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Monotonic and Fatigue Performance of Double-skin Push-out and Tensile Segments of Divers Shear Connectors – Review

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Abstract

Double skin composite (DSC) construction or Steel/concrete/steel sandwich construction (SCSS) is an innovative and relatively new form of composite construction that can be used in submerged tube tunnels, bridges deck, nuclear structures, liquid and gas containment structures, offshore and onshore structures, military shelters, and shear walls in buildings. The system consists of a plain concrete core sandwiched between two steel plates interconnected together by various types of mechanical shear connectors. The DSC construction perceives advantages that the external steel plates act as both formwork and primary reinforcement, and also as impermeable, blast and impact resistant membranes. The major duty of the shear connectors is to withstand longitudinal shear force and beam/slab separation, while in the bi-steel type where shear connectors are friction welded at both their two ends to two parallel steel plates, the longitudinal and transverse shear force, as well as plate buckling are resisted. The present paper highlights the previous prime researches concerning the subjects of SCSS composite construction, specifically on the conducted tests (push-out tests, tensile, direct shear tests, and bending tests) in which the components of partial interaction (uplift and slip forces) are resisted by various types of shear connectors.

Keywords: Steel-Concrete-Steel, Push-out Test, Double Shear Connectors, Bi-Steel Plate

ألأداء الراتب وأداء الكَلال لقِطَع الدفع الخارجي وقِطعَ الشد ثنائية القشرة بأنواع متباينة من روابط القص – ورقة عرض

زينب حسام الزهاوي ، ليث خالد الحديثي

الخلاصة:

تعتبر المشيّدات المركّبة ثنائية القشرة DSC أو المشيدّات السندويجيّة فولاذ - خرسانة - فولاذ SCSS أحد الأنواع المبتكرة والتشكيلات المعاصرة للمشيّدات المركبة المرَشّحة للإستخدام في الأنفاق الأنبوبية، أرضيات الجسور، ألمنشآت النووية، ألمنشآت الحاوية للسوائل أو الغازات، ألمنشآت المائيّة المحاذية للسواحل، ألملاجئ الحربية، والجدران المقاومة للقص في المباني العالية. تتكون تلك المنظومة الإنشائية من لُباب خرسانية صمّاء محشوَة بين صفيحتين فولاذيتين مرتبطتين معاً ارتباطاً داخلياً بوساطة روابط قص ميكانيكة متعددة الانواع. تحقِق تلك المنظومة الإنشائية المركبة مزايا إستثنائية اهمها قيام الصفيحتين الفولاذيتين الخارجيتين بوظيفتين اساسيتين احدهما انشائية وهي التسليح الرئيس والاخرى تشييديّة وهي قالبٌ دائم، علاوةً على قيامها بدَورالحاجز الأصّم المقاوم للعصف غير المباشر وللصدمات المباشرة. أمّا بخصوص روابط القصّ- في هذه المنظومة ألإنشائية المركبة ثنائية الطبقات الفولاذية - فإنّها تكون ملحومة الطرفين في كلتا الصفيحتين الفولاذيتين القشريتين لذا فإنّها - إضافة الى قيامها بالوضيفتين الرئيستين لروابط القص التقليدية وهما مقاومة قوى القص الطولية ومقاومة الانفصال العمودي على امتداد الاسطح البينيّة بين الفولاذ والخرسانة- فإنّها تقوم أيضاً بمقاومة قوى القصّ المستعرضة عل ألاسطح البينيّة واسناد الصفيحتين الفولاذيتين من الإنبعاج. تقوم المقالة العلمية الحالية بتسليط الاضواء على الابحاث

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الرئيسة المعاصرة في مجال سلوك المنظومات الانشائية السندويجية فولاذ - خرسانة - فولاذ مع الاهتمام الخاص بالفحوصات الرئيسة لها (لفحوص ألشد، القص المباشر، والدفع الخارجي) حيث يتم فيها مقاومة مركبتي القوى على الاسطح البينية جزيئية الترابط (الانزلاق والانفصال) بوساطة اصناف متنوعة من روابط القص.

Abbreviation:

DSC Double Steel Composite
SCSS Steel Concrete Steel Sandwich
HSS Hollow Structural Section.

1. Introduction

Mechanical shear connectors provide localized bond at discrete points between the steel and concrete along the member, different types of shear connectors as shown in Fig. 1 have been developed and used in the steel-concrete-steel composite structures and there main types are the flexible, the quazi-rigid, the bolted, the demountable and the friction grip ones. They are bound to the steel section by means of welding; such as headed studs, J-hook shear connectors, friction welded connectors, corrugated strip connectors, perfobond connectors…etc., or by tightening such as bolted connectors. Shear connectors mentioned in this paper are classified within four groups: SCSS push-out and tensile investigations, Bi-steel systems with through-depth threaded shear connectors, Bi-steel systems with welded through-depth shear connectors, and non-embedded welded connecter-steel systems.

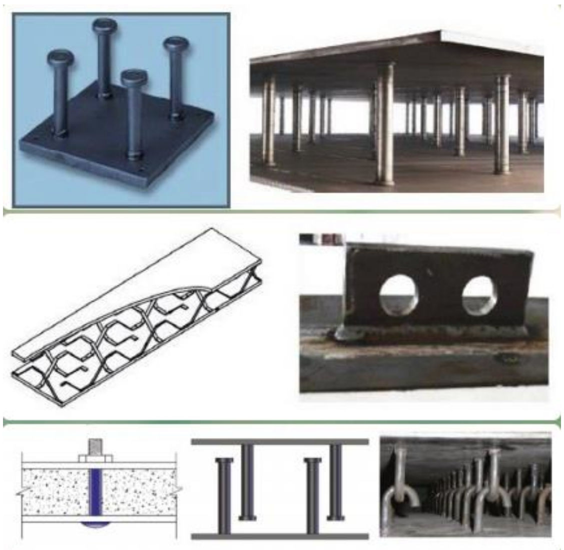


Figure (1): Divers types of mechanical shear connectors.

2. SCSS Push-out and Tensile Investigations

This section covers the most important and recent investigations on the push-out and tensile tests embracing divers' types of shear connectors not fully penetrating the overall depth of the concrete component in the SCSS systems. The first proposed application of the SCSS structure was in 1989 when a tunnel, in the form of a submerged tube, was constructed for highway in North Wales by Tomlinson brothers [1].

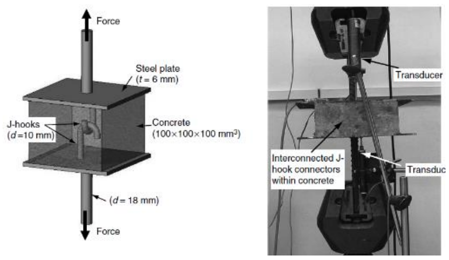
In 2009, Al-Tameemi [2] conducted a series of push-out tests in order to provide information concerning the ultimate shear capacity and load versus slip relationship of the stud shear connectors utilized in fabricating composite steel-concrete arches. He manufactured and tested four modified push-out tests with three types of concrete (normal, self-compacting, and self-compacting lightweight concrete). He conducted one push-out test for each type of concrete and the last one was of conventional concrete tested by repeated loading. He used four headed stud shear connectors of constant diameter which was 9.6 mm as shown in Fig. 2 in all the push-out segments.

a) Steel section with shear connectors

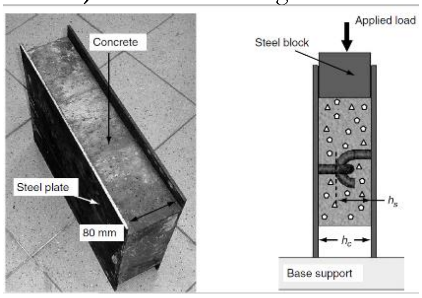
b) Specimen before test.

Figure (2): Modified push-out segment conducted by **[Al-Tameemi, 2009].**

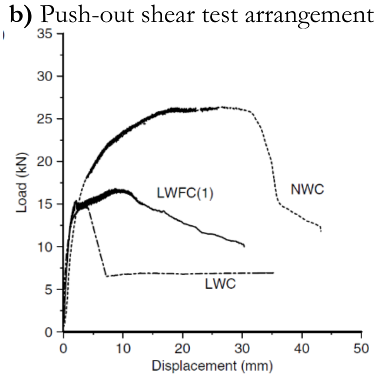
In 2010, Liew and Sohel [3] carried out a series of tensile and push-out tests on J-hooked shear connectors illustrated in Fig. 3 (a, b) in order to examine their performance in transferring tension and shear forces between concrete and steel. For the tensile tests, they used 6 mm steel plate thickness and 10 mm bar diameter with both plain and lightweight concrete core with and without fiber reinforcement. Their tensile test results showed that the tensile resistance of the interconnected J-hooked shear connectors depended on concrete strength (i.e. tensile resistance of the embedded J-hooked shear connectors in normal weight concrete was much more than in the light weight concrete which is provided in Fig. 3(c)). While for the push-out tests, they prepared seven push-out specimens to determine the load-slip relationship using 10, 12, and 16 mm diameters for J-hooked bars and various types of concrete core. Their test results showed that the proposed J-hooked shear connectors were effective like the traditional headed studs, in creating partial interaction and the shear resistance was largely affected by concrete compressive strength. In both normal and light weight concrete the J-hook connector showed a ductile behavior after maximum load was reached while in lightweight concrete the J-hooked connector displayed extra flexible load-slip characteristics in comparison with the normal weight concrete. In comparison with Eurocode 4 [4] (2004) approach (in which the characteristic shear capacity of welded stud connectors is utilized to evaluate the resistance of J-hooked shear connectors). They concluded that the code underestimates the maximum value of the shear resistance of the J-hook connectors which provide better shear transfer mechanism between concrete and steel due to their interlocking.



a) Tensile test arrangement



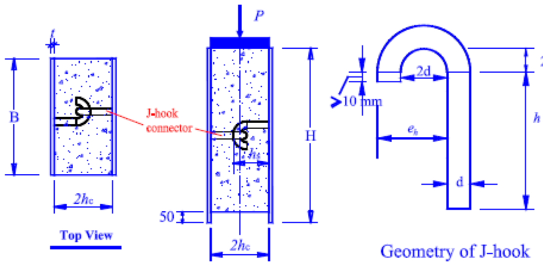
b) Push-out shear test arrangement



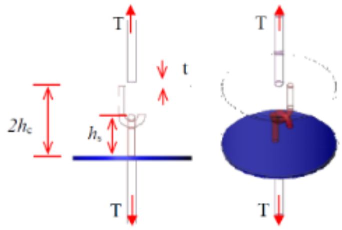
c) Tensile load-dis. Curves (Shear connector Ø10mm).

Figure (3): J-hook connectors tensile and push-out segments conducted by **[Liew and Sohel, 2010].**

For the applications in bridge offshore and building constructions Yan et al. [5], in 2015, proposed a SCSS structure with ultra-lightweight cement composite core and J-hook connectors. They tasted 30 push-out segments and 18 tensile samples, as shown in Fig. 4 (a, b), with J-hook connectors embedded in various types of concrete core to determine their shear and tensile resistance. They also proposed design formulae to evaluate the shear, tensile, and interaction resistances of the J-hooked shear connectors. They developed a nonlinear finite element analysis to predict the ultimate behavior and load versus slip relation of the J-hook connectors under combined tensile and shear loads. They supported their proposed design formulae by comparing the FE results with those predicted from those formulae.



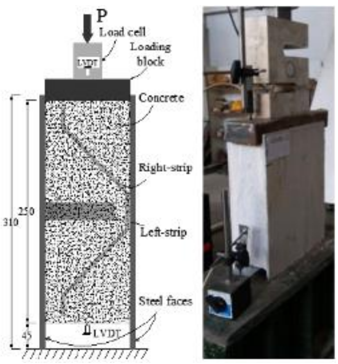
a) Push-out test setup and specimen geometry.



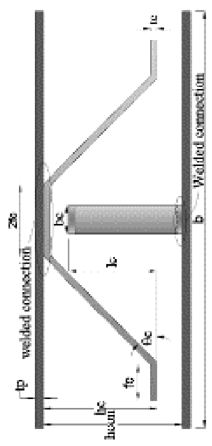
b) Tensile tests on J-hook connector

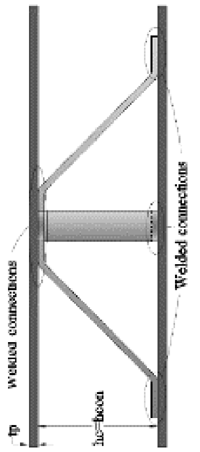
Figure (4): Tested specimens details conducted by **[Yan et al., 2015]**

In 2017, Yousefi and Ghalehnovi [6] proposed a new system of corrugated-strip connectors which was bi-directional corrugated-strip connectors. They tested sixteen push-out segments under static loading as provided in Fig. 5(a), fifteen of them were with only one welded end of the shear connectors and the other end was embedded in concrete as shown in Fig. 5(b), the remaining sample embraced two-end welded connectors as provided in Fig. 5(c). Their experimental results estimated the effects of the geometrical parameters on failure modes, ductility, and the ultimate shear strength of the proposed shear connectors. They concluded that the two head welding increased the shear strength of connectors and provided ductility twice as that of the one-head welding. Also, they proposed several relations to evaluate the ultimate shear strength and load versus slip behavior of the corrugated-strip connectors and compared them to those of the famous codes and standards. Consequently, they concluded that these relations were more reliable.



a) Test arrangement





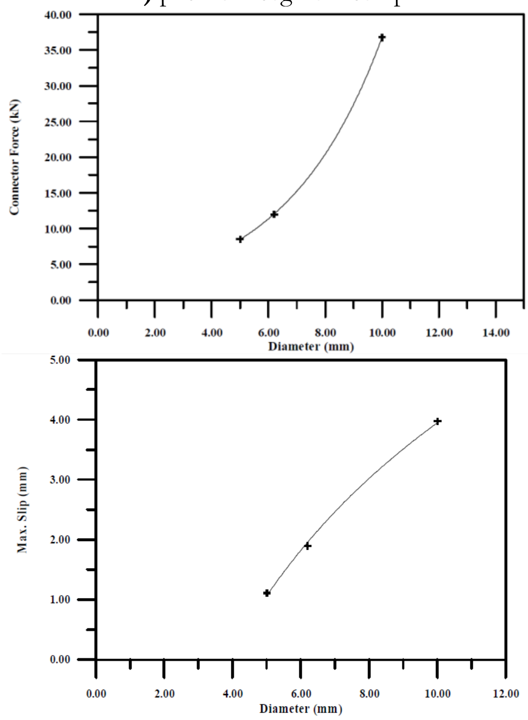
b) One end welded **c)** Two end welded

Figure (5): SCS sandwich systems with corrugated strip connectors tasted by **[Yousefi and Ghalehnovi, 2017].**

3. Bi-steel Systems with Trough-depth Threaded Shear Connectors

In 2005, Zebun [7,8] suggested an altered push-out segment in order to study the load versus slip relationship for shear connectors in SCSS beams, which represent the prime agent needed in the SCSS beams analysis and design with partial interaction. He introduced steel HSS-concrete slab-steel HSS as shown in Fig. 6(a), to replace the standard push-out segment consisting of concrete block, steel (I-section) and concrete block so as to be more suitable for representing and modeling the double-skin beams than the standard test. He used four threaded bar shear connectors with variable diameters tightened to the steel HSS by using nuts which prevent the separation of steel and concrete components, and penetrates to the other steel HSS through the concrete core (i.e double shear action of connector). He considered the shear connector diameter as the main parameter and measured the slip at each connector as shown in Fig 6 (b). He concluded that there were two failure modes (as shown in Fig. 6(c)) which were: control failure represented by fracturing of the connector by direct shear, and local failure represented by crushing of concrete surface around the connector. He suggested an experimental relationship of load-slip to simulate the behavior of this type of connection in SCSS construction.

a) push-out segment setup



b) Connector force and max. Slip vs. stud dia.

c) Failure modes

Figure (6): Typical modified push-out segment investigated by **[Zebun, 2005, 2006]].**

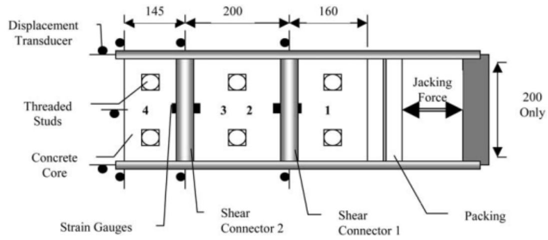
At the same year, Zebun [9] studied the influence of pre-heating on the load versus slip relationship in a modified push-out test. He carried out eight push-out tests, tested three specimens without any previous heating and heated five specimens of concrete slabs with embedded connectors to varying temperatures. He elucidated that the pre-heating to varying temperatures was unable to influence the strength of shear connector (because the connector diameter was small, and the fracture was controlled by the shear cut-off of the shear connector rather than splitting of the concrete slab even if it is without steel reinforcing bars). After heating the specimens to temperatures greater than 300 C° the concrete compressive strength was significantly reduced when compared with the unheated concrete, and cracks were seen clearly at temperature 500 C° at the concrete surface. The conclusion denoting that the pre-heating influence on the concrete resistance was much less than on the concrete stiffness due to the concrete cracks' existence after heating to relatively high temperatures.

4. Bi-steel Systems with Trough-depth Welded Shear Connectors

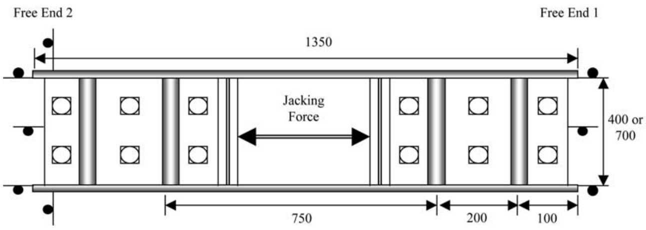
Bowerman proposed further improvement on SCSS constructions in 1999. He perceived that the buildability of the DSC would be mutated if the bar connectors are friction welded to the steel plate at both ends. The bar connectors were subjected to tension or compression, shear, and bending. Finally, design recommendations [10] were published.

At the same year, Clubley and Xiao [11] discussed the shear strength and deformation ability of the Bi-steel unit undergo push out loading. They conducted a numerical modeling by using finite element analysis with ANSYS computer program on the Bi-steel plates with and without in-filled concrete in order to model the experimental behavior of Bi-steel panels including a vast range of variables. They took into account both geometrical and material non-linearities in the computing analysis. They also proposed a preliminary design formula for Bi-steel plate shear strength taking into consideration rod diameter and plate spacing. They compared the analysis results with the experimental data and concluded that the Bi-steel plates and rods had significant shear strength affected by many important parameters such as plate spacing, and rod diameter and spacing, in addition to the high deformation capacity and ductility. They derived Laplace equation to establish the deformation shape of plates. They claimed that validation against test results verified the accuracy of the suggested equation.

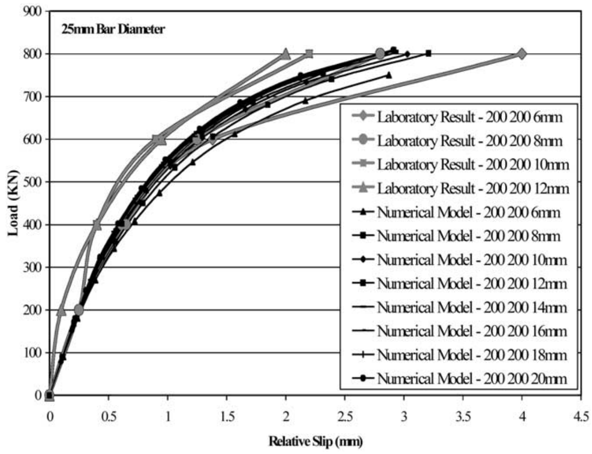
Later in 2003 Clubley et al. [12] carried out further testing and detailing results and conclusions. They conducted twelve push-out tests on two types of specimens; standard specimens, having single concrete blocks, and double-ended specimens with two concrete blocks, with different steel plate spacings and thicknesses, and 25 mm shear connector diameters as shown in Fig. 7 (a, b). One of the tested segments contained at each end four shear connectors. They represented the interface between concrete and steel in finite element analysis by using advanced techniques of smeared and discrete contact element modeling. From their experimental testing and numerical modeling, they concluded that the double-ended specimens experienced decreasing failure load compared to the standard ones. The specimen with four shear connectors reached a greater failure load while the shear resistance per weld stayed the same as in the panel with two shear connectors. They showed that plate thickness and connector spacing governed the failure modes while the plate spacing represented the achievable shear failure load. They introduced two failure modes; a brittle failure (happened by using thick steel plates and small numbers of shear connectors and the failure initiated by shearing of individual friction weld), and ductile failure (happened when the used steel plates were thin and the failure initiated by a large localized deformation of the steel plate followed by plate tearing around the weld). They stated that an excellent agreement between the numerical modelling and the experimental behavior was achieved. Fig. 7(c) shows the effects of their selected parameters on longitudinal slip.



a) Standard size test panels.



b) Double ended test panels.

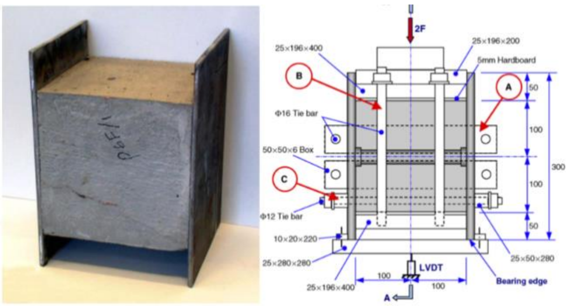


c) Load vs. slip for various geometries

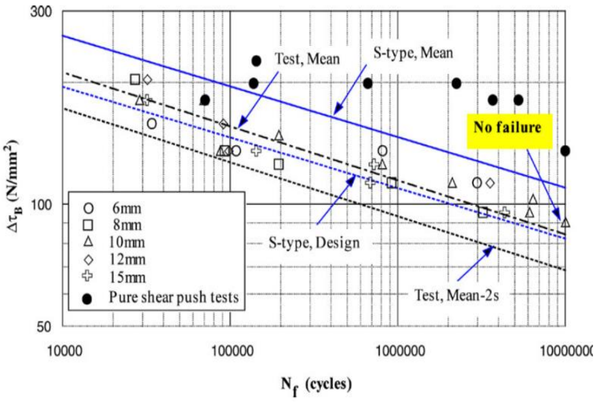
Figure (7): Push-out tests used by **[Clubley et al., 1999]**.

At the same year, Clubley et al. [13] examined with details, in a further work, the localized behavior affecting the shear strength of the SCSS panels. They examined the stress distribution through the plate thickness and on the shear connector surface. They modeled, in details, the effects of variable weld strength and transverse plate separation. The main conclusion from their work was that the effect of the plate thickness and spacing on connector shear strength must be taken into consideration in the subsequent design guidance.

In 2004 Xie et al. [14] carried out experimental and numerical studies on the static performance of the friction-welded embedded connections with the bar in shear in order to determine the bar connector shear strength, stiffness, and tensile stress caused by the applied shear force. Twenty-four specimens of various plate thicknesses were statically tasted as shown in Fig. 8(a). They observed three failure modes: plate tearing, bar shear fracture, and interface shear fracture. The ultimate shear resistance of their embedded connection was increased by about 25% when the steel plate thickness was increased from 6 to 10 mm and further increases did not affect the shear strength and there was a significant tension caused by bar shearing. They carried out finite element analysis by ABAQUS computer program to examine the effects of geometric and material parameters diversities. They used the experimental results to predict the shear strength of the embedded connections by deriving an empirical equation which was compared with existing test results and code specifications such as Eurocode 4 [4], BS5400 Part 5 [15] and the Bi-Steel design guide [10]. They also derived the shear stiffness from the experimental shear force versus slip curve and from the finite element analysis.



a) Test setup



b) Embedded connections under bar shear **[17]**
Figure (8): Push-out test setup conducted in **[References 14 and 17].**

Xie and Chapman [16], in 2005, also carried out experimental and numerical studies on fillet-welded steel connections with single tensioned bars under static and fatigue loading as shown in Fig. 9. They accomplished a finite element analysis to study the effects of plate thickness, the collar (flash) created after welding process, and either possible initial defects or induced fatigue cracks. They found that the static tensile resistance of the embedded connections was governed by the bar tensile strength, except for 6 mm plate specimens. In the fatigue tests, they observed single and double fracture mechanisms. From the results of the fatigue test, they derived experimental stress versus life S–N curves, which were lying between F-type and S-type curves given in BS5400 Part 10.

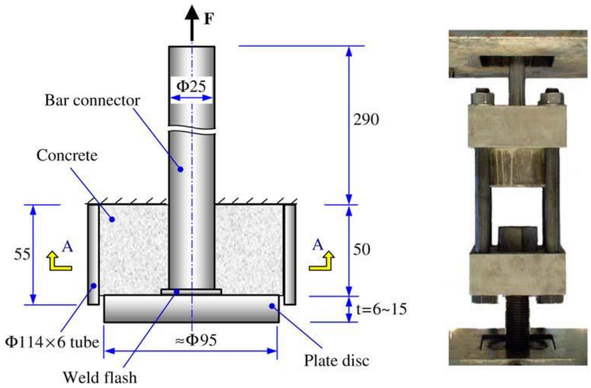


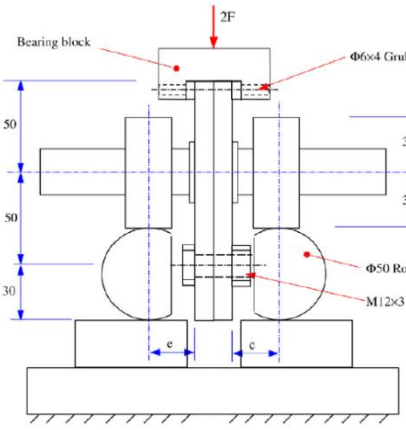
Figure (9): Tensile test rig conducted by **[Xie and Chapman, 2005]**.

Foundoukos et al.[17] carried out, in 2007, 27 fatigue push-out tests whose results are given Fig. 8(b).They compared the test mean and mean-2s curves with the BS 5400 S-type curves. They found that BS5400 S-type design curve could be used for estimation of the fatigue shear resistance of shear studs embraced by concrete. They used test results to derive experimental S-N curves. They obtained four types of fatigue failure: plate cracking, plate tearing, interface shear fracture, and double fracture. They found that the plate thickness had no obvious effect on the fatigue shear strength but affected the fatigue failure mode. They explained the internal behavior of the embedded bar by finite element analysis using a model of nonlinear concrete material.

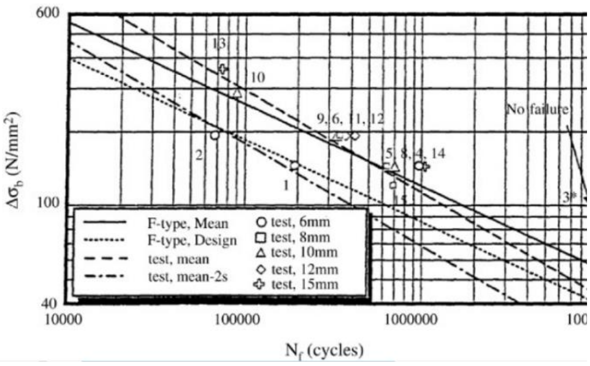
5. Non-embedded Welded Connecter-steel Systems

Xie et al. [18], in 2002, tested a bar-interconnected plate system subjected to bending whose test set-up is provided in Fig. 10(a). Since the dominant bending behavior attained 90% of the whole stress resultant, they reasonably neglected the contribution of shear stress. In specific, the tensile stress and the bar diameter were the prime parameters governing the life of system under high-frequency cyclic load; a phenomenon announced by the diagrammatic S versus N relationship for purely bent bars provided in Fig. 10(b).

Few months later Xie et al. [19] tested plates under tension with unloaded bars and under fatigue action illustrated in Fig. 11 (a). They explained that when onset of failure took place in an exterior bar, fracture befell to a plate accompanied by continuous cyclic action till failure of the neighboring bars. such stress-versus-life history of the plate is diagrammatically explained in Fig. 11(b).

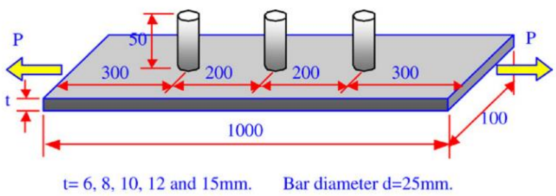


a) Test arrangement.

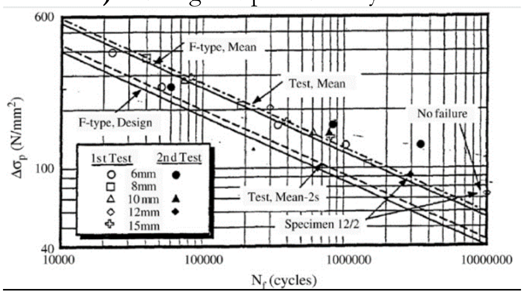


b) S–N lines for bars in bending.

Figure (10): Diagrammatic S versus N relation for bars under pure bending conducted by **[Xie et al., 2002]**.



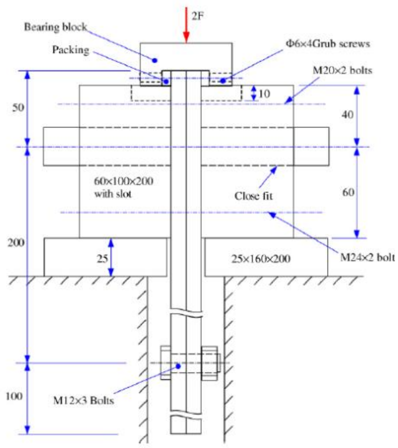
a) Investigated plate-bars system.



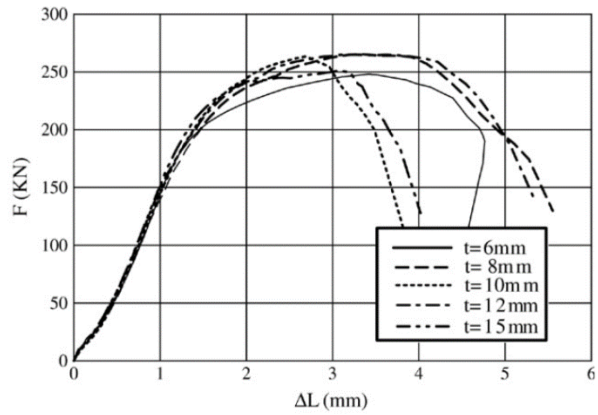
b) Diagrammatic S versus N relation for free plate-bars system.

Figure (11): Samples of cyclically tensioned plate-bars systems tested by **[Xie et al. , 2002]**.

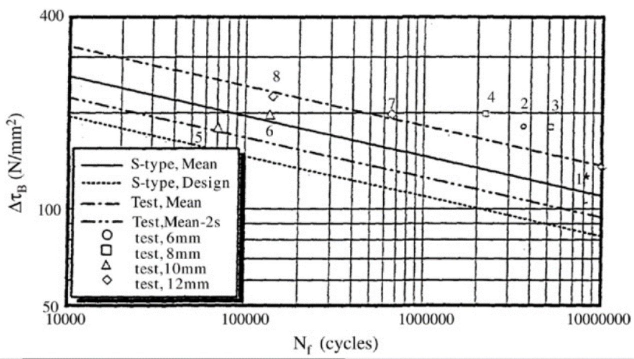
In 2005, Foundoukos et al. [20] carried out a pure shear test as provided in Fig. 12(a). Simulating the traditional push-out test embracing bars, the test plates were subjected to compression at connection and above it. They removed the flash of the fillet-weld to prevent bending of bar, thus obtaining the relationships for static load versus displacement provided in Fig. 12(b), and for pure shear versus N under high-frequency cyclic loading provided in Fig. 12(c). They noticed that the thickness of the plate had an insignificant influence. They also subjected tension to plates in a pull-out manner, as provided in Fig. 12(d), to represent the pure shear state of stress. Finally, they compared their test results with those of tests applying pushing force also charging pure shear stress state to provide an insight into the relationship of beam connection (including tension plates and bars) with push tests embracing embedded bars.



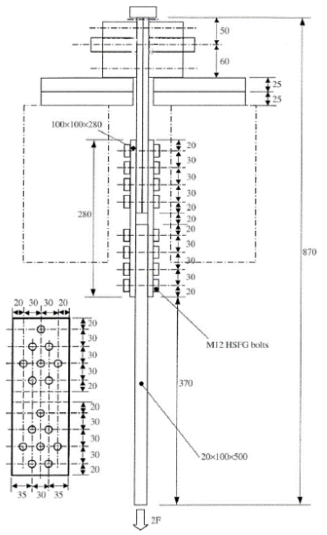
a) Test arrangement for bars in pure shear



b) Pure shear force versus deflection relation for bars.



c) Diagrammatic S versus N relation for bars subjected to pure shear.



d) Test arrangement for bars in pure shear with bars in tension.

Figure (12): pure shear tests conducted by **[Foundoukos et al., 2005]**.

6. Summery and Conclusions

1. SCSS structural systems attain several achievements, relative to the RC ones, like limitation of flexural-resistance steel reinforcing bars, better waterproofing, dispensing with casting formworks, allowing for prefabrication, decreasing time and cost. of the site construction, excellent resistance to blast and impact loading, and easier to repair.
2. The shear connectors may be joined to the steel sections either by welding such as; headed stud, J-hook shear connectors, friction welded connectors, corrugated strip connectors, perfobond connectors…etc., or by tightening such as bolted connectors.
3. The profound role of the mechanical shear connectors in DSC structures is not limited to bonding steel plate faces and concrete thus providing steel-concrete interaction only. It, moreover, resists interface separation and prevents buckling of the steel plates.
4. The Bi-Steel composite system reveals substantial shear resistance depending on various important parameters such as plate thickness and spacing, rod diameter and spacing, and the core material strength. It also exhibits high deformation capacity and ductility under different loading conditions.
5. The utility of J-hook connectors in push-out segments prevents separation, and keeps structural integrity and provides an effective shear strength that largely influenced by strengths and geometries of the concrete and steel components. It also provides an equivalent ultimate strength, stiffness and ductility as the headed stud shear connectors in addition to providing high capability of resisting monotonic, cyclic and impact loads.
6. Sandwich system is similar to reinforced concrete ones in the probabilities of flexural, brittle (shear) failures, or combination of them.

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