Performances of Steel-Concrete Composite Construction with Demountable Shear Connectors – Review

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Abstract. Composite steel-concrete constructions with demountable (bolted) have the prime privilege of the capability to be untied and taken to pieces, furthermore, they remain suitable for tying again to assemble efficient composite structures. Long-term behavior and durability issues may need replacement of concrete slabs or their parts through maintenance of composite bridge decks. It is a complicated procedure and requires a lot of time in case of the popular traditional welded head stud. Dismantling and replacement of concrete slabs can be effortless by using bolted shear connectors. It is also so important for the sustainability stand point owing to remove of the structure at its life time end easily. Construction by using demountable shear connectors permits the development of faster erection methods. During casting of the reinforced concrete slab bolts can be embedded in it. Then, on site, they are assembled to the predrilled top flange of the steel section of the composite member. For certain application, composite structures with demountable shear connectors can prove their competition economically for their faster erection and lower life cycle costs. The present paper provides a comprehensive overview of most recent published research on composite steel-concrete systems in which the two partial interaction components (slip and uplift resistances) are furnished by demountable shear connectors. It also describes, in detail, properties of the main types of shear connection demount abilities innovated so far.

1. Introduction

Very limited published work on the behavior of bolted demountable headed stud shear connectors has been met in literature in comparison with traditional welded studs shear connectors. Some types of demountable shear connectors shown in Figure 1, were investigated in only nine research papers [1], [2], [3], [4], [5], [6], [7], [8], [9]. They are classified according to types defined in Figure 1, with their high lights and outcomes being presented in chronological order through the subsections coming later on.
2. Composite Specimens with Friction grip bolts

With reference to Figure 1 (a), shear transfer forces are transferred in those composite systems by means of frictional interaction between the concrete and the steel media provided by pre-burdening of the bolts. Such composite systems are almost used in car parks [10]. As the bolt pre-burdening is created through the thickness of the concrete part, it is often highly compressed. Hence, helical reinforcement around the bolt hole becomes necessary to elevate the strength of the concrete media embracing locations of high-stress concentration.

Dallam, 1968 [1] studied experimentally behavior of high strength friction-grip bolts embedded at loaded push-out segments, as shown in Figure 2 (a). He used ASTM A325 and A449 bolts of 12.7, 15.9 and 19.1 mm diameters (1/5, 5/8, 3/4 in.), which varied with lengths. They were linked to holes in flanges of a steel section and situated properly using springs, then pre-burdening by turn-off-nut method (i.e. “snug tight” plus 1/2 turn) to attain the minimum specified pre-burdening force. He used two bolts for each of the two flanges of a specified push-out test segment as shown in Figure 2 (b).

ASTM A449 bolts ($f_u = 951$ MPa) of 16 mm diameter Figure 2 (c) shows the shear-slip curves for specimens embracing with each other with results belonging to welded headed studs of the same diameter. He elucidated that bolts did not slip at load level of the serviceability stage and up to two
times the ultimate shear resistance in comparison with welded headed studs of similar material properties and similar dimensions.

Marshall, 1971[2] carried out monotonic loading on push-out segments embracing friction-grip bolts of 16 mm diameter, as shown in Figure 3 (a). Their variables were type construction (either precast or in-situ), and grade of concrete ($f_{cu}$ range from 36 to 50 MPa) of their conducted eleven push-out segments. Failure of concrete took place in only one case (of cube strength of 36.2 MPa). The achieved approximately 90 kN forces for preloading of bolts, thus they realized high values of the friction coefficient attaining a value of 0.45 for cases of precast slabs.

![Figure 3. Friction-grip bolts push-out segment and beam test.](image)

The shear-slip response for a typical precast concrete push-out segments is shown in Figure 3 (b). Directly after the friction force been overcome, first slip-took place that relationship reveals that the ultimate resistance was at least two times higher than the pure frictional resistance indication onset of slip. In addition, they conducted five tests on beams of 4.00 m and 2.03 m spans with conserving the changing of the construction type (precast or cast in-situ). Figure 3 (c) and (d) shows the beams test set-up and results, respectively. They examined the slip influence on a score of partial interaction and compared it with the theory of partial interaction of Newmark 1951 [11]. They conducted that slip friction coefficient 0.45 is accurate enough for the precast slabs. Furthermore, they found that full interaction between the overlying concrete deck and the top steel flange and may be conserved within serviceability range.

Section 10 of BS 5400-5, 1979 [12] provides guidelines and limitations for the applicability of friction-grip demountable bolts in steel-concrete composite beams. That article states that: “The resistant of longitudinal shear per unit length can be achieved by friction between steel flange and the concrete beam and should not be less than the longitudinal shear force per unit length at the serviceability limit state”. The following Eq. 1, extracted from that section, gives the design frictional capacity, generated by each shear connectors at the interface, as follows:

$$P_{fric} = \mu \cdot F_{p,C} / 1.2$$  \hspace{1cm} (1)

where: $\mu = 0.45$ (recommended value)

$F_{p,C}$ = bolt preloading force.
Losses in the bolt pre-burdening force caused by the concrete shrinkage in additional to the creep of the steel have to be taken in to account. However, it does not give any practical recommendations. Eq. 1 satisfies the ult. Lim. State but its values within the level of serviceably. It has been found that shear resistance's lower values can be obtained by Eq. 1 in comparison with values determined by Dallam, 1968 [1]. However, predictions of Eq. 1 are close to results of Marshall, 1971 [2]. Hence, their investigation stands as acted as a basis for provision of BS 5400-5, 1979 [12].

Kwon, in 2008 [7] investigated bolts of friction grip type, shown in Figure 4 (a), as post installed shear connectors to strengthen girders existing non-composite bridges. He conducted one bolt shear tests under monotonic and repeated loadings. He used ASTM A325 bolts of 22 mm diameters and 127 mm lengths on top of the steel section and 175 kN pre-burdening force. He drilled 25 mm diameters hole in concrete, with gaps between the holes and the bolts kept unfilled. He tested two segments for monotonic loading and single for 5 million-cycle fatigue loading. Shear-slip curves for monotonic single bolt tests are presented in Figure 4 (b). Single test specimen failed by bolt fracture while the other failed by concrete crushing when the shear stress did not exceed 241 MPa he acquired high performance since the five-million cycles did not cause failure of the shear connectors.

![Figure 4. High-tension friction-grip bolt (HTFGB)](image)

Finally, he conducted that high-tension friction-grip bolt revealed high shear resistance of values net less than those of the conventional headed studs, Moreover, he got fatigue strength much better than the welded ones. Additionally, he carried out beam tests with different types of shear connectors, which shown later in Figure 12 (a), additionally to the results shown in Figure 12 (b). When compared to a non-composite beam he achieved 50% elevation in load carrying capacity even when with 30% shear connection ratio used.

Lee and Bradford, 2013 [13] investigated loading test on two push-out segments on the bases of EC4, 2004 [14] by preloading the bolts by a 145 kN force through the concrete slab depth using large steel plates as shown in Figure 5 (a).

They made holes the concrete slab of diameters 4 mm larger than the bolt diameter using 48 MPa compressive strength polymer concrete slabs. Shear-slip response for one specimen is exhibit in Figure 5 (b).fracture of the bolts give rise to failure of both specimens. They conducted that after exceeding the frictional resistance, excessive slip took place due to that oversize in the concrete slab cores till ultimate stage, thus indicating ductile behavior.

![Figure 5. Friction grip bolts.](image)
3. Composite specimens embracing demountable shear connectors without embedded nut

Hawkins, 1987 [4] conducted an experimental investigation on bolted shear connectors without embedded nuts which is shown in Figure 1 (b). It was loaded in combined shear and tension. His variables were the anchor bolt diameter (19 and 25 mm), bolt shank length (76, 127 and 178 mm) and concrete grade ($f_{cu}$ 20.7 and 34.5 MPa). Referring to Figure 6, he found that such bolted shear connectors attain shear resistance of welded headed studs but only 15% of their shear stiffness.

![Figure 6. Curves for Force-slip showing studs and bolts without embedded nut.](image)

Lam, 2013 [8] studied experimentally performance of bolted shear connectors, shown in Figure 7 (a) to evaluate their capability of superseding the traditional welded headed studs. They conducted loading test on eight push-out segments each with four 19 mm diameters stud (identical) connectors but diverse concrete grades. They observe two failure patterns near thread termination, fracture of bolt end and crushing of concrete. They indicated the easy removal of slabs after failure which refers to dismantling ability of the structure. They also carried out refers tests on traditional welded headed studs to compare their performance as presented in Figure 7 (b). They concluded that those bolted shear connectors had composite shear resistance relative to traditional welded headed stud with better ductility but have less stiffness.

![Figure 7. Demountable shear connectors.](image)

a) bolts model b) curve of force-slip

4. Composite specimens embracing demountable shear connectors with embedded nuts

Demountable shear connectors each supplied by single or double embedded nuts revealed close performances. They were generally examined to reform purposes for strengthening the existing non-composite steel-concrete bridges destitute of partial interaction. The thesis object was investigating the resistance of demountable shear connectors each having a single embedded nut. Hence, it presented in detail, previous research on that type of demountable shear connectors. Scarce published research work on bolted shear connectors with embedded nuts have ever been met. Yet, seven published research papers have been extracted and reviewed herein.

Dedic and Klaiber, 1984 [3] investigated performance of four push-out segments each embracing four ASTM A325 high strength bolts of 19 mm diameter as shown in Figure 8 (a). They also carried out push-out tests with traditional welded headed studs for comparison. They got similar shear-slip response and shear resistances as shown in Figure 8 (b). They reported bolt failure, but they were
unable to show the entire force-slip curve, up to failure (for the case of bolts with embedded nuts) of the force-slip curve is not presented.

![Graph showing force-slip curve](image)

**Figure 8.** Demountable shear connector with embedded nut.

Sedlacek, in 2003 [5] carried out an investigation established by the European Commission for the purpose of designing composite bridges of small and medium spans.

First, they investigated, several thoughts on various levels of partial prefabrication of the concrete slab by using either welded headed studs or shear connectors, previously done at the University of Wuppertal by Prof. Dr.-Ing. Gerhard Hanswille. They paid special attention on investigating the performance of demountable shear connectors for assessing the possibility to strengthen the concrete deck during design life time of temporary bridges. The main part of that study was to investigate bolted shear connectors where they tested three specimens embracing high strength bolts with double embedded nuts: two for monotonic loading and one for fatigue loading in 3 million cycles as shown in figure 9 (a). They did not get any Fatigue failure at all with no significant increase in the slip.

![Graph showing force-slip curve](image)

**Figure 9.** Demountable shear connectors M20.

Schaap, 2004 [6] conducted shear tests on three demountable shear connectors of 19 mm diameter with double embedded nuts individually. Illustrative figure 1 (d), the nominal tensile strength of the tested bolts material was 1034 MPa (150 ksi). Typical shear connectors profile is illustrative in Figure 10 (a).

First, he made a 50 mm diameter drill in the concrete, installed the bolt. Then, he filled cavity with grout as shown Figure 10 (b). Figure 10 (c) gives the shear-slip response. Initial relative slip in the hole due to exceeding the friction resistance is observed at a relatively small load and no occurrence of any shear failure. Reporting the preloading force of the bolts was, unfortunately, missed. He conducted that this type of demountable shear connectors has good performance and recommended further investigation.
Kwon, 2008 [7] extended the research carried out by Schaap, 2004 [6] by investigating the behavior of the demountable shear connector with double embedded nuts, presented in Figure 1 (d). They are planned to be post-installed in existing reinforced concrete bridges for strengthen purpose. He conducted the shear test set-up for the single bolt as shown in figure 11 (a).

He drilled larger diameter holes in the concrete, installed the bolts, and filled the clearance with high-strength grout after the connectors installation. As a total, he tested three specimens for monotonic loading and one for 5-million cycle fatigue loading. Shear-slip responses for monotonic shear tests for single bolt are shown in Figure 11 (c). All bolt fractured thoroughly causing explicit failure. He conducted that DNLNB revealed high shear resistance not less than that of welded headed studs. Moreover, the conventional headed stud as the connection is free of welding.

In addition, he made beam tests which are shown in Figure 12 (a). As a total, he conducted four beam tests; one non-composite and three composite beams, their results are shown in Figure 12 (b). While
he noticed initial slip caused by the bolt-to-hole clearance in the shear test as presented in Figure 11 (c), he did not observe any loss of initial stiffness in the beam test illustrated in figure 12 (b).

![Image of shear test](image1)

![Image of beam test](image2)

**Figure 12.** Test of beam.

Lee and Bradford [13], carried out in 2013 two push-out tests on the basis of EC4, 2004 [14] specifications by using demountable shear connectors with the single embedded nut (Figure 1 (c)) and geopolymer concrete slabs. They preloaded the bolts within the steel flange thickness.

They determined shear-slip responses shown for one specimen, in Figure 13 (a). Both specimens suffered fracture in their bolts causing characteristic failure as shown in Figure 13 (b), which distinguishes of the bolts, accompanied by front crushing of concrete. They elucidated that bolt failure first occurred at its shank rather than in its threaded part if particularly designed clamps were used.

![Image of M20 demountable shear connectors](image3)

**Figure 13.** M20 demountable shear connectors

Lawan [9] investigated, in 2016 the performance of bolted shear connectors in self-compacting concrete SCC integrated with cold-rolled steel CFS sections as composite beam systems. They fabricated, cast and tested up to failure eighteen push-out test specimens of those two specific types of concrete and steel. Their main variables were the size and longitudinal spacing of the shear connectors.

They found that all bolted shear connectors revealed high resistance. Due to CFS failure they found no significant effect of the longitudinal spacing of bolted shear connectors.

![Image of bolt and nuts](image4)

Finally, in 2017 Ahmed [15] has studied the performance of novel demountable shear connectors (i.e. bolt) for precast steel-concrete composite bridges. He has fastened the bolts to the top flange of the steel beam of a special configuration of nut locking which prevents bolts from slipping within their holes as shown in Figure 14 (a). Further, those connectors corroborate rapid construction and surmount the common construction tolerance problems of precast structures. Moreover, those connectors allow disassembly of bridges. They conducted a series of push-out tests to evaluate the performance of the connectors and assess the effects of the important parameters. They concluded that the shear resistance, stiffness, and slip ability have been significantly higher than those of welded shear studs accompanied by higher uplift resistance. Identical tests reveal negligible scatter in the shear load-slip displacement behavior. In end, they proposed design equation to predict the shear resistance with an 8% margin of error.
5. Summary and Conclusions

1. Due to the lack of detailed research and design rules concerning their specific behavior, the demountable shear connectors are rarely used in composite construction.

2. Yet, demountable shear connectors are strongly suggested for the erection of composite deck structures including precast concrete slab panels to construct residential and car parks, commercial building and modular building systems. They have high competition in the field of implementing systems of modular temporary and short span overpass bridges.

3. So far, there are four possible uses of demountable shear connectors: the friction-grip bolts, the threaded bolts tightened by exterior nuts but destitute of interior nuts embedded in concrete, exterior-nut-tightened threaded bolts with single embedded nuts, and exterior-nut-tightened threaded bolts with double embedded nuts.

4. Friction-grip bolts transfer interface shear force through friction between the flange of the steel profile and the concrete slab. Their preloading is made through the concrete slab thickness subjected to highly localized compressive stresses loading to an unfavourable loss of preloading force because of concrete creep.

5. The three specified exterior-nut-tightened threaded-bolt shear connectors transfer interface-shear force by twin concrete-steel flange hole bearing and also by cross shearing of the threaded bolt shank. Hence, double shear resistance can nearly by achieved by bearing in compression with the mechanism of friction transfer provided by same grade bolts.

6. Preloaded demountable shear connectors proposed for connections of efficient slip resistance have to be if higher quality than the high strength bolts not capable of resisting the connection slip.

7. On basis of the last elapsing item, bolts tightened by both exterior and embedded nuts are more feasible as demountable shear connectors in prefabrication composite decks in comparison with friction-grip bolts.

8. The singular drawback of the nut-tightened bolted shear connectors is their low slip resistance, where it is required to account for the effect of the imperfect interaction on the performance of the composite system.

9. Finally, shear stiffnesses of the bolted shear connectors with embedded tightening nuts are much higher than those of bolts destitute of concretely embedded nuts (but only exterior once). The former (more qualified) ones are more feasible for casting in prefabricated concrete slabs owing to their mountability by the nuts on both sides of the shuttering.

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