems, and that such systems, when adequately protected, represent a viable solution for achieving standard fire resistance requirements in multi-storey buildings.

4. DIAPHRAGM BEHAVIOR OF DEMOUNTABLE STEEL-CONCRETE COMPOSITE FLOOR SYSTEMS

The structural integrity of composite buildings subjected to lateral actions, such as wind or seismic loads, depends strongly on the in-plane stiffness and strength of the floor diaphragms. In conventional composite construction, diaphragm action is commonly provided by cast-in-place concrete toppings, welded connectors, or other permanent jointing techniques. However, such solutions are generally incompatible with the principles of deconstructability, reparability, and component reuse. The development of fully demountable diaphragm systems therefore requires a detailed understanding of the force-transfer mechanisms between individual precast floor elements and the supporting steel frame, without relying on traditional wet joints or irreversible connections. This section reviews recent experimental and numerical investigations focused on the in-plane performance and force transmission capabilities of innovative demountable shear connection systems. *Chen et al.* [48] experimentally investigated a novel demountable interlocking web connection for precast floor diaphragms that relies on neither welding nor bolting. Through 17 monotonic in-plane shear tests, they demonstrated that failure can be deliberately directed to the demountable connectors by pairing low-strength connectors with high-strength faceplates, thus preserving the concrete slabs for reuse. A subsequent parametric FE study identified three distinct failure modes and provided corresponding design equations. *Wang et al.* [11] analysed the diaphragm behavior of a deconstructable composite floor system with precast planks and clamping connectors. Their full-scale FE diaphragm models under cyclic loading exhibited ductile behavior with no strength or stiffness degradation. Two limit states were observed: joint sliding between planks at lower compressive stresses, and clamp slip on the girder at higher stresses. Both were governed by friction, with concrete remaining largely undamaged.

5. CONCLUSION

The reviewed studies show the growing research interest in demountable steel-concrete composite floor systems, particularly in the last few years, driven by sustainability, circular economy, and design-for-deconstruction principles. A wide range of demountable shear connectors has been proposed, with the main objective of achieving adequate initial stiffness, shear resistance, and ductility in order to ensure reliable composite action while enabling disassembly and reuse. Although several full-scale investigations have provided valuable insight into the global behavior of demountable composite beams and floor systems, the available research is still predominantly focused on push-out tests and the local response of individual connectors. Fire performance and diaphragm behavior represent especially important aspects that remain insufficiently explored. Recent studies indicate that demountable composite beams can achieve satisfactory fire resistance when adequate passive protection is provided, and that existing Eurocode-based approaches may be extended to such systems with appropriate modifications. In parallel, the available studies on diaphragm behavior suggest that demountable floor systems can develop a ductile in-plane response. However, this aspect has still been investigated for a limited number of structural configurations and connection details. Numerous authors have proposed connector-specific expressions for predicting shear resistance and stiffness of different demountable shear connector types; however, broader experimental validation is required before these formulations can be incorporated into design standards.

Recently, data-driven and machine-learning-based approaches have also begun to emerge in this field, particularly for predicting the shear resistance of demountable bolted shear connectors and supporting the development of design-oriented models. Future research should therefore place greater emphasis on full-scale testing, fire and post-fire performance, diaphragm action, robustness, resilience, and repeated disassembly-reassembly cycles. Such investigations are necessary for a more comprehensive structural verification of demountable composite systems and for their wider implementation in practical design.

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