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Brief overview on high-strength bolt shear connectors for steel-concrete composite beam

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ABSTRACT

To meet the requirements of sustainable development of building structures, the application of detachable connectors for steel-concrete composite beams has attracted increasing attention. The high-strength bolt connection point, which is based on the assembly and fastening of threads, can very conveniently realize the assembly connection of the steel beam-flange plate in the composite beam, and has broad prospects for engineering application. This paper analyzes and summarizes the connection characteristics and bearing performance of two different structural forms of connectors, namely the embedded anchorage and the through connection of high-strength bolts, providing a reference for the engineering application of this type of connection.

KEYWORDS; *High-strength bolted shear connector, Embedded high strength bolt connector, Through bolts connector*

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I. INTRODUCTION

The high-strength bolt shear connector of steel-concrete composite beam, as a detachable (deconstructable or demountable) assembly connection method for composite beams, can be traced back to the 1960s. This connection method can effectively reduce construction waste and is beneficial to environmental protection. Considering that the structural forms of this type of connection are diverse (typical connection structure as shown in Figure 1), and the force transmission mechanism is also relatively complex, currently no unified design and calculation specifications have been established by various countries to support the engineering design practice of this type of connection. This paper aims to summarize and analyze the relevant research results of high-strength bolt connections to provide a reference for the engineering application of high-strength bolt shear connector of steel-concrete composite beams.

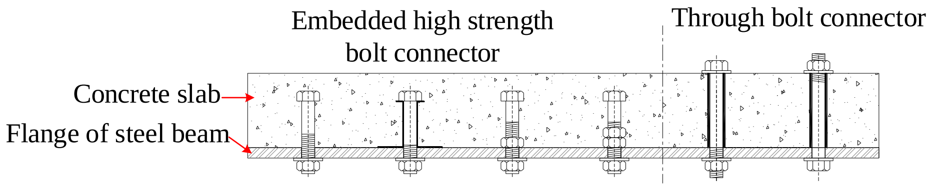

Figure 1:Typical Construction Form of High-Strength Bolted Shear Connectorfor Steel-Concrete Composite Beams

II. EMBEDDED HIGH STRENGTH BOLT CONNECTOR

The most frequently studied form of construction is the sleeve bolt. Its construction is to place the structural bolts into the pre-drilled holes in the flange before the concrete is poured. The first report on this topic was published in international literature by Dallam [1] in 1968. He conducted a pull-out test on the prestressed high-strength frictional (HSFG) bolts for shear connections (Figure 2) and found that the bolts did not slip within the working range of the load, and their shear bearing capacity was approximately twice that of the studs..

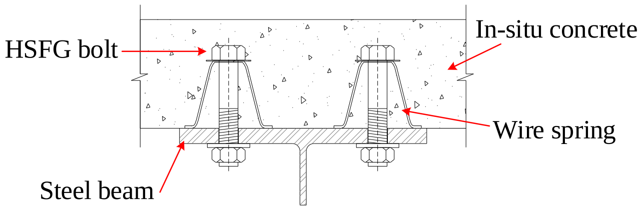

Figure 2: High-strength friction grip bolts tested by Dallam [9]

Dedic and Klaiber [2] conducted two sets of push-out tests on high-strength bolt shear connectors used for the reinforcement of existing bridges. In the first set of tests, they used bolts placed in the concrete holes, and then filled the holes with grout (Figure 3(a)). In the second set of tests, they studied bolts passing through concrete with grooves, and after tightening the bolts, they filled the grooves with grout (Figure 3(b)).

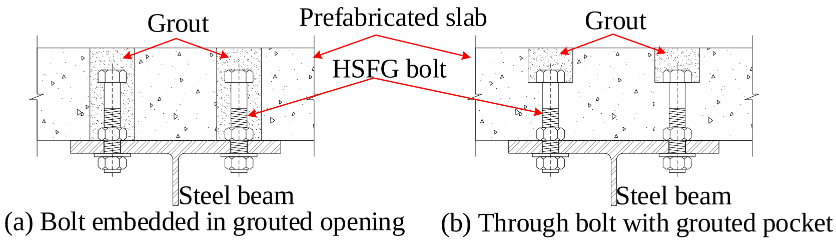

Figure 3: Bolted shear connectors tested by Dedic and Klaiber [11]

Schaap [3] conducted multiple push-out tests on post-tensioned shear connectors. In his paper, he discussed the behaviors of embedded bolts, friction-type bolts and anchor bolts (as shown in Figure 4). Kwon et al. [4], [5] continued to study this type of connection. They summarized the possibility of using post-tensioned shear connectors to reinforce existing non-composite steel bridges. They studied the shear connection performance under static and fatigue loads. They suggested using the following formula to calculate the shear bearing capacity of bolted shear connectors:

$$F_{v,R} = 0.5 \cdot f_{ub} \cdot A \quad (1)$$

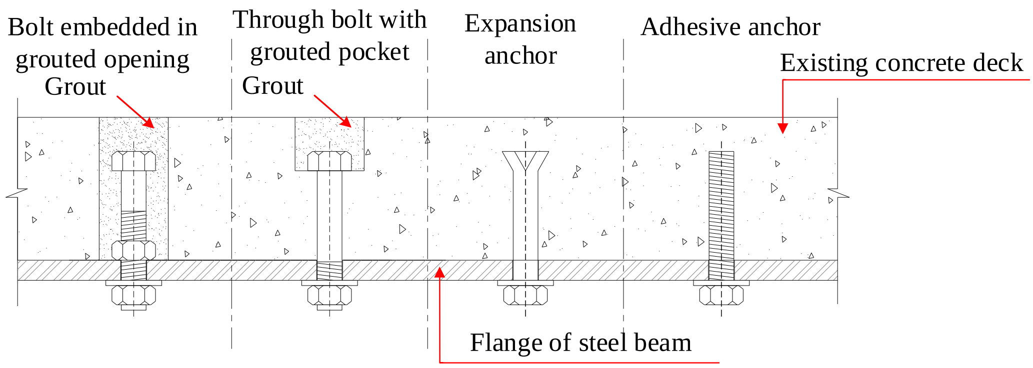

Figure4: Post-installed demountable shear connectors tested by Schaap [3] and Kwon et al. [4]

Through research, Chen [6] discovered that in the elastoplastic loading phase of shear-resistant connector using high-strength bolts with embedded nuts, external loads cause the embedded nuts to indent the top surface of steel beam flanges, forming pit indentations. This process generates metal cutting forces which can effectively resist connection slip. Based on these findings, the following calculation method for the shear bearing capacity of such connections was proposed:

$$F_u = F_c \le F_{EN} \quad (2.1)$$

$$F_c = 0.605 \phi_s A_b \sqrt{f_{cd} E_c} \quad (2.2)$$

$$F_{EN} = 1.25 \phi_s A_b f_u^{'} \quad (2.3)$$

Herein, F_u is the design shear capacity of the connection; F_c is the concrete-controlled partial design shear capacity; F_{EN} is the bolt-controlled partial shear capacity considering the cutting action between the nut and steel beam flange; ϕ_s is the partial safety factor for resistance. When the diameter-to-width ratio of the embedded nut is between 1.4 and 1.8, ϕ_s =1.0; otherwise, ϕ_s =0.76; A_b is the effective cross-sectional area of the bolt (mm^2); f_{cd} is the design value of concrete compressive strength (MPa); E_c is the elastic modulus of concrete; $f_u^{'}$ is the design value of the bolt material's tensile strength (MPa).

Pavlovic [7] conducted a study on the wrapped bolts. He carried out two sets of push-out tests with different bolt diameters (Figure 5). He used precast concrete components with openings for shear connections. After placing the floor components, these openings were filled with concrete. Based on the test results, he developed a numerical model and derived the following formula for determining the shear capacity of the studied shear connections:

$$P_{b,u} = a_b f_{ub} A_s, with\, a_b = 0.6(34/d)^{0.23} \quad (3.1)$$

$$P_{c,u} = 55 \cdot a_c \cdot d^{1.9} (f_{cm} \cdot h_{sc}/d)^{0.4} + 22000, with\, a_c = 22.5/(d+3) \leq 1.0 \quad (3.2)$$

Herein, P_{bu} represents the resistance of the bolt, f_{ub} represents the tensile strength of the bolt material, A_s is the shear area of the bolt, d is the diameter of the bolt, P_{cu} represents the resistance of the concrete, f_{cm} is the average compressive strength of the concrete cylinder, and h_{sc} is the height of the shear connection component.

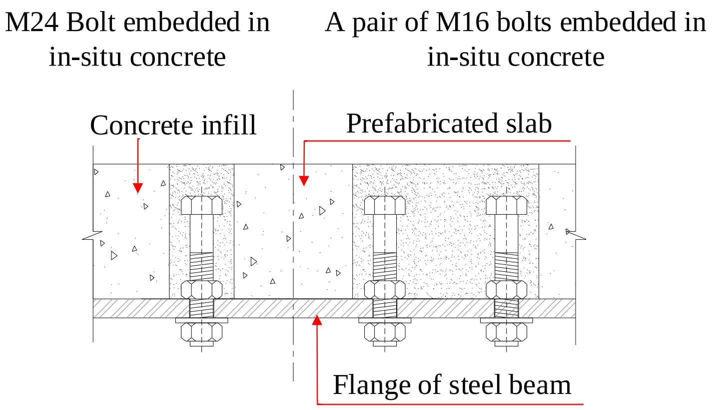

Figure5: Demountable shear connectors tested by Pavlovic [7]

Moynihan and Allwood [8] conducted tests on three different-length composite beams using M20 bolts as detachable shear connectors (Figure 6). Two of the beams were loaded to the service load, then unloaded, disassembled and reassembled to test the detachability and reusability of the system. Subsequently, all three beams were loaded until failure. They found that the performance of the longer specimens (5 meters and 10 meters) was similar to that of similar composite beams using welded shear connectors. The bearing capacity of the test beams was higher than the results calculated according to Eurocode 4 [9].

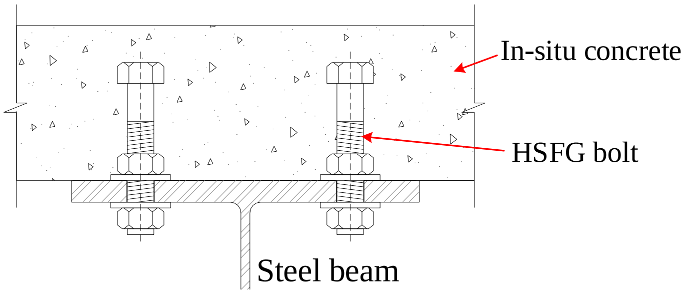

Figure 6: Demountable shear connectors tested by Moynihan and Allwood [8]

III. THROUGH BOLTSCONNECTOR

The earliest identified research on tests with through bolts was conducted by Marshall et al. [10] in 1971. He conducted eleven push-out tests and five beam tests on friction grip connectors. He observed that the friction coefficient was 0.45 between the precast slab and the steel beam, and it was possible to achieve full interaction under service loads.

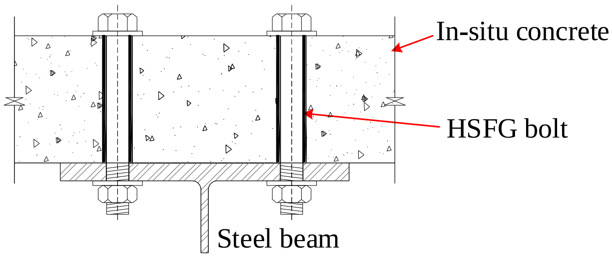

Figure 7: Bolted shear connection tested by Marshall [10]

Roik and Bürkner [11] investigated the friction coefficient between steel and prefabricated concrete decks in 1978. They conducted four types of tests: Group 1 used two 15 mm thick steel plates and two concrete elements. Group 2 had an identical test setup to Group 1 but with 10 mm thick steel plates.The test setup of Group 3was similar to the push-out test setup given by Eurocode 4 [9]. These testsconsisted of an IPE 300 steel profile and four prefabricated deck elements (Figure 2.10). Each of thedeck elements were connected to the steel profile by three pretensioned M16 bolts. These three test groups were subjected to a single load cycle in displacement controlled mode with a speed of 1 mm / min without unloading . Group 4 used identical specimens to Group 1 but it was subjected to a dynamic loading that included 3 million cycles with 10 Hz frequency. They tested different levels of pretension and found that the friction coefficient varied between 0.501 and 0.555.

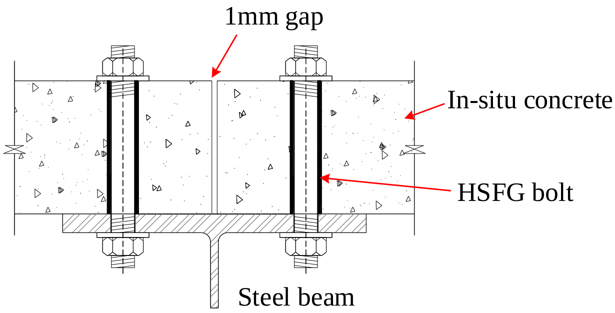

Figure 8: Friction connection tested by Roik and Bürkner [11]

Bürkner[12]inhisthesisinvestigatedcompositebeamswithheadedstudsexperimentallyand numerically. While reviewing the different shear connection systems he gave the following connection type as a possible shear connection for carparks:

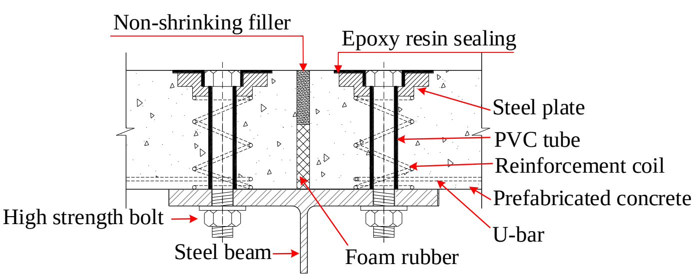

Figure 9: Demountable shear connectionfor carparks proposed by [12]

A similar system was developed by the company Krupp-Druckenmüller GmbH in Germany. Their system was called as the Krupp-Montex system [13] and was applied majorly in carparks in the 1970s. The schematic drawing of their system is presented in the following figure:

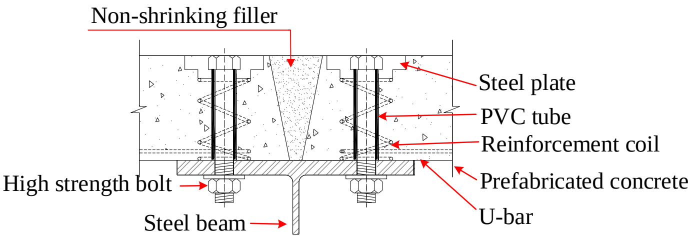

Figure 10: The Krupp-Montex system [13]

The research of Dedic and Klaiber [2], Schaap [3] and Kwon [4], [5] included tests on throughbolts;however, in these tests the pockets above the bolt head was filled with grout or concrete.

Therefore, these types of bolts are not accessible from the top of the deck after installation (seeFigure3andFigure 4). Chen et al. [14] conducted push-out tests using through bolts placed in PVC tubes (Figure 11). The test parameters included the bolt diameter, the level of the bolt pretension and thesteel-concrete contact surface properties.They observed that the ultimate shear capacity was similar to the one of welded studs, but the first slip occurred in a significantly lower load level. A mechanical model was proposed to predict the ultimate capacity. Afterwards, a finite element model was built to investigate the behaviour of demountable composite bridge girders using the proposed demountable connectors.

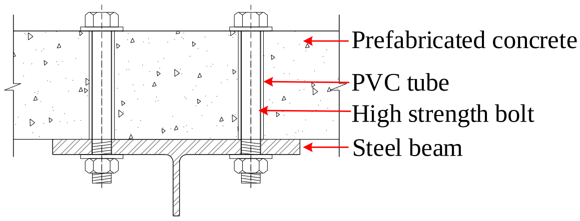

Figure 11: Through bolts tested by Chen et al. [14]

They gave the following equation for the bolt shear resistance:

$$V_R = (k_s \cdot sin\,a + cos\,a)\cdot T_{tot} + 0.6 \cdot A_b \cdot f_{ub} \cdot \sqrt{1 - \left(\frac{T_{tot}}{A_b \cdot f_{ub}}\right)^2} \quad (4)$$

Where ksis the friction coefficient, the first part of the equation is the contribution of the friction, α is angle of the bolt measured from its original axis after deformation, T_{tot} is the sum of the bolt pretension and the tension due to connection slip, A_b is the area of the bolt and f_{ub} is the ultimate tensile strength of the bolt. In this formula the first part represents the contribution of the friction to the load bearing capacity. This contradicts the findings of Pavlovic [7] who pointed out that the pretension force and the friction resistance do not influence the load-bearing capacity.

Through bolts used as demountable shear connectors were tested extensively at the University of NewSouth Wales by Lee and Bradford [15], Ataei et al. [16], [17] and Liu et al. [18], [19]. The shearconnection was similar to the ones tested by Marshall et al. [10] (Figure 7). They conducted severalpush-out tests [16], [17] on high strength friction grip bolted shear connectors and found that the load- slip behaviour can be divided into three distinct parts.

1)First, there is full interaction between the steel and the concrete until the friction resistance is overcome.

2Second, bolt slip occurs until the bolt become in contact with the inner surface of the bolt hole.

3)Third, bearing and shear deformationtakesplaceuntiltheultimateshearcapacityis reached.

IV. SUMMARY

During the past period, many researchers have developed and studied HSFG shear connectors. Although all the solutions reviewed previously are beneficial for the disassembly process, the degree of their reusability varies. The main focus often lies only in the reusability of the steel beams, without considering the reusability of the concrete slabs.

For example, when using embedded bolts and studs (refer to Figures 2.7 and 2.8), the bolts protrude from the slab surface. This makes them vulnerable to damage during operation, transportation, and storage. If the threads are damaged, since these bolts embedded in the concrete cannot be replaced, the reusability potential of the slab is lost, and thus the slab cannot be reused. If using through bolts (Figure 2.13), they are easier to replace, and thus more preferable in terms of reusability. However, their manufacturing is a more complex task. If the slab is precast, special attention to tolerances is required. Moreover, when using friction-type high-strength bolts, creep and shrinkage will cause the preload loss in the bolts. BS 5400-5 [20] mentions that this effect should be considered, but does not elaborate on how to consider it.

Regarding the load-slip behavior, the pre-tightened through bolts (friction-type high-strength bolts) behave differently from traditional welded studs. Their behavior can be divided into three different parts: a rigid part before overcoming the friction resistance, representing the more or less horizontal part of the bolt sliding in the bolt hole, and a linear or non-linear part caused by shear and compressive deformation. On the other hand, embedded bolts and studs reach the ultimate load when the relative slip is about 1-2 mm, and can maintain this load level at least within a 6 mm slip range. This means that among the studied detachable shear connectors, this is the only type that behaves similarly to welded studs.

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