EXPERIMENTAL EVALUATION OF A NOVEL DEMOUNTABLE SHEAR CONNECTOR FOR ACCELERATED REPAIR OR REPLACEMENT OF PRECAST STEEL-CONCRETE COMPOSITE BRIDGES

Ahmed S. H. Suwaed
Dr Civil Engineer
School of Engineering, University of Warwick
Coventry, UK
A.S.H.Suwaed@warwick.ac.uk

Theodore L. Karavasilis
Professor of Structures and Structural Mechanics
Faculty of Engineering and the Environment, University of Southampton
Southampton, UK
T.Karavasilis@soton.ac.uk

1. ABSTRACT

A novel demountable shear connector for precast steel-concrete composite bridges is presented. The connector (i) uses high-strength steel bolts fastened to the top flange of the steel beam with the aid of a locking nut configuration that prevents slip of bolts; (ii) promotes accelerated construction; (iii) overcomes construction tolerances issues; and (iv) allows rapid bridge disassembly, and therefore, rapid replacement of any deteriorating structural component. A series of push-out tests are conducted to assess the behavior of the connector. The experimental results show shear resistance, stiffness, and slip capacity significantly higher than those of welded shear studs; superior stiffness and strength against slab uplift; and negligible scatter in the shear load-slip displacement behavior. A design equation is proposed to predict the shear resistance of the connector.

2. INTRODUCTION

Bridge decks typically deteriorate faster than other bridge components, e.g. the decks of a large percentage of the bridges in America are in the need of repair or replacement after an average service life of 40 years [1]. In the case of steel-concrete composite bridges (referred to as composite bridges), removing and replacing their deck is a challenging process due to the connection among the deck and the steel beams. Such connection is traditionally achieved with the aid of shear studs, which are welded on the top flange of the steel beams and are fully embedded within the concrete deck. Therefore, removing the deck involves drilling and crushing the concrete around the shear studs and then breaking the deck into manageable sections [2]. Such processes are costly and time-consuming, and involve the use of hazardous equipment. A radical way of addressing deck deterioration as well as other bridge deterioration mechanisms (e.g. fatigue or corrosion in shear connectors) is the development of novel structural details that allow bridge disassembly so that any deteriorating component can be rapidly replaced with minimal traffic disturbance. In the case of composite bridges, disassembly calls for a demountable shear connector.

3. BACKGROUND

An extensive literature review on the use of steel bolts as shear connectors can be found in [3]. All the previous tests on friction-grip bolts as shear connectors revealed an undesirable large slip displacement due to bolts sliding inside the bolt holes when friction resistance in the steel beam-concrete slab interface was exceeded. Moreover, all the previously proposed bolted shear connectors are not suitable for precast construction. In the case of shear connectors that are pre-embedded in the concrete slab, precast construction tolerances make their alignment with the pre-drilled bolt holes on the top flange of the steel beam extremely difficult if not impossible. In the case of shear connectors that are fastened underneath the steel beam after positioning of the precast slab on the top of the steel beam, gaps in the concrete slab - steel flange interface may prevent adequate bolt fastening and cause slab cracking [4]. It is also noted that connectors that are fully embedded within the concrete slab allow uplift and replacement of the slab as a whole but not full disassembly of the composite beam, i.e. replacement of the shear connectors is not possible.

4. NOVEL DEMOUNTABLE SHEAR CONNECTOR

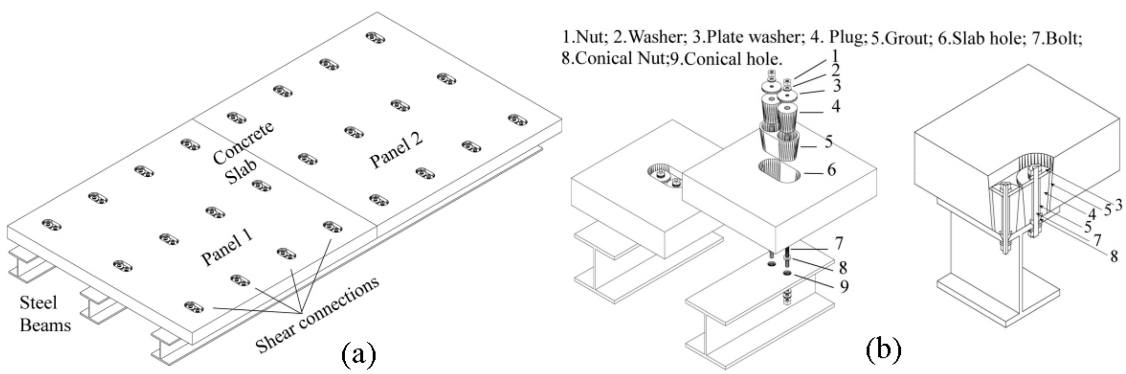


Fig. 1. a) Precast steel-concrete composite bridge using the LNSC; b) 3D disassembly and inside view of the LNSC

Fig. 1(a) shows a composite bridge, which consists of precast concrete panels connected to steel beams with the aid of the proposed locking nut shear connector (LNSC). The concrete panels have several pockets to accommodate the LNSCs. Fig. 1(b) shows the 3D disassembly along with the inside 3D view of the LNSC where all its components are indicated. Moreover, Fig. 2(a) shows the cross-section of a beam using the LNSC.

The LNSC consists of a pair of high strength steel bolts (e.g. Grade 8.8 or higher) with standard diameter (e.g. M16) as shown in Fig. 2(a). The bolts have threaded ends and are fastened to the top flange of the beam using a double nut configuration, which consists of a standard lower hexagonal nut (nut 1 in Fig. 2(a)) and an upper conical nut (nut 2 in Fig. 2(a)). The upper part of the bolt hole is a countersunk seat with chamfered sides following an angle of 60 degrees as shown in Fig. 2(b). The upper conical nut (see Fig. 2(b)) is a standard type nut threaded over the bolt and has geometry that follows the same 60 degrees angle so that it can perfectly fit within the countersunk seat. The upper conical nut locks within the countersunk seat, and in this way, prevents slip of the bolt within the bolt hole. Few millimetres of the total height of the upper conical nut appear above the top surface of the beam flange (see Fig. 2(a)) to resemble the height of the collar of welded shear studs. Moreover, Fig. 2(b) shows the M16 conical nut after removing five millimetres of its internal threading. In this way, the bolt is partially hidden inside the conical nut and shear failure within its weak threaded length is prevented. A proof load is applied between the lower nut and the conical nut to ensure a robust locking configuration.

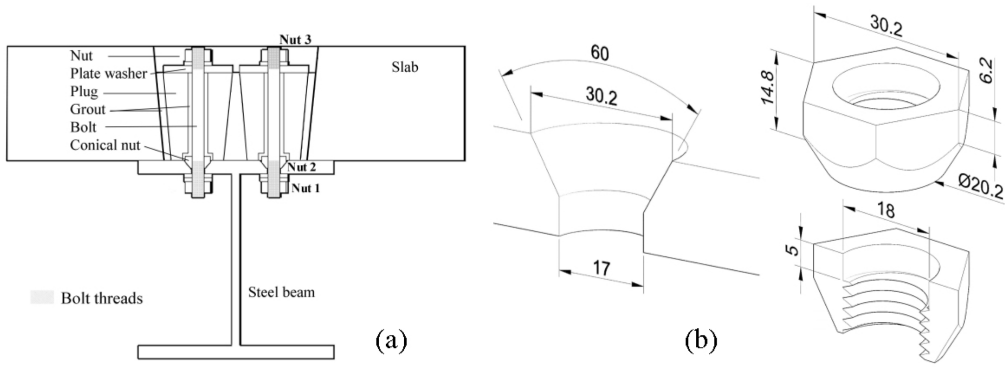


Fig. 2. a) Cross-section of a composite beam using the shear connector; b) Geometry of the locking connection, i.e. half countersunk hole, full nut, and half nut

The slab pocket is a countersunk hole with an inclination of 5 degrees. A typical geometry of a slab pocket, relevant to the test specimens presented later, is shown in Fig. 3(a). Inside each slab pocket there are two inverted conical precast concrete plugs (see Fig. 2(a)) with geometry following the inclination angle of the slab pocket. A typical geometry of a plug, relevant to the test specimens presented later, is shown in Fig. 3(a). Each plug has a central circular hole with a 26 mmm diameter that accommodates an M16 bolt with 10mm clearance. The diameter of the central circular hole increases from 26 to 40 mm at the base of the plug to accommodate an M16 conical nut with 10 mm clearance as shown in Fig. 3(a). The diameters of the plugs are small enough compared to the diameters of the slab pocket to overcome construction tolerances issues. Grout is used to fill the gaps between the bolt and the hole of the plug as well as the gaps between the plugs and the slab pocket.

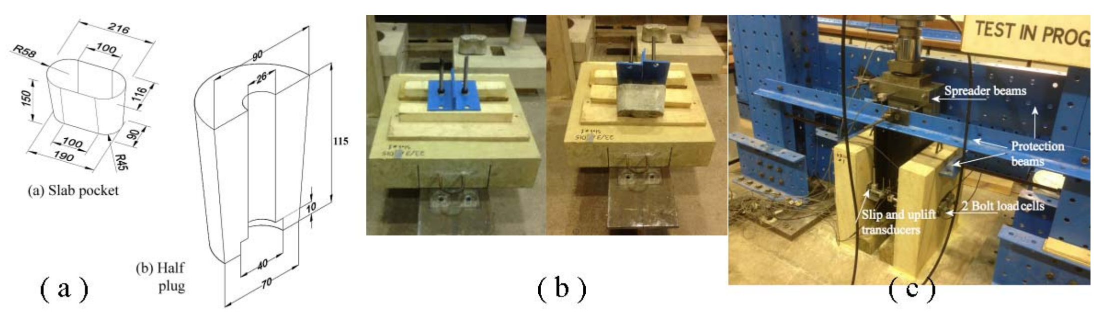


Fig. 3. a) Dimensions of slab pocket and half plug; b) Disassembly procedure; c) Push-out test setup

Fig. 2.(a) shows that a hardened plate washer is used to uniformly distribute the bolt thrust on the upper face of the concrete plug without inducing cracks. The plate washer has a

diameter of 90 mm, a central hole of 18 mm diameter, and a 10 mm thickness. Tightening of nut 3 (see Fig. 2(a)) is carried before hardening of the grout.

5. ACCELERATED BRIDGE DISASSEMBLY

The LNSC allows rapid disassembly and replacement of any deteriorating structural component of a precast composite bridge. In case of deterioration in a precast concrete panel, the lower nuts (nut 1 in Fig. 2(a)) are removed and the precast panel along with its shear connectors can be rapidly uplifted together. If there is no access underneath the bridge, the upper nuts at the top of the plugs (nut 3 in Fig. 2(a)) are removed and the precast panel can be rapidly uplifted along with its plugs by leaving the bolts in place. To achieve that easily, it is important to design the bolts so that their threaded length is not in contact with the grout. In case of deterioration in shear connectors, the plugs along with their surrounding grout can be rapidly extracted (pulled out) and replaced as shown in Fig. 3(b), i.e. first the lower nuts (nut 1 in Fig. 2(a)) are unfastened and then the plugs and their surrounding grout are removed by applying uplift forces while using the slab as support. It is emphasized that dry joints among the precast concrete panels, such as those proposed in [5], would further enhance bridge disassembly.

6. EXPERIMENTAL SETUP AND SPECIMENS

Test No.	Bolt Dia. (mm)	Bolt preloads (kN) Nuts 1-2*	Bolt preloads (kN) Nuts 2-3*	Slabs Comp. Strength (MPa)	Slabs Tensile strength (MPa)	Plugs Comp. strength (MPa)	Plugs Tensile strength (MPa)	Grout Comp. strength (MPa)
1	16	88-106	88-106	31	2.5	65	4.2	122
2	16		0.0					
3	16	88-106	88-106	31	2.5	65	4.2	-
4	16	88-106	10	31	2.5	83	5.2	43
5	16	88-106	88-106	37	-	71	4.3	58
6	16	64	88-106	41	4.0	86	5.1	44
7	12	47-56	24	50	4.0	91	4.8	28
8	14	68-81	23	50	4.0	95	4.6	32
9	16	failed	23	42	3.6	80	4.8	39
10	16	88-106	24	43	3.1	50	3.7	27
11	16	88-106	26	43	3.2	96	4.8	28
12	16	88-106	26	42	3.5	91	4.9	28

* See *Fig. 2.(a)* for locations of nuts 1, 2 and 3

Table 1. Specifications of push-out tests

Push-out tests on the LNSC were conducted using the test setup shown in Fig. 3(c), which follows the recommendations of EC4 [7]. The steel beam has length equal to 80 cm, a 254x254x89 UC section, and S355 steel grade. Four holes with countersunk seat upper parts were drilled on the beam flanges. Four bolts (threaded at both ends) and four compatible conical nuts were fabricated. The bolts along with their conical nuts were inserted into the countersunk seat holes of the steel beam. Then, the lower nuts (nut 1 in Fig. 2(a)) were tightened to the proof load.

The precast concrete slab has a 650*600*150 mm geometry and a central countersunk conical pocket with exact dimensions shown in Fig. 3(a). Table 1 lists specifications for all push-out tests, while properties of the steel bolts are listed in Table 2.

	Modulus of elasticity (GPa)	Yield stress (MPa)	Tensile strength (MPa)	Maximum elongation %	Bolt tensile resistance (kN)
Avg. of 9 specimens	209	787	889	8	
Min.	201	719	832	5	
Max.	215	847	950	15	
Standard deviation	5	50	41	5	
D12 mm					100.5
D14 mm					136.9
D16 mm					178.7

Table 2. Properties of bolts

7. EXPERIMENTAL PROGRAM

7.1 Preliminary tests and confirmation of results with identical tests

Push-out tests were carried on 12 LNSC specimens with specifications listed in Table 1. The first five tests were preliminary and served to investigate how different design details influence the strength and ductility of the LNSC. Discussion of the results of the first five preliminary tests can be found in [3]. Test 6 was conducted on a specimen representing the actual robust structural details of the LNSC. In all experiments, the ultimate load is the maximum load in the shear load-slip displacement curve, while the slip capacity is calculated as the slip displacement corresponding to the ultimate load. In all the shear load-slip displacement curves presented in this paper, the shear load is the applied load divided by four (i.e. number of bolts), while the slip displacement is the average of the slip displacements measured close to the four bolts.

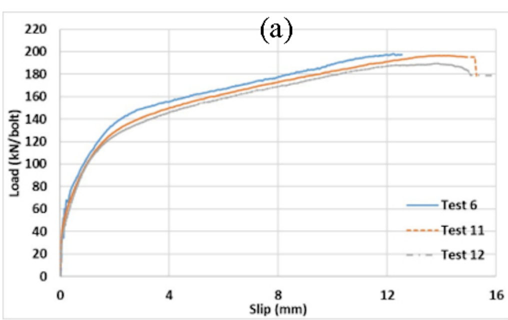
Test No.	Ultimate load (kN)	Slip capacity (mm)
6	198.1	12.2
11	196.7	13.9
12	189.5	13.8
Average	194.8	13.3
Stdv.	3.76	0.779
Error %	2	6

Table 3. Results of tests 6, 11, and 12

Following the recommendation of EC4 [6], the results of test 6 were confirmed by conducting two additional push-out tests with approximately the same specifications (i.e. tests 11 and 12 in Table 1). Table 3 lists the ultimate loads and slip capacities from the 'identical' tests 6, 11, and 12. The deviation of the ultimate load of any of the individual tests from the mean value is less than 2%, i.e. significantly below the 10% limit of EC4 [6]. Therefore, the characteristic shear resistance may be safely determined as the minimum ultimate load from the three identical tests reduced by 10% according to EC4 [6], i.e. P_{Rk}=0.9*189.5=170.55 kN. Fig. 4(a) compares the shear load-slip displacement behavior from the three identical push-out tests 6, 11, and 12. The results highlight that the robust structural details of the LNSC result in superior strength, superior stiffness, large slip capacity, and repeatability in the load-slip behavior.

7.2 Comparison with welded shear studs

The shear resistance of the LNSC from Test 6 is equal to 198.1 kN for a slab concrete strength equal to 41 MPa, bolt diameter equal to 16 mm, and bolt tensile strength equal to 889 MPa. For the same bolt geometry and material properties, the shear resistance of the corresponding welded shear stud is calculated equal to 73.02 kN according to EC4 [6]. Therefore, the shear resistance of the LNSC is significantly higher than that of welded studs. The reason of such higher shear resistance is that the smart structural details of the LNSC promote failure in the shank of a high tensile strength (e.g. 889 MPa) bolt without premature concrete failure. The slip capacity of the LNSC from test 6 is equal to 12.2 mm, i.e. two times higher than the typical 6.0 mm slip capacity of welded studs. For slip displacements from 0.0 to 1.0 mm in Fig. 4(a), the shear load reaches values up to 100 kN, i.e. approximately equal to 50% of the shear resistance. The latter means that the stiffness of the LNSC for M16 bolt is 100 kN/mm. Similar stiffness can be offered by 19 mm diameter welded studs according to EC4 [6]. The LNSC does not show appreciable scatter in its behaviour compared to the scatter seen in the behavior of welded shear studs. The main reason is that the smooth flowable grout used to cover all gaps among the elements of the LNSC ensures uniform distribution of bearing stresses in the conical nut - grout, bolt shank - grout, and plug - grout interfaces.



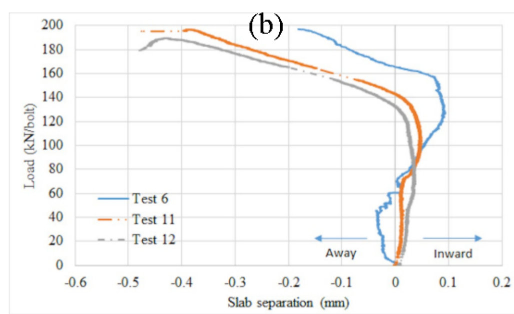


Fig. 4. a) Shear load – slip displacement and b) shear load – uplift displacement of the LNSC from three identical push-out tests (6, 11, and 12 in Table 1)

7.3 Load-slab uplift behaviour

During a standard pushout test, slabs tend to uplift as they slide over the collar of welded studs. EC4 [6] recommends that the slab uplift (i.e. slab separation) should be no more than 50% of the corresponding slip displacement at a shear load equal to 80% of the shear resistance. Fig. 4(b) shows that slab separation is less than 0.1 mm at 80% of loading, i.e. only 4% of the corresponding slip displacement. Pushout tests on welded studs of the same bolt diameter showed uplift displacements equal to 9-15% of the corresponding slip displacements [7].

8. DESIGN EQUATION

According to EC4 [7], the shear resistance of a welded stud failing due to steel fracture is equal to $0.8 f_u(\pi d^2/4)$; where d is the shank diameter and f_u the ultimate strength of steel. For the LNSC, this formula should be modified to account for the effect of friction, the effect of the inclination of the deflected shape of the bolts, and the effect of shear failure through an elliptical cross-section of the bolt shank. On the basis of a bolt tensile force at the onset of failure equal to 40% of the bolt tensile resistance [3], the following equation is proposed

$$P = \frac{\pi d^2 f_u}{4}\left[\frac{0.8}{\cos\beta} + 0.4\left(\sin\beta + \mu\cos\beta\right)\right] \tag{1}$$

where β is the angle of the deflected shape of the bolt from the vertical at the level of the shear failure plane and μ is the coefficient of friction between concrete and steel. by After substitution of $\mu = 0.5$ and $\beta = 12.1^{o}$ (both values are verified in [3]) into Eq. (1), the shear resistance of the LNSC becomes equal to 1.1 times the bolt tensile resistance. Eq. (1) provides good estimations of the experimental shear resistance with error less than 8% [3].

9. CONCLUSIONS

On the basis of the results presented in this paper, the following main conclusions are drawn (see [3] for a more extensive discussion): **(1)** The LNSC allows easy bridge disassembly and rapid repair or replacement. **(2)** The LNSC has very high shear resistance and stiffness, e.g. the corresponding characteristic values for an LNSC using an M16 bolt were found equal to 170.5 kN and 100 kN/mm, respectively. **(3)** The LNSC has very large slip capacity, i.e. up to 14.0 mm. **(4)** The LNSC has superior stiffness and strength against slab uplift in comparison to welded studs, e.g. the uplift displacement is less than 4% of the corresponding slip displacement at a shear load equal to 80% of the shear resistance.

REFERENCES

[1] ASCE. "Report card for America's infrastructure - Bridges." 2016.

[2] Tadros M.K., Baishya M.C. "Rapid replacement of bridge decks." NCHRP Rep. 407, Transportation Research Board, Washington, DC, 1998

[3] Suwaed S.H.S., Karavasilis T.L. "Novel demountable shear connector for accelerated disassembly, repair or replacement of precast steel-concrete composite bridges" J. of Bridge Engineering (ASCE), in press, 2017.

[4] Biswas M. "On modular full depth bridge deck rehabilitation." J. Trans. Eng. (ASCE) 112, 1, 105-120, 1986.

[5] Hallmark R. "Prefabricated Composite Bridges – a Study of Dry Joints." Licentiate thesis, Department of Civil, Mining and Natural Resources Engineering, Lulea University of technology, Sweden, 2012.

[6] British Standards Institution. "Eurocode 4: Design of composite steel and concrete structures, Part 1-2: General rules and rules for Bridges." BS EN 1994-2, UK, 2005.

[7] Spremić M., Marković Z., Veljković M., Budjevac D. "Push–out experiments of headed shear studs in group arrangements." Advanced Steel Construction an International Journal, 9(2),170–91, 2013.

ΠΕΙΡΑΜΑΤΙΚΗ ΜΕΛΕΤΗ ΝΕΟΥ ΔΙΑΤΜΗΤΙΚΟΥ ΣΥΝΔΕΣΜΟΥ ΓΙΑ ΤΑΧΕΙΑ ΑΠΟΣΥΝΑΡΜΟΛΟΓΗΣΗ, ΕΠΙΣΚΕΥΗ, ΚΑΙ ΑΝΤΙΚΑΤΑΣΤΑΣΗ ΠΡΟΚΑΤΑΣΚΕΥΑΣΜΕΝΩΝ ΣΥΜΜΙΚΤΩΝ ΓΕΦΥΡΩΝ ΧΑΛΥΒΑ-ΣΚΥΡΟΔΕΜΑΤΟΣ

Ahmed S. H. Suwaed
Διδάκτωρ Πολιτικός Μηχανικός
Σχολή Μηχανικών, Πανεπιστήμιο του Warwick
Coventry, Ηνωμένο Βασίλειο
A.S.H.Suwaed@warwick.ac.uk

Θεόδωρος Λ. Καραβασίλης
Καθηγητής Κατασκευών και Μηχανικής των Κατασκευών
Τομέας Έργων Υποδομής (Κατασκευών και Γεωμηχανικής)
Σχολή Μηχανικών και Περιβάλλοντος, Πανεπιστήμιο του Southampton
Southampton, Ηνωμένο Βασίλειο
T.Karavasilis@soton.ac.uk

ΠΕΡΙΛΗΨΗ

Η εργασία παρουσιάζει ένα νέο διατμητικό σύνδεσμο για προκατασκευασμένες σύμμικτες γέφυρες χάλυβα-σκυροδέματος. Ο σύνδεσμος χρησιμοποιεί κοχλίες υψηλής αντοχής οι οποίοι εξασφαλίζονται έναντι ολίσθησης στις οπές του πάνω πέλματος της μεταλλικής δοκού μέσω ειδικής διάταξης διπλού κωνικού περικοχλίου. Μέσω της χρήσης επιπρόσθετων κατασκευαστικών λεπτομερειών, ο σύνδεσμος εξασφαλίζει σύμμικτη λειτουργία χωρίς να είναι πλήρως ενσωματωμένος στη πλάκα σκυροδέματος και μπορεί να αφαιρεθεί και να αντικατασταθεί πολύ εύκολα στο πεδίο. Ουσιαστικά ο σύνδεσμος επιτρέπει την πλήρη αποσυναρμολόγηση προκατασκευασμένης σύμμικτης γέφυρας και την εύκολη και γρήγορη αντικατάσταση κάθε δομικού στοιχείου (πλάκα σκυροδέματος, μεταλλική δοκός, διατμητικός σύνδεσμος) που έχει υποστεί βλάβη. Με αυτό τον τρόπο επιτυγχάνεται επισκευή και επέκταση της διάρκειας ζωής της σύμμικτης γέφυρας χωρίς την ανάγκη εκτεταμένης διακοπής της κυκλοφοριακής ροής. Η εργασία παρουσιάζει εκτεταμένο πειραματικό πρόγραμμα βασισμένο σε δοκιμές τύπου “push-out” σύμφωνα με τον Ευρωκώδικα 4. Τα πειραματικά αποτελέσματα δείχνουν ότι ο σύνδεσμος έχει εξαιρετική διατμητική αντοχή, πλαστιμότητα σε ολίσθηση, καθώς και μεγάλη δυσκαμψία και αντοχή έναντι ανασήκωσης της πλάκας σκυροδέματος. Επαναλαμβανόμενες πειραματικές δοκιμές σε όμοια δοκίμια δείχνουν πολύ μικρή αβεβαιότητα στη συμπεριφορά του συνδέσμου. Η εργασία προτείνει εξίσωση εκτίμησης της διατμητικής αντοχής του συνδέσμου με απόλυτο σφάλμα μικρότερο του 8%.