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SHEAR BEHAVIOR OF NOVEL DEMOUNTABLE BOLTED SHEAR CONNECTOR FOR PREFABRICATED COMPOSITE BEAM

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ABSTRACT

Bolted shear connectors offer alternatives to achieve steel-concrete composite action instead of conventional welded headed studs especially for prefabricated constructions and demountable composite structures. This paper firstly proposed a new type of demountable steel-concrete bolted shear connectors based on the double-nut friction-grip high strength bolted connector, which modify the upper nut into conical locking nut. This paper performed ten full scale push-out tests to study shear behaviors of the developed new type of connectors. Testing parameters included bolt configuration, strength, diameter of bolts and strength of infilled grout. Test results indicate that shear behaviors and slip capacity of the conventional bolted connectors are significantly improved when the bolted connector incorporating with conical locking nut. The influences of these studied parameters on shear behaviour of novel bolted shear connectors are revealed and discussed. The developed novel demountable connector exhibits an average 25% improvement in ultimate shear resistance over conventional bolted connectors. Moreover, the shear stiffness of the developed bolted connectors is about six times of the conventional bolted connector through eliminating the clearance between steel flange hole and bolt shank.

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1. Introduction

Owing to the combined advantages of steel tension and concrete compression, steel-concrete composite structures (SCCSs) becomes popular and put into use in civil engineering constructions. The steel-concrete composite action in SCCSs is usually achieved using shear connectors. Various kinds of connectors have been proposed for SCCCs among which welded headed studs may be the most widely used type of connector due to easy installation, high capacity and low cost. However, considering the sustainability of steel-concrete composite structures such as steel frame with decking floor slab and bridges with steel-concrete composite girders, replacement, rehabilitation or strengthening needs to exerting to extend their service life. The composite structural components with embedded welded headed stud shear connectors will face challenge due to their difficult removal and recycle use in the reconstruction process.

In comparisons with traditional welded headed studs, post-installed high strength bolts exhibit more advantages of easy disassembling and rapid replacement of the concrete parts. Such bolted connectors can extend the life cycle and improves the sustainability of SCCSs. Moreover, bolted connectors exhibit more significant advantages of shortened construction period, reduced labor force for casting on site, improved construction quality, and savings on constructional costing for prefabricated constructions. Therefore, researches on shear performance of bolted connectors are important for in-depth understanding on structural behavior of prefabricated steel-concrete composite members.

Dedic and Klaiber [1] carried out push-off tests to study mechanical behavior of high strength bolts. Kwon et al. [2] conducted push-out tests on post-installed bolt connectors (PIBCs), and found that they exhibit higher fatigue resistance than welded headed studs. Kwon et al. [3] proposed a strengthening strategy for non-composite bridge girder using PIBCs, and their strengthening effectiveness was confirmed through five full-scale beam tests. Pavlović et al. [4] proposed high-strength friction-grip (HSFG hereafter) bolts for prefabricated composite structures and examined the shear performance of M16 and M24 HSFG bolts by push-out tests. Moynihan and Allwood [5] conducted static loading test for composite beam using M20 HSFG bolts, to investigate their mechanical performance. Dai and Lam [6] developed a novel type of bolted connectors through machining headed studs that achieved about 84% ultimate shear resistance of welded headed studs. Moreover, it achieved a slip capacity of more than 6 mm as observed in the corresponding push-out tests. Liu et al. [7] studied the mechanical behavior of HSFG bolts in composite beam with precast slabs. The load-slip behavior of bolted connector showed identified three distinct stages with excellent shear behaviors. Ataei et al. [8] further investigated structural performances of composite beam using bolted connectors developed by Liu et al. [7]. Ban et al. [9], Henderson et al. [10,11] and Pathirana et al.[12] contributed to structural behaviors of composite beams using blind-bolt type of connectors. They observed that compared with welded headed studs, blind bolts offered comparable composite actions to SCCSs. Yang et al.[13] performed push-out tests to investigate shear behaviors of novel demountable bolted connectors. Their test results showed that the shear stiffness of their novel bolted connectors was significantly affected by the shank-hole clearance of bolts.

2. The development of locking nut shear connectors

Nonetheless, it should be noticed that all the previous tests on HSFG bolted connectors exhibit an unfavorable large early stage slip. Such bolts sliding occurs inside the bolt holes as the acting shear load exceeds the slab-steel beam interfacial friction resistance. Therefore, although Eurocode 4 [14] includes HSFG bolts type of connectors, restrictions are imposed to prevent the fully exploitation of their shear resistance. Johnson and Buckby [15] suggested that for friction-grip bolts, their shear resistances should be limited by the friction resistance if they are used as shear connectors. To overcome such problem of the friction-grip bolts as shear connector, Suwaed et al. [16] proposed a locking nut shear connector (LNSC hereafter) as shown in Fig.1. In the proposed LNSC, a special conical locking nut configuration, restricting the slipping of bolts within the holes, is adopted to connect the bolts to beam flange. In addition, in the locking nut shear connectors, the two ends threaded bolts with conical locking nut work with precast concrete plugs and plate washers. Pretension load is applied to the bolts shank between the lower No. 1 nut and the upper conical locking No. 2 nut to fasten the bolt as shown in Fig.1, and also applied to the bolts shank between Nut 3 and Nut 2 to produce friction resistance between the steel beam flange and the precast concrete plugs.

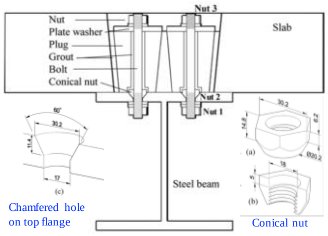


Fig. 1 Cross section of composite beam using locking nut shear connectors [17]

Suwaed et al. [17] carried out push-out tests to investigate the shear behavior of novel LNSC. Their test results showed that the shear resistance, shear stiffness, and slip capacity are much higher than welded headed studs. However, although the shear performance is proved to be satisfactory, yet the configurations, which includes too many components and are rather complicated for on-site assembly.

This paper proposed a simplified application of the LNSC for steel-precast concrete composite beam as shown in Fig. 2. In such application, the configurations of grout plug, slab pockets and plate washer are not included, only the bolted connector with conical locking nut and the chamfered countersunk seat on beam flange remains. Briefly speaking, the LNSCs are proposed to substitute HSFG bolted connectors in the steel-precast concrete composite structure.

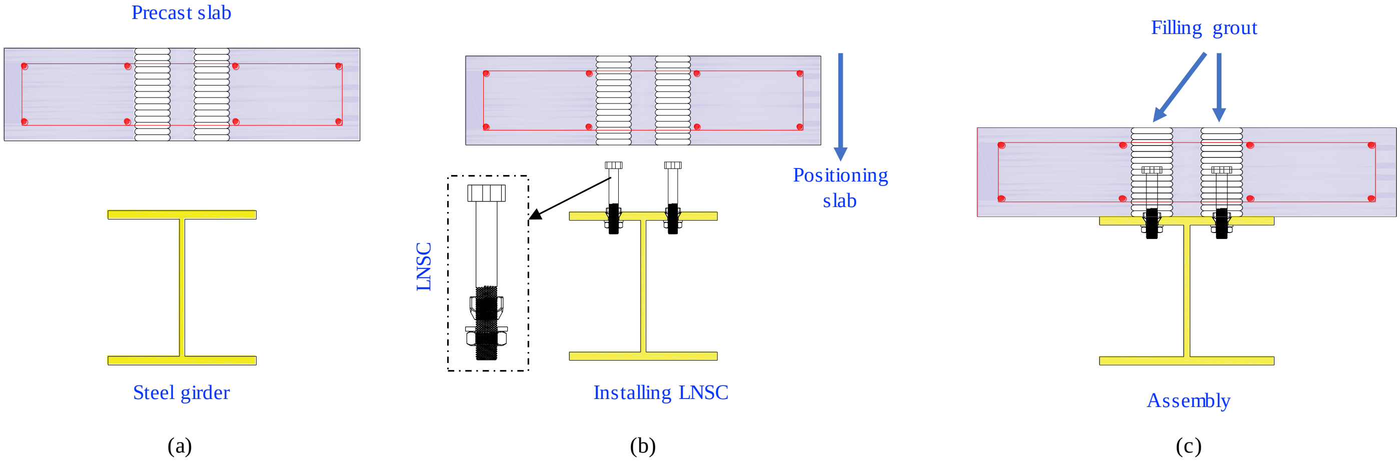


Fig. 2 Assembly of steel-precast concrete composite beam using LNSC

The LNSC is expected have several advantages against conventional HSFG bolt connector, which are: (1) larger shear stiffness due to the elimination of bolt slip between bolt shank and bolt hole; (2) larger shear capacity due to the shear contribution from the conical nut; (3) more favorable shear-slip behavior as shear connector; (4) require lower pretension load to fasten the bolted due to its locking nut mechanism.

Nonetheless, the mechanical behavior of LNSC connects steel beam and precast slab, with embedding in preformed hole filled with grout, has not been investigated through experimental study. The main purposes of this study are to check the shear performance of bolted connector post-installed in steel-precast concrete composite beam, with the configurations of locking conical nut and chamfered countersunk seat.

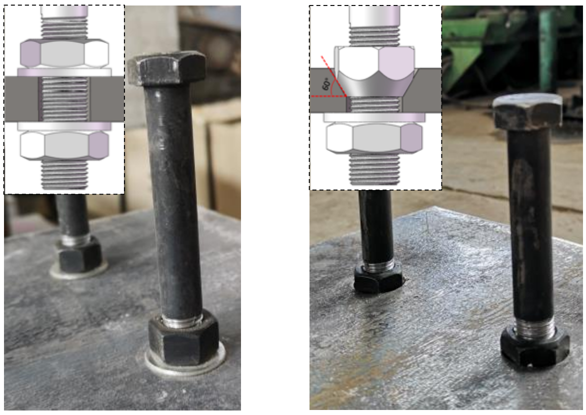
3. Details of push-out test specimens

3.1. Bolt configuration

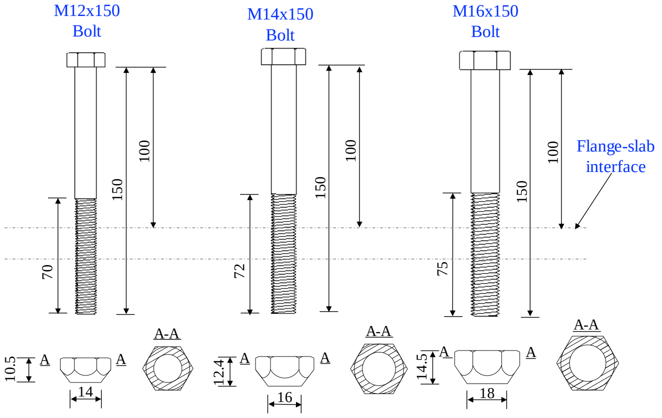
Fig. 3 shows the configuration for the conventional HSFG bolt and the novel demountable LNSC, and geometric details of novel bolted connectors installed to the steel beam flange in the test specimens.

As shown in Fig.3a, the conventional HSFG bolted connection consist of a bolt shank with thread and an upper hexagonal nut, an upper washer, a lower washer, and a lower hexagonal nut. Between the upper and lower nut, preloading was applied to fasten the bolted connectors to underneath steel beam.

The novel demountable LNSC bolted connector is proposed on the basis of the HSFG bolts, with the root of upper nut in the conical shape. The bolts are with threads in a length of 70 mm at in one end. The bolts are installed to the flange of steel beam through the two clapping nuts as shown in Fig.3(b). The upper part of bolt hole is a countersunk seat with chamfered sides in 60-degree to horizontal direction, as shown in Fig.3(b). The upper conical nut is modified on the basis of a standard hexagonal nut, with the lower part machined in to conical shape following the same 60-degree angle to fit the bottom countersunk seat in the flange of beam. Thus, the upper conical nut restrains the bolt within the countersunk seat. While the lower part of conical nut fits into the chamfered hole, the upper part of conical nut appears above the top surface of the beam flange with a height of a few millimeters. Such upper part of conical nut appeared above the flange-slab interface is expected to play a role similar to welded collar of headed stud shear connectors, the positive effect of which on shear resistance have been reported by many experimental and numerical studies. The lower hexagonal nut is used along with a hardened washer [see Fig.3(b)]. Pretension is applied to bolts between the upper conical nut and the lower hexagonal nut by fastening the lower nut using a torque wrench.



(a) Configurations of HSFG bolt (b) Configurations of LNSC bolt



(c) Dimensions and details of the bolted connectors

Fig. 3 Configurations and dimension of bolted connectors

Bolts with nominal diameter of M12, M14 and M16 were selected as bolted connectors for the push-out tests as depicted in Fig.3(c). The height of bolted connector is 150 mm with varying length of threads of 70 mm, 72 mm and 75 mm. All the embedded length of bolts in the concrete slab is 100 mm. The dimensions of nut vary when the corresponding nominal diameter of bolts changes from 12 to 16 mm. The height of M12, M14 and M16 bolt nuts are 10.5, 12.4, and 14.5 mm, respectively. The inclined angle of the conical part of the upper nut is a 60-degree angle. The lower part of the conical nut is grinded following such 60-degree angle till the external diameter of the lower end of nut is 2 mm larger than the nominal diameter of the corresponding bolt.

The pretension load, which represents 20% of its ultimate tensile resistance is applied between the upper conical nut and the lower hexagonal nut using a torque wrench. By applying such pretension load, a robust locking configuration is ensured, and bolts from slipping within the bolt hole can be prevented. It should be noticed that, the applied pretension load is relatively low when compared to that of 70% of its ultimate tensile capacity, which was adopted in LNSC application suggested by Suwaed and Karavasilis[17]. Such relatively low pretension load is determined based on the following consideration. According to experimental study and numerical analysis by Pavlović et al. [4], it was not found any influence on shear resistance for pretension load up to 100% of the ultimate tensile capacity. Therefore, bolt preload does not have significant influence on the shear resistance when the failure mode is shear-off of bolt shank.

The ultimate tensile strength of bolted connectors was obtained from uniaxial tensile tests. The ISO bolt grades, ultimate tensile resistance, the gross diameter for bolt shank and effective diameter for bolt thread part, for each group of high strength bolts are summarized in Table 1. It reflects that, the gross diameter is slightly smaller than nominal diameter of bolts, and effective sectional area in thread region of bolts to its sectional area out of thread region equals to about 0.8. The tensile strength is calculated by dividing the tensile force to the effective area.

Table 1
Tensile strength and dimension of bolts

Bolts group	Tensial resistance（kN）	Gross diameter (mm)	Effective diameter (mm)	Effective area/Gross area	Tensile strength (MPa)
M12 (8.8)	91.0	11.86	10.08	0.83	1140.3
M14 (8.8)	124.4	13.88	12.12	0.76	1078.3
M14 (10.9)	146.2	13.88	12.08	0.76	1308.8
M16 (8.8)	169.7	15.78	14.14	0.80	1012.5

3.2. Specimen details

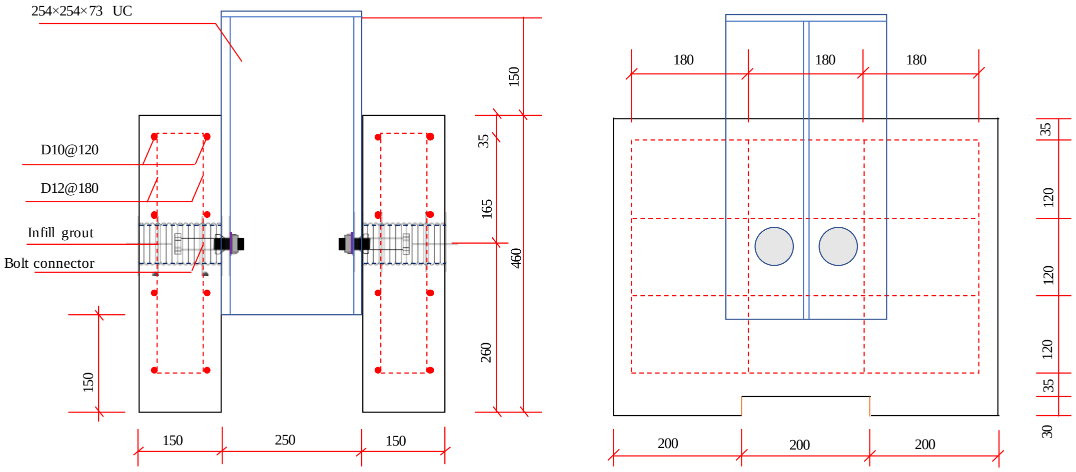


Fig. 4 Geometric configuration of push-out test specimens (unit: mm)

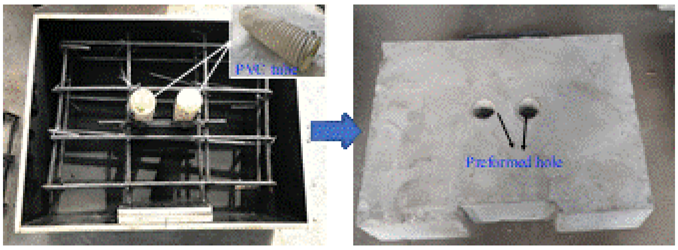
3.2. Specimen details

Totally ten push-out specimens were fabricated with different parameters and divided into five groups as summarized in Table 2. The tested parameters are diameter of bolts (M12, M14 and M16), bolt configuration (conventional HSFG bolts and novel demountable bolts), steel grade of bolt (grade 8.8 and grade 10.9), and the strength of infilled grout. Each push-out specimen consists of a steel beam segment with 254 × 254 × 73 UC section and two precast concrete slabs (see Fig. 4). The dimensions of all the test specimens are the same following EN 1994-1-1. The length, width and thickness of the precast concrete slab are 460, 600, and 150 mm, respectively. Each precast concrete slab was cast with two preformed holes using PVC corrugated tube, which is 50 mm in diameter and 1.5 mm in thickness. Steel reinforcements for concrete slabs were designed accordingly to Eurocode 4. The precast concrete slabs were all cast in a horizontal position.

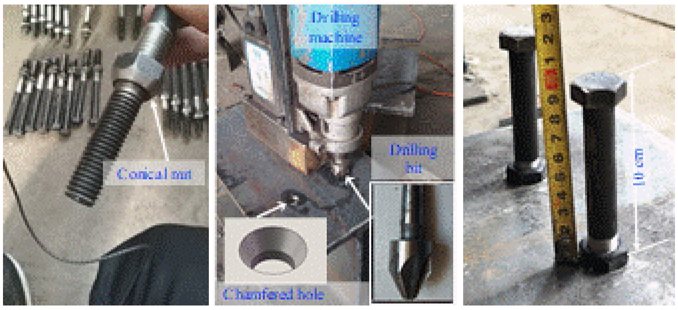
Table 2
Parameters of push-out specimens

Group	Specimen	Diameter of bolt (mm)	Strength grade	Bolt configuration	Grade of infilled group
SP1	SP1-1	14	Grade 8.8	Conical nut	C50
	SP1-2				C90
SP2	SP2-1	12			C50
	SP2-2				C90
SP3	SP3-1	16			C50
	SP3-2				C90
SP4	SP4-1	14	Grade 10.9		C50
	SP4-2				C90
SP5	SP5-1	14	Grade 8.8	HSFG bolt	C50
	SP5-2				C90

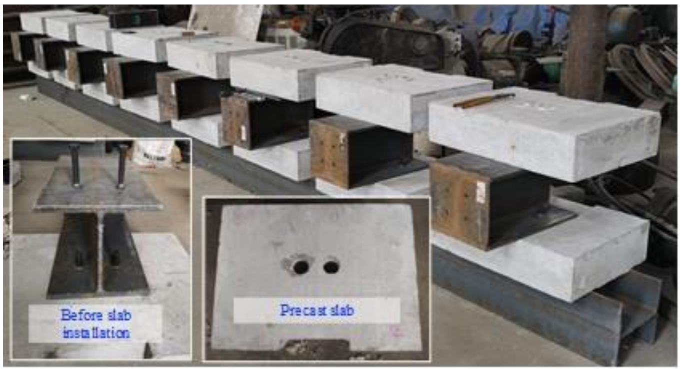
Fig. 5 illustrates key steps of the prefabrication of specimens, which includes machining of conical nuts on the basis of the standard hexagonal nut, drilling chamfered holes on beam flange, positioning and fastening the bolts by the locking nut configuration, as well as casting concrete slabs with performed holes, were performed in the workshop. After fabrication of all these components, the assembly of the steel beam and precast concrete slabs was performed. First, a pair of bolts were installed on the top flange of beam. Each precast slab is installed on the top of steel beam to make sure its opening geometric center coincide with the center of two installed bolts. Fast-hardening infilled grout is then poured into the preformed holes in precast slab. After seven-days hardening of the grout, the specimens was turned up-side-down, and the same assembly procedures were implemented between the precast concrete slab and the steel beam at opposite side. Hardening of infilled grout completes the whole fabrication process of the push-out specimen.



(a) Casting of precast concrete slab with preformed hole



(b) Machining of conical nut, drilling chamfered hole and bolt positioning



(c) Assembling of specimens

Fig. 5 Fabrication of specimens

The design mixes for the concrete slabs and the grout are given in Table 3. The grout used to fill the preformed holes are commercial cementitious grout with nominal strength of C50 and C90. The material properties of the concrete slab, infilled grout and steel beam were evaluated. Cylinder specimens for concrete and grout, with a 100-mm diameter and 200-mm height, were used to obtain the respective compressive strength. The elastic modulus, tensile strength and characteristic compressive strength were calculated based on ACI 318-08 [18].

Table 3
Typical Mix proportions and material strength for slab and grout

Material	Slabs	Grout C50	Grout C90
Cement (kg/m3)	432	-	-
Water (kg/m3)	168	-	-
Sand (kg/m3)	558	-	-
Gravel (kg/m3)	1242	-	-
Compressive strength (MPa)	42.3	49.8	95.1
Tensile strength (MPa)	3.2	2.6	4.5

3.3. Test setup and measurement

Fig. 6 shows the setup and instrumentations of push-out tests. The specimen was installed on a rigid base and tested by a loading machine with a capacity of 5,000 kN. The displacement load was applied to the top end of I-beam. Vertical displacements of loading end of specimens were measured by two linear variable displacement transducers (LVDTs) as shown in Fig. 6. Four LVDTs attached to the concrete slab, with two LVDTs in the front and back, measured concrete slab-steel beam interfacial slips. The precision of the LVDTs is 1/1000 mm.

During the test, the uniaxial displacement-controlled load was applied to the specimen with a speed of 1/10 mm/min. The load-slip behavior was measured until the applied load was reduced to 20% of the obtained maximum load.

Fig. 6 Test setup and instrumentation

4. Test results

4.1. Failure mode

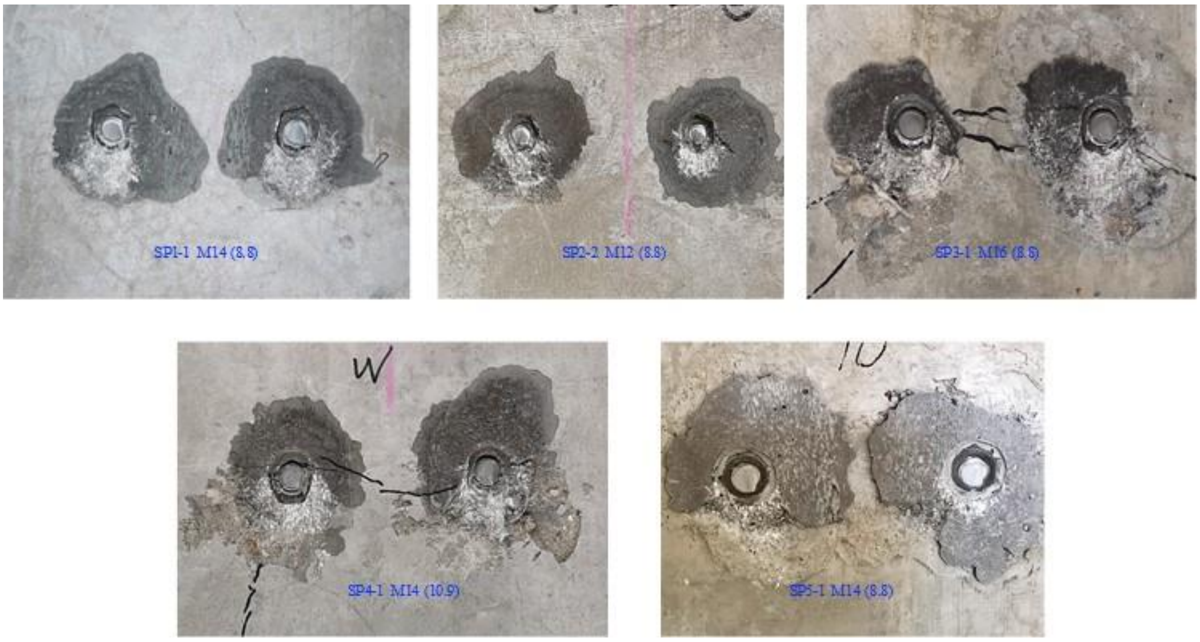
Failure modes of all the five groups of push-out specimens were shearing of bolts directly from the I-beam at the threaded portion of bolts. As shown in Fig.7(a), the specimens with LNSC all exhibit bolt shear off at the section right above the upper conical nut; meanwhile, in the specimens with conventional high strength friction grip bolts the shear off section locates at right below the upper hexagonal nut, aligning to the interface between the top flange and the concrete slab.

Fig. 7(b) illustrates the damage on concrete slab of tested specimens. It can be noted that only minor spalling occurred to slabs without global cracking or splitting. The local spalling of concrete occurred mainly within the region of infilled grout surrounding the bolt. The chamfered hole on steel flange sustained the shear force transferred through the conical nut during the push-out loading.

Fig. 7(c) illustrates the local deformation of chamfered hole after removing the fractured bolted connector. It shows that no obvious deformation occurred to the steel around the chamfered hole in the specimens SP1-1 with M14 bolts (grade 8.8), while slight local deformation in front of chamfered hole can be found in the specimen SP3-1 with M16 bolts (grade 8.8), which had developed the largest shear capacity among all the tested specimens.


SP1-1M14 (8.8)
SP2-1M12 (8.8)
SP3-2 M16 (8.8)
SP4-2 M14 (10.9)
SP5-1M14 (8.8)

(a) Bolted connector after shearing off



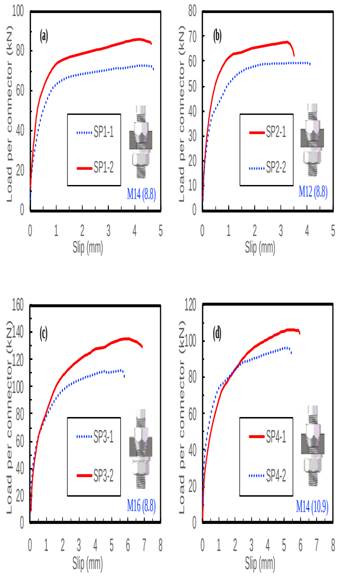
(b) Damage on concrete slab

(c) Steel beam flange after removing failure bolts

Fig. 7 Failure modes and damages of specimens

4.2. Shear-slip relationship curves

Fig. 8(a)~(e) plots the load-slip curves of tested specimens. The curves in each sub-figure are obtained from the test results of specimens varied only in strength of infilled grout, grade C50 for the first series (denoted with '-1' in the nomination of specimen) and grade C90 for the second series (denoted with '-2' in the nomination of specimen). The load of single connector was obtained through dividing the total measured force over total number of connectors, while the relative slip between the slab and steel flange was obtained by taking average of the measured values from the four LVTDs.



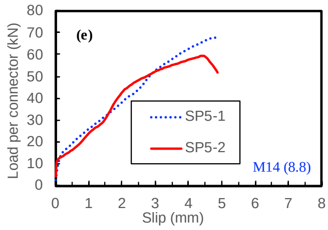


Fig. 8 Shear-slip curves for push-out specimens

Test results including the shear resistance, the ultimate slip capacity, and the shear stiffness are summarized in Table 4. The shear stiffness (K) for each bolted connector is defined as the ratio of 70% of the shear resistance (Vu) to its corresponding slip value sk [19] as specified in Clause A.3(3) of EN 1994-1-1.The shear resistance V_u and the slippage corresponding to $0.7V_u$ are obtained from the tested shear-slip relationship curves. The results are discussed in the following sections.

Table 4
Summary of push-out test results

Spec.	V_u(kN)	T_u(kN)	V_u/T_u	s_u(mm)	$0.7V_u$(kN)	s_k(mm)	K(kN/mm)
SP1-1	72.8	124.4	0.585	4.73	50.94	0.521	97.9
SP1-2	86.1		0.692	4.64	60.26	0.473	127.5
SP2-1	59.2	91	0.651	4.17	41.41	0.413	114.3
SP2-2	67.4		0.741	3.50	47.19	0.546	75.8
SP3-1	111.6	169.7	0.658	5.78	78.09	1.006	77.6
SP3-2	135.7		0.800	6.89	94.98	1.386	68.5
SP4-1	96.4	146.2	0.659	5.44	67.47	1.286	57.6
SP4-2	105.9		0.724	5.96	74.12	0.737	91.5
SP5-1	67.6	124.4	0.543	4.92	47.3	2.692	17.6
SP5-2	59.5		0.478	4.88	41.65	1.952	21.3

5. Discussions

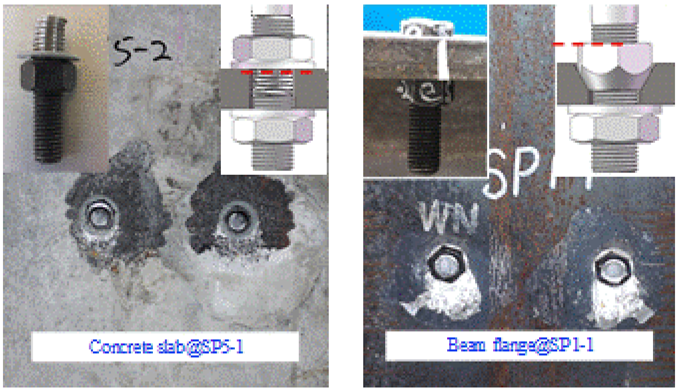
The main test parameter included configuration of bolted connector (with/without conical nut), diameter, strength of bolts, and compressive strength of infilled grout. The effects of these parameters are discussed below.

5.1. Effect of the strength of infilled grout

For the specimens using bolted connector with conical locking nut, as shown in Fig.8(a)~(d), it can be noticed that the specimens with higher strength of infilled grout developed larger shear resistance, it may owe to the fact that stronger grout around the bolted connector provided larger confining effect to the connector, thus increased the ultimate shear capacity. Fig.8(e) compares the shear-slip curves of specimens SP5-1 and SP5-2, in which the conventional HSFG bolts were used, it can be found that using stronger infilled grout did not increase the ultimate shear capacity. Nonetheless, the ultimate relative slip does not seem to be relative with the strength of the infilled grout.

5.2. Effect of the bolt configuration

Two types of configuration of bolted connector, conventional bolt with single nut embedded in slab and novel bolt with conical locking nut embedded in slab and chamfered hole on steel flange, are used in specimen group SP1 and SP5, respectively. The bolt shear off locations for different shear connectors are compared in Fig.9. The shank of HSFG bolt shear off at the cross-section along the beam flange-concrete slab interface, while the shank of LNSC bolt shear off at the cross-section right above the conical locking nut. As show in Fig.7, after the shank shear off, the end part of the HSFG bolt and the lower nut detach from the concrete slab and steel beam flange; while in the LNSC bolt, after the shank shear off, the conical locking nut and the lower nut still fasten to the beam flange, and crushed infilled grout remain in front the of conical locking nut, which indicates that the conical locking nut have sustained large load from the surrounding infilled grout.



(a) HSFG bolt specimen (b) LNSC bolt specimen

Fig. 9 Comparison on bolt shear off locations

The load-slip curves are compared in Fig.10. The curves for the two configurations are significantly different. The specimens with conical locking nut exhibit a shear-slip relationship with much larger initial stiffness and more than 25% larger shear resistance than the specimens with conventional bolt configuration. This is a favorable mechanical property for shear connector used in composite structural element, since it avoids the drawbacks of the conventional bolted connector that its shear stiffness is very sensitive to the clearance between bolt shank and flange hole [13].

As shown in Table.4, the average shear stiffness of specimens SP1-1 and SP1-2 is 112.7 kN/mm, while the average shear stiffness of specimens SP5-1 and SP5-2 is 19.4 kN/mm. The shear stiffness of specimens with the developed novel demountable bolted connectors is about 600% of that of specimens with conventional HSFG bolted connectors.

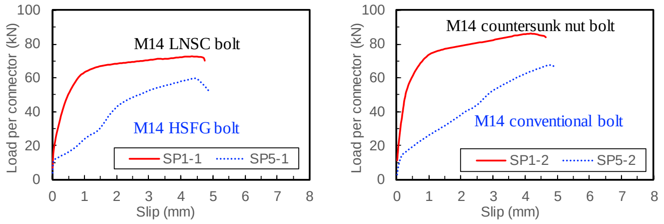


Fig. 10 Specimens with different bolt configurations

5.3. Effect of the diameter of bolt

Shank diameter is a critical parameter for shear capacity of shear connector. Specimens with different nominal bolt diameters, 12 mm, 14 mm and 16 mm, are compared in Fig.11. The shear capacity as well as the ultimate slip increase as the bolt diameter increases. The effective cross section area of M16 bolt and M14 bolt are 1.71 and 1.26 times of that for M12 bolt, and 1.86 times and 1.36 times of shear capacity were developed in the M16 bolt and M14 bolt.

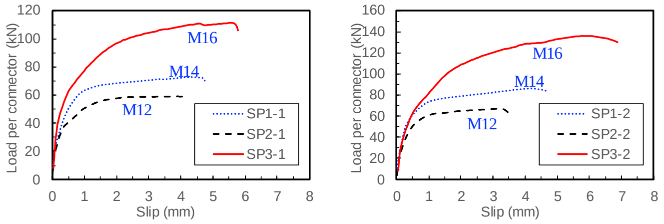


Fig. 11 Specimens with different bolt diameter

5.4. Effect of the strength of bolt

The effect of bolt strength is verified by adopting different grades of bolts for the bolted connector, which are grade 8.8 and grade 10.9. Specimens with grade 10.9 bolted connector developed about 25% larger shear capacity than those with grade 8.8, as shown in Fig.12. It can be also found that specimens with higher bolt strength shown larger ultimate slip, this is because of the reason that bolted connector with higher strength caused larger plastic deformation to the surrounding grout thus the connector can deform more before its final sheared off.

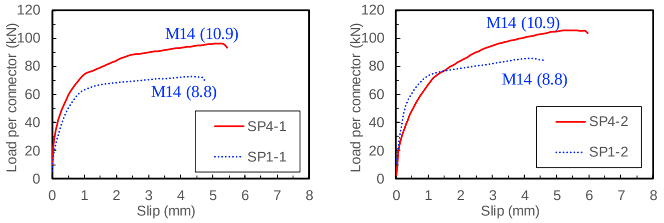


Fig. 12 Specimens with different bolt strength grades

6. Analysis on shear behavior of novel bolted connectors

6.1. Shear resistance

The test results showed that for novel bolted connectors, their shear resistances relate to their diameter, strength of bolt, and strength of surrounded grout/concrete. The specific design equation for the shear resistance of bolted connector is not yet available, and design guidance for shear resistance of welded headed studs is used to predict the shear resistance of bolt. The design equations for shear resistance of welded headed shear connector are available in Eurocode 4 [20] and other design specifications such as ANSI/AISC 360[21], AASHTO [22].

The shear resistance of single welded headed stud in Eurocode 4 is given as below.

$$V_u = \min\,(V_{u,s}, V_{u,c}) \tag{1}$$

$$V_{u,s}=0.8f_u(\pi d^2/4)=0.8T_u \tag{2a}$$

$$V_{u,c}=0.29d^2\sqrt{E_c f_{ck}} \tag{2b}$$

where f_u is ultimate strength of the stud, MPa; f_{ck} is characteristic cylinder strength of the concrete, MPa; d is diameter of stud, mm.

A number of design engineers used the Equ. (1) and (2) to predicting the shear resistance of bolted connectors. Kwon et al. [3] conducted several experimental studies on high strength friction grip bolts in steel-concrete composite structures. According to their test results, it is found that the ultimate strength of HSFG bolts is dominated by shear fracture of the bolt shank. The ultimate strength is given as:

$$V_{u,s}=0.5T_u \tag{3}$$

where T_u is the tensile resistance of the bolted connector, the corresponding values for the tested specimens in this paper are summarized in Table.1.

The predicted results calculated using the aforementioned Equ. (1) and (3), are compared to the tested results on shear capacity in Fig.13(a) and Fig.13(b). As shown in Fig.13(a), when the ratio of V_u/T_u is 0.8 (Equ.(1), for welded headed stud), the predicted results is generally overestimating the shear capacity and the maximum relative error is 36%; while the ratio of V_u/T_u is 0.5 (Equ.(3), for HSFG bolts), the predicted results is underestimating the tested results by a maximum relative error of 32%.

Since the none of two ratio of V_u/T_u, 0.8 and 0.5, is capable to provide satisfactory prediction for the shear capacity. A compromise is made by modifying the ratio of V_u/T_u to 0.65, which is the average of 0.5 and 0.8. The shear capacity is given as followings:

$$V_u=0.65T_u \tag{4}$$

The comparison is shown in Fig.13(c), the coefficient of variation is reduced to 0.08 and the maximum relative error is reduced to 19%. It should be noted that the maximum relative errors for nine out of ten specimens are smaller than 10%.

According to the test results, the strength of infilled grout has siginificant effect on the shear resistance of the novel demountable bolted connector, even though all of the specimens failed in bolt-shank shear off. Equation (4) can provide acceptable predictions on shear capacity for practical design with certain conservation; however, the formula is determined only by the tensile strength and the dimensions of the bolt shear connector, while the effect of strength of the infilled grout can not be considered. To provide a more reasonable prediction formula for the novel bolted connector, the shear resistance is assumed to be the sum of shear capacity of the bolt shank and the bearing force sustained by the conical locking nut portion embedded in the infilled grout.

Luo et al. [23] proposed an empirical equation to evaluate the shear resistance of welded headed stud embedded in ultra-high performance concrete (UHPC) by considering the contribution of welded collar portion at the root of the headed stud. The ultimate shear capacity is given as:

$$V_{u,s}=0.5T_u+\eta f_c' D h_c \tag{5}$$

where $0.5T_u$ is the shear capacity of high strength friction grip bolts when the failure mode is bolt shank shear off; $\eta f_c' D h_c$, represents the contribution of the bearing force imposed to the collar portion, from surrounding concrete; η is empirical coefficient considering the tri-directional confining effect that increase the concrete strength, η=2.5 for high strength concrete is suggested by Luo et al.[23]; f_c' is the compressive strength of concrete in the vicinity of the shear connector, for the tested specimens in this paper, f_c' is the compressive strength of the infilled grout; D is the equivalent diameter of the collar portion for the hexagonal nut; h_c is the height of the conical nut referring to the top flange upper surface.

The comparisons between predicetd and tested results are shown in Fig.13(d). When the contribution of the conical locking nut is considered, the predicted result match well with the tested results, with the maximum relative error within 10% and the coefficient of variation (COV) of 0.06.

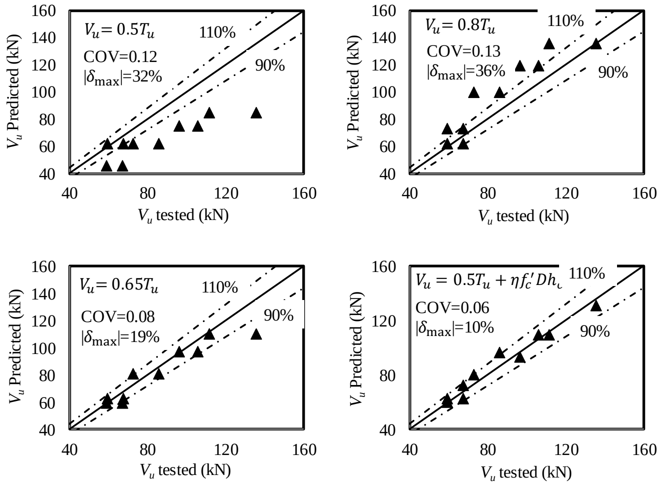


Fig. 13 Comparisons between tested and predicted results on shear capacity

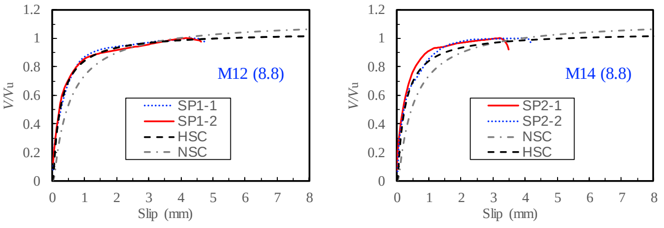
6.2. Characteristic load-slip response

The novel bolted connectors exhibit similar shear-slip relationship curves to that of conventional welded headed stud. One of the most widely used empirical formulas to simulate the shear-slip relationship curves of welded headed studs were proposed by An and Cederwall [24]. The expressions are given by Equ.(6) for welded headed stud embedded in normal strength concrete (NSC), and given by Equ.(7) for those embedded in high strength concrete (HSC), respectively.

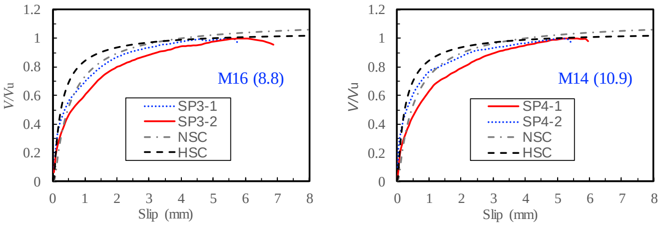
$$\frac{V}{V_u}=\frac{2.24(s-0.058)}{1+1.98(s-0.058)}\quad \text{（NSC）} \tag{6}$$

$$\frac{V}{V_u}=\frac{4.44(s-0.031)}{1+4.24(s-0.031)}\quad \text{(HSC)} \tag{7}$$

where s in mm, is slip of the welded headed stud. The measured shear-slip relationship curves obtained from the tests are compared to the above two empirical curves in Fig.14.



(a) M14 (8.8) (b) M12 (8.8)



(c) M16 (8.8) (d) M14 (10.9)

Fig. 14 Shear-slip relationship curves from empirical formula and test

It can be found that the empirical formulae for high strength concrete (HSC) can simulate the shear-relationship curves pretty well for the specimens with M14 (8.8) and M12 (8.8) bolted connectors. However, for the specimens with M16 (8.8) and M14 (10.9) bolts, which had developed relatively larger shear resistance, the shear-slip relationship curves are better simulated by empirical formula for normal strength concrete (NSC). Apparently, a preliminary conclusion can be drawn as following: smaller bolted connectors are more likely to develop shear-slip relationship similar to conventional welded headed stud.

7. Conclusions

In this paper, a new type of demountable steel-precast concrete bolted connector, employing the conical nut and chamfered hole on steel beam flange, was proposed to improve the shear performance of conventional bolted connector with double nut embedded. In order to investigate the shear performance of this novel bolted connector, ten push-out specimens in total for bolted connector have been implemented, with parameters including two types of bolt configuration, three bolt diameters, two bolt strength grades and two strength grades of the in-filled grout. The following conclusions can be drawn from the static push-out tests.

1) The failure mode of the push-out specimens with novel demountable bolted connectors is that the direct sheared off at the bolt cross-section right above the upper face of the conical nut. Few fine cracks and limited local concrete crushing can be observed in the vicinity of bolt and basically within the in-filled grout region.

2) The modified configurations of the bolted connectors, taking advantage of conical locking nut and chamfered flange hole to eliminate the initial clearance between bolt shank and bolt hole on flange, can achieve much better shear performance such as 25% larger shear resistance and much larger shear stiffness up to 600%, compared to the respective performance for specimens with conventional bolted connector.

3) The shear resistance of the novel demountable bolted connector increases with the increase of the bolt diameter, the bolt strength grade as well as the strength of infill grout. The shear resistance of the novel demountable bolted connector can be predicted as 0.65 times of the bolt characteristic tensile resistance. When considering the shear contribution of conical locking nut, a formula including effect of conical locking nut is found to agree well with the tested results.

The parameters investigated in the current experimental studies in still limited. Comprehensive parametric investigation should be carried out through validated numerical models cooperating experimental work in the future studies.

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Nomenclature

A_{sc}	area of cross section for bolt shank
d	diameter of bolted connector
D	equivalent diameter of hexagonal nut
f'_c	concrete/grout compressive strength
f_u	ultimate tensile strength
h_c	height of the conical nut referring to the top flange upper surface
K	connector shear stiffness
s_k	slippage of shear connector at 70% maximum shear resistance
s_u	slippage of shear connector at maximum shear resistance
s	slippage of shear connector
T_u	ultimate tensile resistance of shear connector
V_u	connector ultimate shear resistance
V	shear force

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