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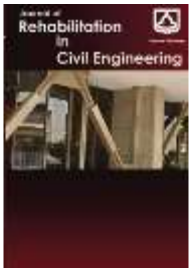

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Testing and Numerical Modelling of Steel-Concrete-Steel with Stud Bolts Connectors Subject to Push-Out Loading

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ABSTRACT

Steel-concrete-steel (SCS) sandwich panels are composed of two steel plates with low thicknesses and high densities and strengths and one thick layer between both plates with low strength and density known as core that is composed of concrete. Cohesive material-epoxy resin or shear connectors are usually applied in order to connect the plates to the concrete core. SCS sandwich composites are being developed so they can be utilized in offshore structures and buildings. Stud bolt is one of the shear connectors and their interlayer shear behavior is examined in the present study. In order to inspect the effect of parameters on interlayer shear behavior of steel-concrete-steel sandwich structure with stud bolt connectors, push-out test is performed under progressive loading. Pursuant to the tests performed, relations are proposed to predict ultimate shear strength and load-slip behavior of samples with stud bolt shear connectors. Consequently, numerical model of push-out test is presented on the basic component of Steel-Concrete-Steel sandwich structure (SCS) with stud bolt connectors. The results indicated that finite element model is consistent with test results applying mass scaling in Explicit Solver with a suitable analysis speed. Applying the regression analysis on the results of 80 numerical models of push-out test,a relation was proposed for shear strength of push-out samples with stud bolt connectors.

1. Introduction

In construction industry, concrete and steel form a large part of structural members in buildings. These materials are applied as ordinary reinforced concrete, prestressed concrete and composite structures. Steel has a strong compression and tension. However,

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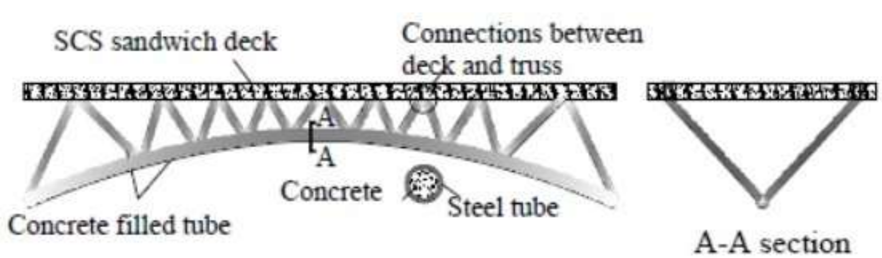
it is a problem in compressive members of buckling. Concrete has a strong compression. Despite to that, it has a very low tensile strength. Concrete is a suitable insulator against fire and is strong under environmental conditions. The reason that these materials are used together is their suitable adhesion and bonding. In reinforced concrete and prestressed structures, steel reinforcement and concrete sections are often applied together due to limited strength and they create an effective design.

Steel-concrete-steel (SCS) sandwich structure is a rather new structure dating back to 1970s (Solomn et al. [2]). This structure exploits the advantages of compressive strength of concrete and tensile strength of steel. SCS sandwich structure has more benefits than reinforced concrete (RC). Some of its benefits include the absence of limitation in flexural reinforcement, removal of concrete formwork, prefabricated application, reduction of cost and construction period, impermeability, higher resistance against scaling under impact loads, and easier repair. SCS sandwich structures are widely applied in civil engineering and onshore and offshore structures as a result to their better performance and advantages [3]. Applications of SCS sandwich structure are indicated in figure 1.

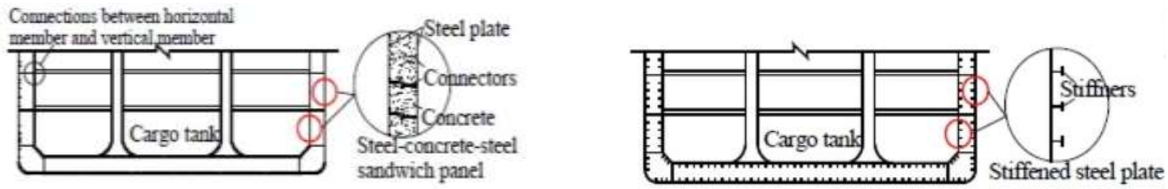
On the other hand, due to suitable concrete confinement by metal shells, suitable behavior is expected against impact and burst. It provides advantages beyond prestressed concrete or steel in terms of safety, serviceability, toughness, economy and easy fabrication [4].

One of shear connectors applied in SCS structures is stud bolt shear connector (figure 2). These connectors are easily accessible and are applied easily in construction sites that produce SCS sandwich structures with stud bolt connectors. On the other hand, they provide full connection between two face plates without any limitation in the thickness between two face plates. Hence,in the present research, the behavior of such these connectors is examined in SCS structures. In figure 3, SCS sandwich slab with stud bolt shear connectors is exhibited that is one of the important applications of such these materials.

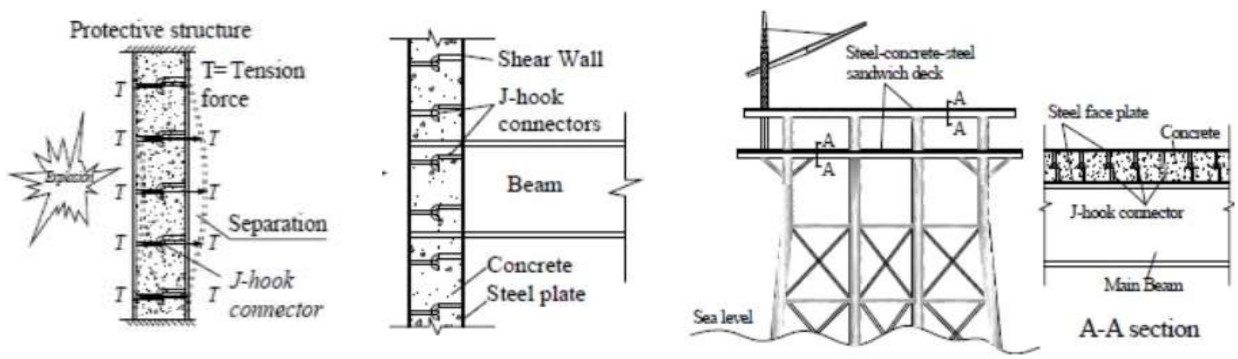
One noteworthy behavior in structural systems such as slab that can be examined in small dimensions is interlayer shear behavior. In the present article, push-out test is performed on SCS test samples with ordinary concrete core and stud bolt connectors to examine interlayer shear behavior. A numerical model is presented based on test results.



a. bridge deck with SCS structure.



b. comparison of ship body with stiffener plate and SCS sandwich panel.



c. SCS protective structure. d. SCS shear wall. e. SCS marine structure deck.

Fig. 1. Applications of SCS sandwich structure [1].

Fig. 2. Stud bolt connector.

Fig. 3. SCS sandwich slab with stud bolt connectors.

2. Literature Review

In SCS sandwich structure, adhesive materials and shear connectors are applied to bond concrete and steel face plates and to achieve composite performance. SCS sandwich structures with adhesive materials have small resistance against vertical shear. Shear connectors can be consider as a solution to this problem and they can connect shear cracks developed in SCS sandwich concrete core and increase shear strength of the section [2].

Different shear connectors are proposed, developed and applied in SCS sandwich structure. Among them, Nelson stud is used extensively. Overlapped shear Nelson studs can transfer interlayer shear forces and prevent from separation of plates from concrete and buckling of steel face plates [5].

The second type of shear connectors in SCS structure is friction welding technology known as bi-steel structure [6]. These connections in bi-steel structures indicate good performance against static loads and fatigue. Friction welding equipment limits the thickness from 200 to 700 mm [7].

Shear strength of shear connectors is azquired by push-out test. In this context, earlier research began by Viest [8] in 1950. Many researches are conducted on this subject by Ollgaard et al. [9,10], Oehlers et al. [11], Xue et al. [12], An et al. [13] etc. Design relations for Nelson stud shear connectors are presented in ACI 318 Appendix D [14], ANSI/AISC 360-10 [15], EC4 [16] and AASHTO [17]. Most of these relations are analytical and are obtained from calibration of push-out test results. Sohel et al. [7] proposed relations for J-hook connectors.

Before performing push-out test, parameters affecting the shear strength of connectors must be chosen. The parameters include geometrical specifications and properties of materials used in SCS sandwich structure. The chosen parameters affecting the shear strength of stud bolt connectors are as follows:

A. Depth at which connector is placed (concrete core thickness)

B. Strength and type of concrete: including compressive strength f_{ck}, slip tensile strength f_{sp}, modulus of elasticity E_c

C. Diameter of stud bolt connector

D. Connector strength: including ultimate strength f_u and modulus of elasticity E_s

3. Properties of Materials

In this section, properties of materials are presented that are acquired by compressive cylindrical samples and cleavage test. Moreover, the results of the strength of tensile samples of plates and stud bolts are presented.

3.1. Mechanical Properties of Concrete

The concrete applied in test samples of the research is ordinary concrete. Push-out samples were concreted in one stage and six standard cylindrical samples were prepared with the diameter 15 cm and height 30 cm to obtain the properties of concrete. Cleavage and compressive tests were performed on the samples at the same time with push-out test. Mean value of the results of cylindrical samples was contemplated as the characteristic concrete strength of push-out samples. Concrete is made in order to achieve the strength 40 Mpa. Table 1 presents values of materials for concrete mixing set up. Cylindrical samples were broken after 28 days by a concrete-breaking jack to obtain the compressive strength. In table 2, compressive strength of cylindrical samples is displayed. Tensile strength test was performed on cylindrical samples with the diameter 150 mm and height 300 mm by cleavage method pursuant to ASTM C496 Standard, and its results are persuaded in table 3.

Table 1. Concrete mixing set up.

Cement	kg/m3	370
Fine aggregate	kg/m3	690
Natural sand	kg/m3	1172
W/C (water to cement ratio)		0.47

Table 2. Compressive strength of cylindrical samples.

Age of sample (days)	compressive strength of specimens (Mpa)	Average compressive strength (Mpa)	Standard deviation	Dispersion coefficient
28	37.1	37.2	0.13	0.0035
	37.4			
	37.2			

Table 3. Tensile strength of concrete cleavage test.

Age of sample (days)	Tensile strength of specimens (Mpa)	Average tensile strength (Mpa)	Standard deviation	Dispersion coefficient
28	2.6	2.87	0.25	0.087
	2.8			
	3.2			

3.2. Mechanical Properties of Steel Materials

Mechanical properties of steel face plates are acquired by push-out test of dog-bone specimens. In table 4, properties of steel plates are presented including yield strength and ultimate strength of push-out test. Stud bolts are made of A193 B7 ASTM steel with the nominal yield strength 725 MPa and nominal ultimate strength 860 MPa. Their detailed properties are portrayed in table 5 based on direct push-out test of tensile specimens.

4. Push-Out Test

In sandwich structures, mechanical connectors are applied in order to provide an effective bond between steel face plates and concrete core. In agreement to Fig. 4, shear connectors must be designed to supply resistance against interlayer slip, concrete pull-out strength and the increase in cross-section shear strength for resistance against vertical load. Therefore, one of the basic parameters in these structures is the interlayer behavior. Many researchers have employed Push-out test to inspect interlayer behavior of SCS sandwiches and other composite structures [18, 19]. Shear strength of stud bolt connectors in SCS panels can be obtained applying push-out test. For the first time, the test was demonstrated to examine the shear behavior of SCS sandwich panels with bi-steel shear connectors [20].

Table 4. Mechanical properties of steel plates.

Thickness (mm)	Yield Stress (Mpa)	Ultimate Strenght (MPa)	Strain at ultimate strenght	E_s (Gpa)
4	250	380	0.3	207
6	285	495	0.23	202
8	411	615	0.176	205
10	367	620	0.198	203
12	310	516	0.180	207

Table 5. Mechanical properties of stud bolts.

diameter (mm)	Yield stress (Mpa)	Ultimate strenght (MPa)	Strain at ultimate strenght	E_s (Gpa)
12.7	760	903	0.065	219
15.88	720	865	0.062	203
19.05	731	870	0.064	210
22.23	718	842	0.060	207

5. Test Samples

Push-out test samples were prepared in two classes. In the first class, concrete thickness was 100 mm, and it was 200 mm in the second class. Geometric parameters of samples are denoted in figure 5 and their values are acquired for 16 samples planned for push-out test as in table 6.

Formwork and concrete work of the samples are presented in figure 5. Steel face plates play the role of a mould at both sides of the concrete core and two wooden pieces are used for formwork of the other sides of the concrete core. Surfaces of wooden pieces are covered by oil before concrete work. Face plates are pierced by a drill to let the stud bolt pass through it. Before fixing the stud bolt, two internal nuts are mounted on it and they pass inside the plates. Likewise, external nuts are fixed outside of the plates and after aligning the distance between plates, the nuts are tightened. Samples are prepared for concrete work and they are compressed by a vibrator.

Table 6. Properties of samples prepared for push-out test.

No.	Sample	h_c (mm)	Steel plate				Stud bolt	
			t (mm)	f_y (Mpa)	f_u (Mpa)	E_s (Gpa)	d (mm)	f_u (Mpa)
1	6S-1	100	6	289	489.39	204.9	12.7	902.85
2	6S-2	100	6	289	489.39	204.9	15.88	902.85
3	6S-3	100	6	289	489.39	204.9	19.05	864.87
4	6S-4	100	6	289	489.39	204.9	22.23	864.87
5	6S-5	200	6	289	489.39	204.9	15.88	864.87
6	6S-6	200	6	289	489.39	204.9	22.23	864.87
7	8S-1	100	8	417	622.27	203.2	15.88	864.87
8	8S-2	100	8	417	622.27	203.2	22.23	864.87
9	8S-3	200	8	417	622.27	203.2	15.88	864.87
10	8S-4	200	8	417	622.27	203.2	22.23	864.87
11	10S-1	100	10	403	622.27	205.9	15.88	864.87
12	10S-2	100	10	403	622.27	205.9	22.23	864.87
13	10S-3	200	10	403	622.27	205.9	15.88	864.87
14	10S-4	200	10	403	622.27	205.9	22.23	864.87
15	12S-1	100	12	306	524.06	208.7	15.88	864.87
16	12S-2	100	12	306	524.06	208.7	22.23	864.87

Notes: Dimensions of steel face plates 250mm*300mm, Dimensions of core concrete 250mm*250mm, f_c=40MPa;E_c=29.4GPa

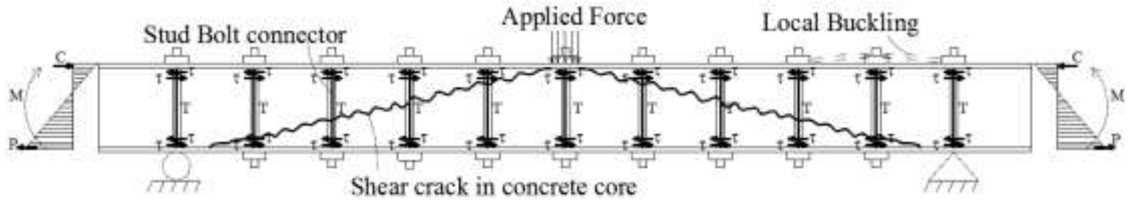


Fig. 4. Transfer of internal forces and supply of transverse shear resistance through Stud bolt shear connectors.

a. samples preparation before concreting b. concreting samples

Fig. 5. Samples preparation.

Equipment of push-out test includes hydraulic jack, load cell with the capacity 500 KN (with the accuracy 0.01 KN), two LVDTs installed at the upper and lower parts of concrete core and data processing system in the present study as is presented in figure 5. A metal rigid plate with the thickness 40 mm is placed on the upper part of the concrete core to help the load spread extensively. The upper surface of samples is aligned horizontally before loading. Loading of all samples continued to the failure limit and the applied load was transferred to the data processing system through load cell and slip of concrete core over steel plates by LVDTs in the upper and lower parts of the core (figure 6).

6. Failure Mode

Failure mode of the samples under push-out test is the failure mode of concrete without remarkable deformation in steel components that occurs as a result to the weakness of the concrete strength to the large diameter and small length of stud bolt, as indicated in figure 7. In this case, cracks develop around the stud bolt and reach the upper surface of concrete. The failure mode is observed in samples with the thickness 100 mm. In some samples, the concrete crack is perpendicular to the stud bolt and in other cases, crack development destroys the concrete as wedge-shape.

The next failure mode is the combination of concrete failure and deflection of stud bolt (figure 8). This failure occurred in samples with the thickness of concrete 200 mm, in which the stud bolts could deflect as a result of the increase in their length. In this case, stud bolt deflection resulted in the crack of the concrete around it and crack development reached the concrete surface.

Load-slip curves of samples with the thickness 100 mm and samples with the thickness 200 mm are given as normalized load in figure 9. Pursuant to the figure, ductility and energy absorption of the samples with the thickness 200 mm increased due to deformation of steel components.

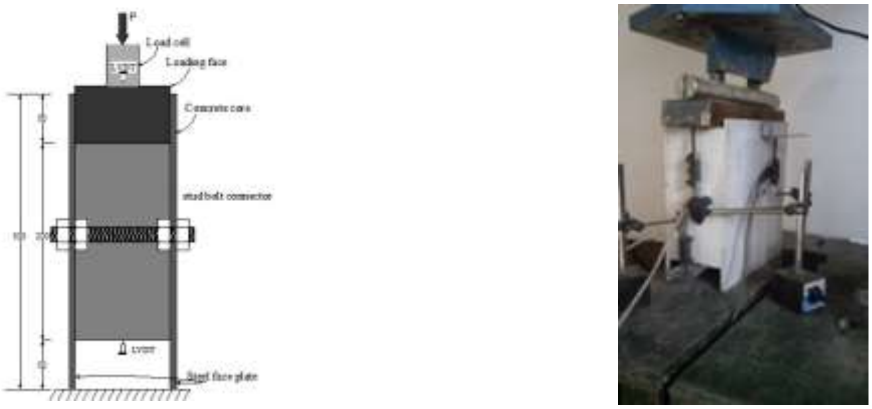


Fig. 6. Push-out test set up.

a. set up of the device b. status of sample after failure

Fig. 7. Loading of 10S-1 sample.

a. set up of the device b. load application c. status of sample after failure

d. effect of stud bolt inside the concrete | e. bending effect of stud bolt inside concrete | f. stud bolt bending

Fig. 8. Loading of 6S-6 sample.

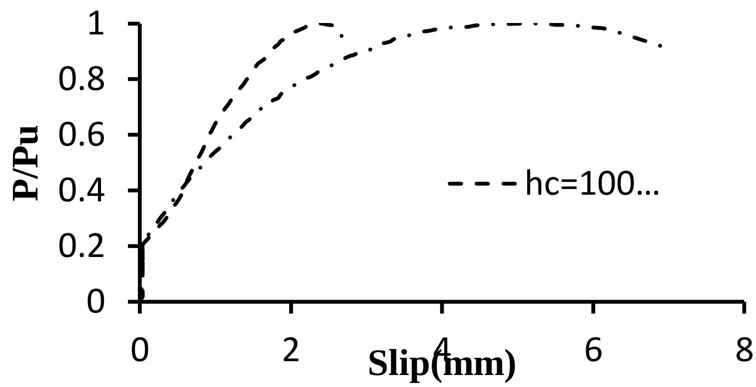


Fig. 9. Load-slip curves.

7. Behavior of Stud Bolt Shear Connectors under Push-Out Test

In this section, interlayer behavior of SCS sandwich panels is examined in samples introduced in the testing plan. To this end, the results of tests of the research on SCS sandwich samples with bi-steel connection are compared with those in earlier research. Table 7 displays the maximum load registered in push-out test and their failure modes.

7.1. Comparison with Previous Results

In order to compare the results, earlier researches are applied that are conducted on SCS sandwich samples with bi-steel connection. Like stud bolt samples, both ends are connected to steel plates in bi-steel samples, and their behavior is comparable. To this end, the results of the tests on bi-steel samples performed by M.Xie et al. [20] are compared with those of the tests performed in the present study. In table 3, samples are presented whose geometric parameters are more similar to the samples in M.Xie et al. study. A huge difference in these samples is the higher strength of stud bolt (865 Mpa) than bi-steel shear connectors, which is almost 1.5 times more than the ultimate strength of bi-steel shear connectors. This large difference did not ameliorate SCS behavior with stud bolt shear connectors. However, as a result of weakness of concrete strength, it led to brittle failure and separation of concrete before stud bolts reach the ultimate strength.

In the samples of the study by M.Xie et al., there were failure modes of lamellar tearing and rod cutting, and ultimate capacity of steel components was applied in all samples. According to table 8, average shear strength of bi-steel samples is about two times more than in samples with stud bolt shear connector. Therefore, it is expected that using high strength concrete or ultra-strong concrete can improve the behavior of SCS sandwich panels with stud bolt. Moreover, the decrease in diameter of stud bolts increased ductility and energy absorption in the present study.

Table 7. Maximum load registered in push-out test and their failure modes.

No.	Sample	$P_{exp.}(kN)$	Failure mode
1	6S-1	78.94	Concrete cleavage
2	6S-2	97.18	Concrete cleavage
3	6S-3	103.23	Concrete cleavage
4	6S-4	116.29	Concrete cleavage
5	6S-5	144.35	Concrete cleavage and stud bolt deflection
6	6S-6	164.04	Concrete cleavage and stud bolt deflection
7	8S-1	112.00	Concrete cleavage
8	8S-2	182.12	Concrete cleavage
9	8S-3	151.98	Concrete cleavage and stud bolt deflection
10	8S-4	209.13	Concrete cleavage and stud bolt deflection
11	10S-1	123.13	Concrete cleavage
12	10S-2	190.40	Concrete cleavage
13	10S-3	163.19	Concrete cleavage and stud bolt deflection
14	10S-4	237.04	Concrete cleavage and stud bolt deflection
15	12S-1	132.13	Concrete cleavage
16	12S-2	219.45	Concrete cleavage

Table 8. Comparison of the results of push-out test of SCS samples with stud bolt connectors and those with bi-steel connectors.

SCS with bi-steel connectors						SCS with stud bolt connectors					
Sample	Rod diameter (mm)	F_u (N/mm2)	F_c (N/mm2)	P_u (kN)	Failure mode	Sample	Stud bolt diameter (mm)	F_u (N/mm2)	F_c (N/mm2)	P_u (kN)	Failure mode
6S	25	586	40	359.3	lamellar tearing	6S-6	22.23	865	40	164.04	Concrete cleavage and stud bolt deflection
8S	25	586	40	376.3	lamellar tearing	8S-4	22.23	865	40	209.13	Concrete cleavage and stud bolt deflection
10S	25	586	40	436.9	lamellar tearing	10S-4	22.23	865	40	237.04	Concrete cleavage and stud bolt deflection
12S	25	586	40	450.1	rod cutting	12S-2	22.23	865	40	219.45	Concrete cleavage

8. Numerical Analysis of Push-Out Test

Interlayer shear behavior is an essential behavior in structural systems, including slab, that can be examined in small dimensions. To this end, Push-out test is demonstrated on SCS test samples with ordinary concrete core and stud bolt connectors in the present article. Consequently, a numerical model is introduced based on the test results.

Finite element method is one of the best numerical analysis technique. Although no literature was found on stud bolt finite element modeling in SCS system, limited literature exists on other forms of connectors. Foundoukos et al.[21] presented a 2D model for Bi-steel beams. However, the model could not take the effect of 3D behavior of the interaction between shear connectors and concrete. Shanmugam et al. [22] replaced the increase in concrete shear strength as a homogeneous non-isotropic material by shear connectors in double skin sandwich structure with overlapped headed studs. However, there is no structural behavior of shear connectors in this model. Smitha and Kumar [23] replaced nonlinear spring elements by overlapped headed studs to connect concrete slab to I-shaped steel profile in finite element model of steel-concrete composite structure. In this simplification, transverse shear resistence as a result to the interaction between connectors and concrete is not included. Khorramian et al.[24] conducted numerical simulations of steel-concrete composite with angle shear connectors as well. When modeling J-hook connectors, Yan et al. [8] applied nonlinear spring element instead of geometrical modeling of interlocked and coupled hooks due to the complexity of hooks modeling.

According to literature review, all developed models have limitations in suitable simulation of concrete-connector interaction. In any case, shear connectors in the models introduced in earlier research are dissimilar from stud bolt modeling. Thus, a 3D finite element model is developed by ABAQUS CAE Software to simulate Push-out test under quasi-static loading to achieve a finite element model with a suitable speed and precision. As a result to the geometrical complexity, ABAQUS/Explicit Solver is applied. Mass scaling is utilized for quasi-static loading and to save the time of the analysis with an acceptable precision. Numerical models are verified based on the test results.

9. Finite Element Model

ABAQUS/Standard Software was the first option for model analysis that is mainly suitable for static analysis. Notwithstanding , concrete material model using this software makes the analysis divergent in a small part of maximum load applied. Furthermore, it was observed that convergence problems occurred for the cracked part after tensile stiffening.When tensile strength of concrete vanishes, the element's stiffness vanishes perpendicular to the crack, since no reinforcing factor is defined for resistance against separation in order that tensile stresses and divergence of solution are removed[19]. Hence, ABAQUS/Explicit Solver was employed to analyze Push-out tests with stud bolt connectors. Nonetheless, since the solution is dynamic in this analytical software, quasi-static analysis was defined.

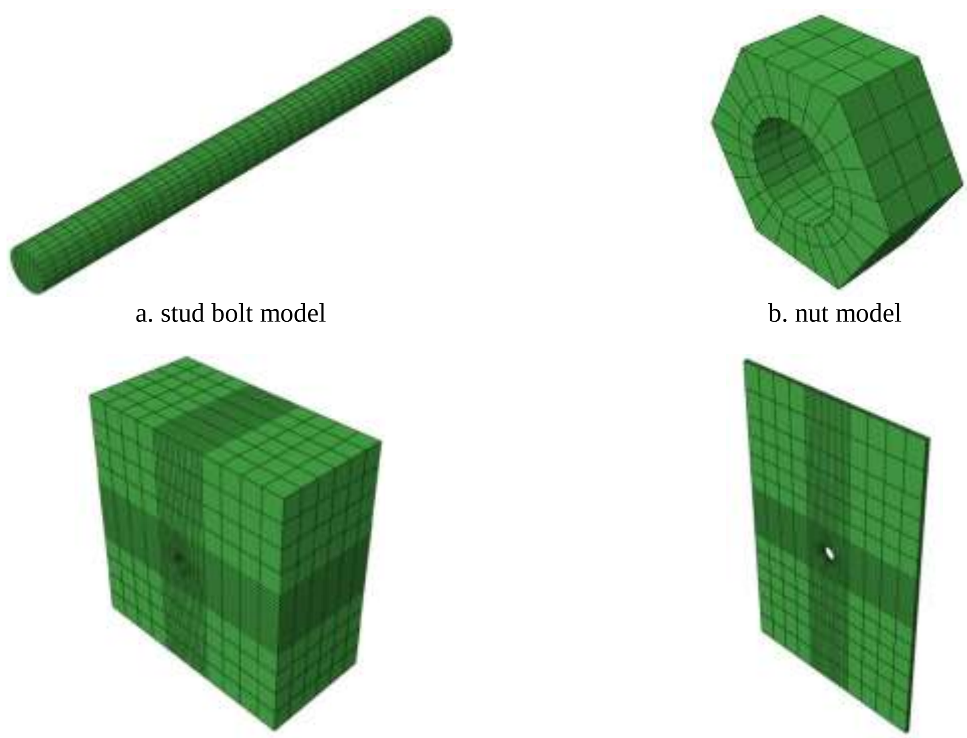
10. Finite Element Model of Push-Out Test

In finite element model of push-out test, components were produced and meshed. The components included stud bolt, nut, concrete core, steel plate and rigid component for loading. Finite element model of the components is illustrated in figure 10.

Finite element model of push-out test is provided as in figure 11. Steel face plates, Stud bolt connector, concrete core and load cell form the main elements of the model. All of the elements are modeled by 3D eight–node continuum element (C3D8). This type of mesh is chosen because of its complexity of the contact region of shear connectors and concrete core . The overall mesh size is 20 mm. Finer mesh size is applied for a better simulation in the bond between shear connector and steel face plates and positions of contact between connector and concrete core.

Concrete damage plasticity model is used for concrete corematerial in push-out test simulation. The model is based on continuous plastic behavior in which two main failure mechanisms are taken into account including compressive crushing and tension crack of concrete. The yield function proposed by Lubliner et al. (1989) and modified by Lee and Fenves (1998) is applied for a different evaluation of the strength under the effect of tension and compression. In this model, isotropic damage and independent potential current law are assumed (ABAQUS and Manual 2010).

Isotropic/kinematic stiffening model with Von Mises yield criterion is applied in order to define yielding for steel material in ABAQUS Material Library. Elastic Young's modulus,, and poisson's ratio must be defined for elastic behavior of steel material.



a. stud bolt model

b. nut model

c. concrete core model

d. steel plate model

Fig. 10. Finite element model of push-out test components.

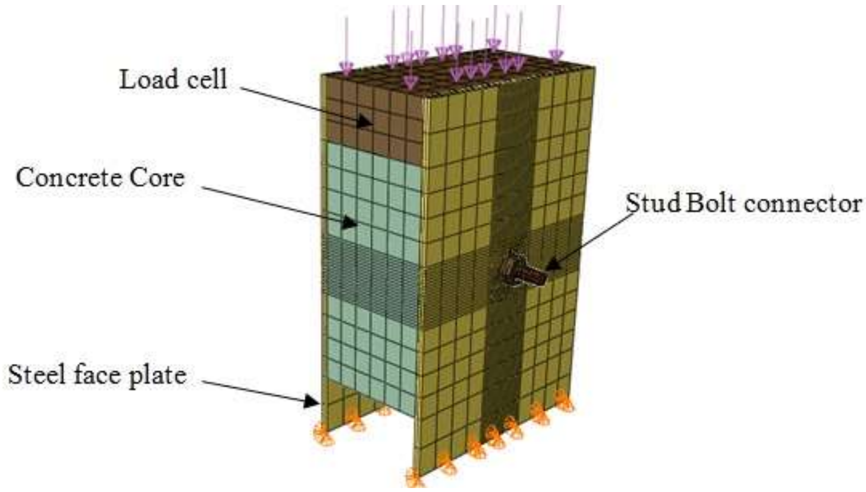


Fig. 11. Finite element model for Push-out test.

10.1. Boundary Conditions, Loading, Interactions and Solutions

The lower end of steel face plates acts as a support in push-out test and hence, their displacement is bound in all directions as in figure 11. Pursuant to the test and the low rate of loading, modeling is performed based on quasi-static loading as well. The contact between concrete and steel elements is “surface-to-surface” and it is “hard contact” in normal direction and is penalty friction in tangential direction. In “hard contact” formulation, the surfaces exert pressure on each other when they are in contact; thus, there is no tensile force for separating them. Penalty friction is also tangent to the surface and depends on the friction coefficient between two surfaces. Only “hard contact” is defined in the contact between steel elements.

Since the loading is quasi-static, ABAQUS/Explicit Solver is applied for the analysis. ABAQUS/Explicit default settings are in a way that the precision and effectiveness of the solution are optimized for a wide range of nonlinear problems. In the next section, quasi-static behavior of finite element model is evaluated.

10.2. Quasi-static Behavior of Finite Element Model

In push-out test, loading rate was low enough to be able to perform the numerical analysis independent of acceleration. On that account, as it was described above, kinetic energy must not exceed 5 to 10% of the internal energy to establish quasi-static behavior in finite element model. Moreover, kinetic energy must not have fluctuations and must display a logical behavior. In figure 12(a), kinetic energy curve(ALLKE) has logical behavior for the sample 6S-4 and its values are low compared to the internal energy curve(ALLIE) in figure 12(b). Applying mass scaling with target time step did not let the kinetic energy exceed 2% of the internal energy in all samples.

10.3. Sensitivity Analysis of Mesh Size

In order to acquire the most suitable mesh size, samples with different mesh sizes of finite elements were analyzed and a sample of their results is obtained pursuant to figure 13. In this figure, 10S-3-10mm sample has the maximum mesh size 10 mm and 10S-3-8-20mm sample has the maximum mesh size 20 mm and 10S-3-30mm sample has the maximum mesh size 30 mm and 10S-3-

35mm sample has the maximum mesh size 35 mm. It is observed that 10S-3-8-20mm sample has the lowest difference with the test sample.

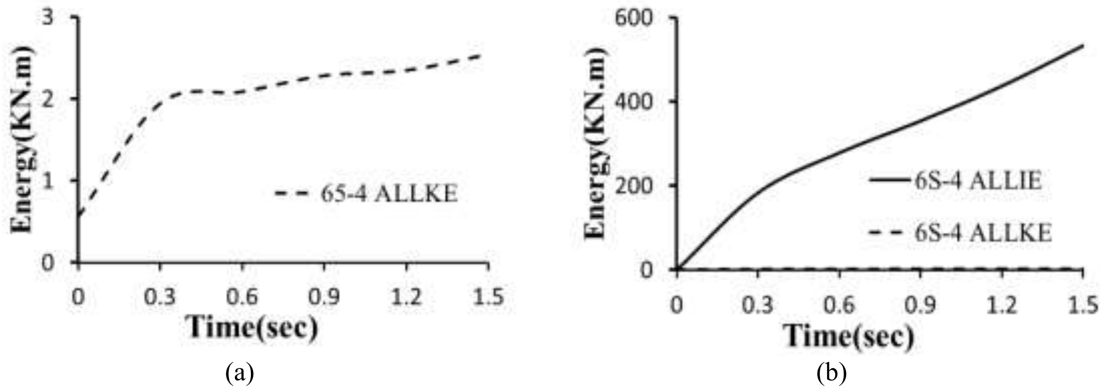


Fig. 12. a. kinetic energy of FE model of the sample 6S-4 b. Comparison between kinetic energy and internal energy of finite element model for the sample 6S-4.

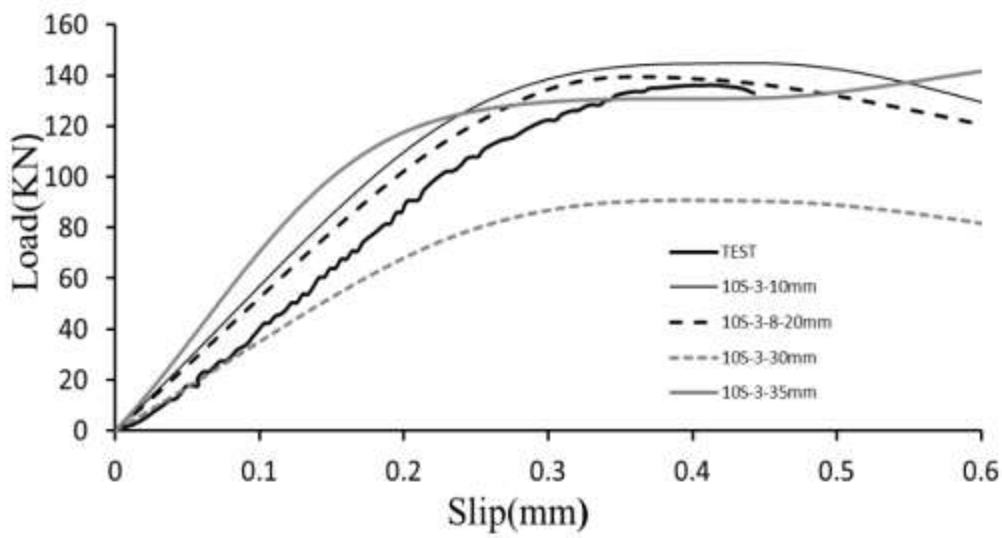


Fig. 13. Load-slip curve of 10S-3 sample with different mesh sizes.

10.4. Verification of FE Model Based on Push-Out Tests

FE is verified based on the load-slip curves, ultimate shear strength and failure modes resulting from Push-out tests.

10.4.1. Load-Slip Curves of Push-Out Test

In figure 14, load-slip curves of the results of test samples and FE model are compared. It is observed that the curves are consistent with each other in terms of initial elastic stiffness and threshold of plastic behavior. Errors in comparison of curves can be due to errors in laboratory equipment and modeling simplifications.

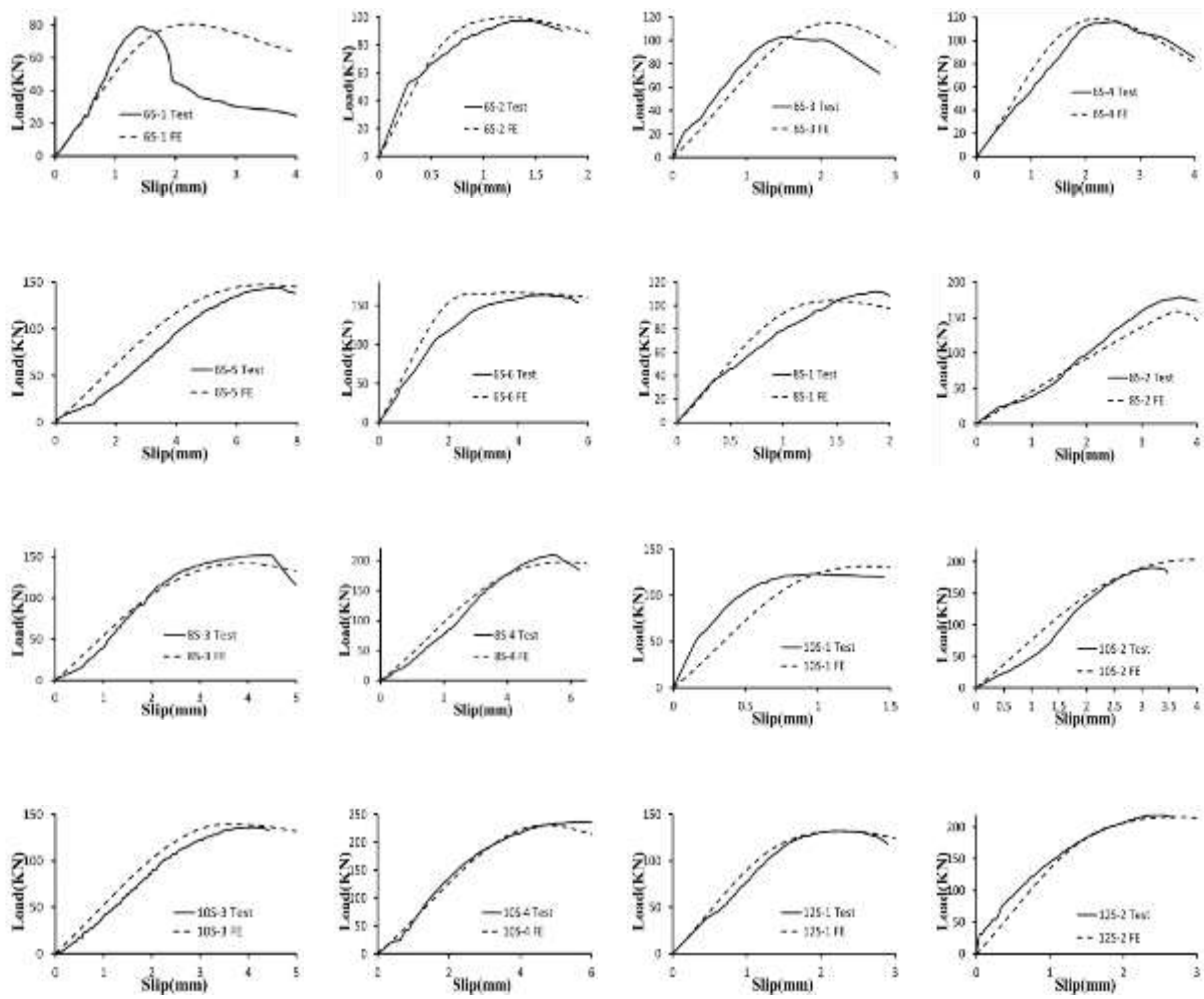


Fig. 14. Comparison of load-slip curve between tests and finite element model.

10.4.2. Ultimate Shear Strength and Failure Modes of Push-Out Test

In table 9, ultimate shear strength of push-out test samples with stud bolt connectors are compared with the results of FE modeling. The mean value and Coefficient of Variance (COV) of the ratio of shear strength acquired from the tests to the ultimate shear strength from FE modeling are 1.016 and 0.058, respectively. The values exhibit that FE modeling is performed correctly.

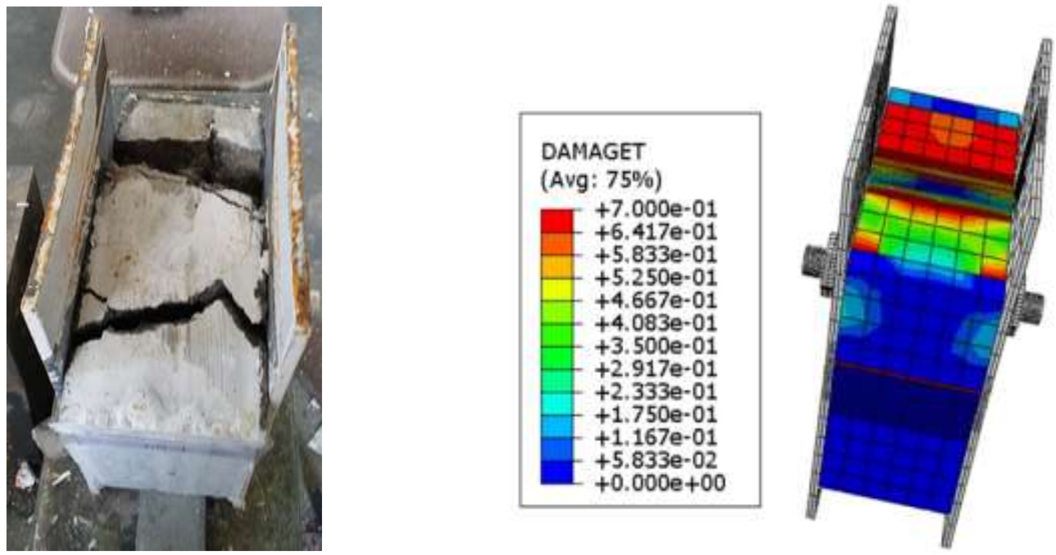
The failure mode observed in push-out test is concrete cracking failure (CC) for all samples. Concrete cracking failure (CC) occurred in the modeling as well. In samples with the concrete thickness 100mm, the concrete destroyed but stud bolt did not deform noticeably. In test samples with the concrete thickness 200 mm, stud bolt also deflected in addition to demolition of concrete.

Table 9. Comparison of the results of test and finite element model.

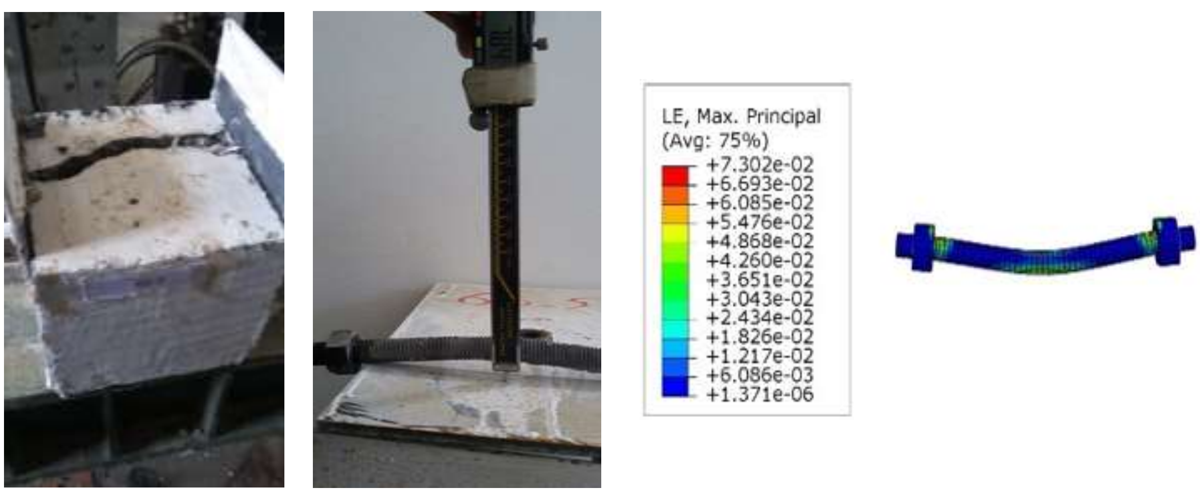
No.	Item	P_{Test}(kN)	Test failure mode	P_{FE}(kN)	FE failure mode	$\frac{P_{Test}}{P_{FE}}$
1	6S-1	78.94	CC	77.68	CC	1.02
2	6S-2	97.18	CC	99.80	CC	0.97
3	6S-3	103.23	CC	114.94	CC	0.90
4	6S-4	116.29	CC	118.54	CC	0.98
5	6S-5	144.35	CC	143.98	CC	1.00
6	6S-6	164.04	CC	165.42	CC	0.99
7	8S-1	97.18	CC	98.71	CC	0.98
8	8S-2	178.87	CC	155.95	CC	1.15
9	8S-3	151.98	CC	141.78	CC	1.07
10	8S-4	209.13	CC	191.62	CC	1.09
11	10S-1	123.13	CC	123.70	CC	1.00
12	10S-2	190.40	CC	203.03	CC	0.94
13	10S-3	136.19	CC	138.02	CC	0.99
14	10S-4	237.04	CC	224.05	CC	1.06
15	12S-1	132.13	CC	122.60	CC	1.08
16	12S-2	219.45	CC	210.93	CC	1.04
Mean						1.016
COV						0.058

Note: CC concrete cracking failure

In figure 15, failure modes of the test are compared with FE modeling. figure 15(a) illustrates concrete cracking in the sample 6S-4. In this sample, concrete cracking occurred with no deformation of connectors due to the low length of stud bolt compared to the high diameter (22.23 mm) of shear connectors. As the stud bolt length increased and the diameter reduced to 12.7 mm in the sample 6S-5, noticeable deformation and failure threshold were observed in shear connectors in addition to concrete cracking (figure 15(b)). The comparison between crack growth path and stud bolt deformation in the test and numerical modeling verifies the results of finite element analysis.



concrete cracking failure (sample 6S-4)



(b) concrete cracking failure with stud bolt also deflected (sample 6S-5)

Fig. 15. Failure mode of the test and FE modeling.

11. The Proposed Relation of Ultimate Shear Strength Based on Numerical Analysis

After verifying the model, relation (1) was proposed to calculate ultimate shear strength per unit area (P_u/A_s) applying regression analysis on the results of 80 numerical models of push-out test. Variables affecting ultimate shear strength include tp, f_c and h_c / d that are contemplated in this relation.

Applying regression analysis on the results of 80 numerical models of push-out test, the relation (1) is proposed for shear strength of push-out samples with stud bolt connectors:

$$\frac{P_u}{A_s} = 0.047 t_p^{0.22} f_c^{0.3} \left(\frac{h_c}{d}\right)^{0.46} \qquad (1)$$

The results from the proposed relation of the prediction of ultimate shear strength are compared with the results of numerical analysis. In figure 16, distribution of the proposed relation is compared with 80 numerical models in the error range $\pm 15\%$. In agreement to the relation (1), mean value and error variance of the numerical analysis results are 0.83 and 0.08, respectively.

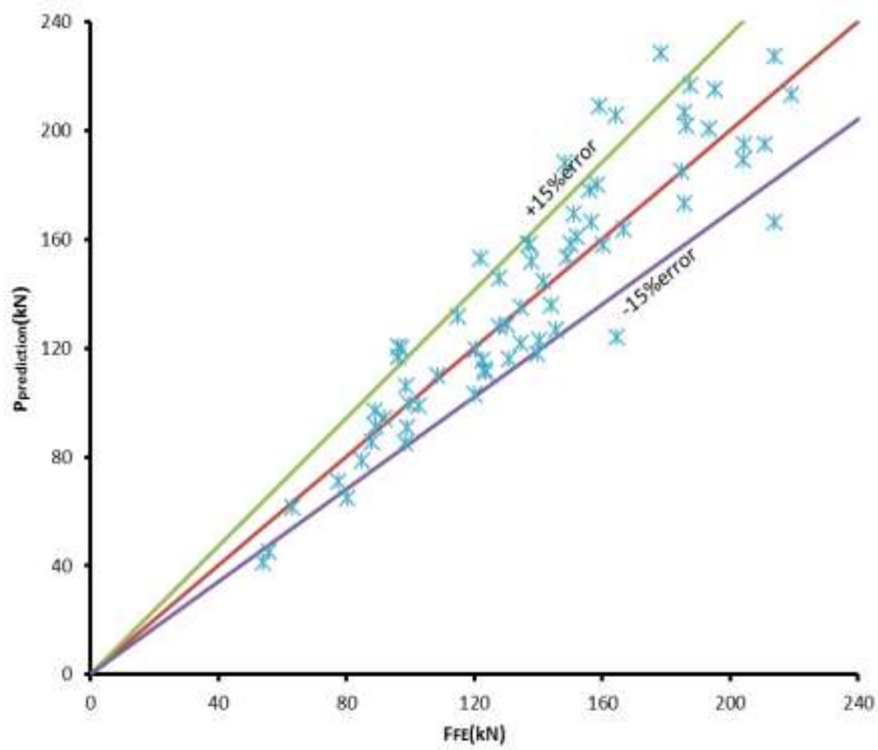


Fig. 16. Comparison of the distribution of the results of ultimate shear strength from the proposed relation and numerical analysis.

12. Conclusions

In the present article, load-slip behavior and shear strength of stud bolt connectors in SCS sandwich composites were examined on 16 test samples to perform push-out test, and after analyzing test data, failure modes were observed including concrete failure and permanent deformation of stud bolts

Pursuant to 16 push-out test samples with stud bolt connectors, a 3D finite element model is presented applying ABAQUS/Explicit Software. The results of push-out tests revealed that despite the complexity of the finite element model, slip-shear behavior of stud bolt connectors and failure modes of SCS sandwiches can be simulated accurately with an acceptable analysis speed using Explicit quasi-static analysis.

Applying the verified model, shear strength of other samples of SCS model of stud bolts was acquired. According to the results of push-out test modeling of stud bolt connectors, diagram of kinetic energy changes was not allowed to exceed 5 to 10% of the internal energy before failure. So, quasi-static behavior of the models was ensured.

Using the regression analysis on the results of 80 numerical models of push-out test, a relation was proposed for shear strength of push-out samples with stud bolt connectors.

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