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STRUCTURAL BEHAVIOR OF STEEL-CONCRETE-STEEL SANDWICH STRUCTURE WITH NEW TYPE OF SHEAR CONNECTORS

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ABSTRACT

The aim of the current research is to investigate the structural behavior of steel-concrete-steel sandwich beams with a new suggested shear connectors. The shear connector was manufactured from deformed rebar in the form of stirrups. Four push out specimens were tested to obtain direct shear strength for the new type of shear connectors. Also four full size steel-concrete-steel sandwich beams were tested under three points loading. All beams were simply supported. The experimental results showed three failure modes as follow: (1) flexural failure; (2) shearing of shear connectors; and (3) buckling in compression plate. The use of proposed shear connectors from deformed steel bars produces a good connection between steel plates and concrete core, where the load capacity of steel-concrete-steel beam with long leg stirrups (L. connector) is larger than other beams. The ultimate load of beam B1 (steel-concrete-steel sandwich beam with L. connector) is 0.125 greater than the ultimate load of beam B2 (steel-concrete-steel sandwich beam with J-hook connectors).

KEYWORDS: Steel-concrete-steel, Shear connector, Sandwich beams, Pushpout.

1. INTRODUCTION

Steel-concrete-steel (SCS) sandwich structures are a new form of construction (Yan et al., 2015) [1], consisting of a layer of central plain concrete sandwiched between two steel plates, connected to the concrete core by shear connectors, Fig. 1. The performance of SCS sandwich structures depend mainly upon efficient interaction and transfer of stresses between steel plates and concrete core. This can be achieve by using shear connectors. The SCS sandwich structures can be classified into two main categories, depending on shear connector types:

- SCS sandwich structures with mechanical shear connectors
- SCS sandwich structures without mechanical shear connectors, in which the steel plate are glued to concrete core (Solomom et al., 1976).

The concept of steel-concrete-steel sandwich construction began when Solomon et al. (1976) submitted steel-concrete-steel sandwich beam as an alternative form of bridge decking for medium and long span deck. In steel-concrete sandwich structure, the mechanical connectors are usually used to transfer shear forces across the steel-plate and concrete core interface. The shear connectors are also used to prevent steel face plate separation and uplift (Liew and Wang, 2011).

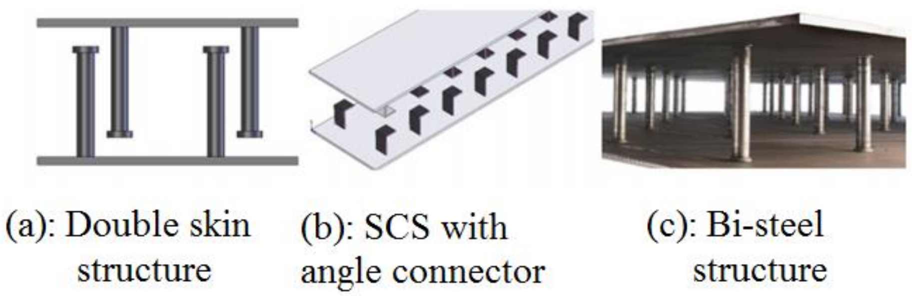


Fig. 1. Types of SCS structures [5].

Double skin composite (DSC) elements are formed from two steel skins connected to an infill of concrete with welded stud connectors, see Fig. (1a). Wright et al., 1991, described design development and experimental studies on DSC system. A design model developed from previously reported scale model tests and similar to that used for reinforced concrete was proposed. A series of full scale DSC beams were tested and then used to verify the theoretical model. Comparisons of analytical and experimental results showed that the design model was suitable for most simple beams and gives a good prediction of behavior, (Wright et al., 1991).

McKinlly and Boswell, 2002, was developed the original shear-stud concept to currently friction-weld round steel bars to both plates in a simultaneous operation. This process not only makes the units easy to handle, but also provides sufficient strength to resist the internal hydrostatic pressures due to fresh concrete. This product is called Bi-steel, see Fig. 1c. In this studied, investigated the elastic and plastic behavior of a series of sixteen full-scale, simply supported beams, under three-point loading. These tests compared existing, double skin method, and new construction methods, Bi-steel method, and were conducted until collapse due to local buckling of the compression steel plate. The test program was supported by a series of analytical solution covering the elastic and plastic performance of specimens. The analytically determined moment of resistance agrees well with experimental data, the standard deviation of the results being 4.25%, (McKinlly and Boswell, 2002).

Schlesman and Russell 2004 studied applications of a SCS sandwich panels for nuclear reactors. The idea was to provide high performance solutions against traditional constructions form such as reinforced concrete structure. The SCS member appeared to be stronger, more solid and more durable than the reinforced concrete member. When comparing two beams with the same load conditions, the SCS beam was shallower than the reinforced concrete beam. This was explained by the fact that the reinforcing steel face plates have an ideal locations. In addition, it was stated that the construction of SCS sandwich structures seems to be better than reinforced concrete structures. It can be estimated that the overall construction time can be reduced by 50% (Schlesman and Russell 2004).

The advantages of the SCS sandwich system are that the external steel face plates act as both main reinforcement and external mold. The steel face plate also acts as impermeable layer, blast, and impact resistant membranes (Farhan and Hussain, 2010). The steel-concrete-steel sandwich applications has been extended to a verity of structures including submerged tunnels, storage vessels, shear walls in buildings and oil production structures, (Farhan and Hussain, 2010; Roberts, 1996).

In this study a new shear connector type is proposed. It was manufactured from deformed rebar in the form of stirrups, as seen from Fig. 2, and welded to the steel plates to serve as shear reinforcement to concrete core in addition to shear connectors. Four full scale simply supported beams were tested under three point-static loading. Stirrups type and the traditional J-hook shear connectors were investigated.

2. EXPERIMENTAL WORK

2.1. Details of specimens

The experimental program is divided into two parts. The first one is devoted for the behavior and strength of the suggested new type of shear connecters. In the second part, tests were conducted on SCS sandwich composite beams. Table 1 lists the SCS sandwich beams dimensions, plate thickness, and the properties of materials, and Table 2 lists the dimensions and plate thickness for push out specimens. Fig. 3 shows the typical push-out specimens, while Fig. 4 displays the typical SCS sandwich composite beam. All the beams have overall length 3000 mm. The effective length is 2800 mm and the width of beam is 500 mm while the thick of concrete core is 300 mm. Thickness of tension plate is 8 mm, while thickness of compression plate is either 4 mm or 8 mm, see Table 1. The shear connectors are connected to top and bottom steel plates by welding. The experimental results of push out test are used to find the spacing of shear connectors. The spacing of shear

Table 1. Dimensions and specifications of SCS sandwich beams.

Beam No.	Shear connector	Top plate thickness mm	Bottom plate thickness mm	Spacing of shear con./ top mm	Spacing of shear con./ bot. mm	Effective span mm	Width mm	Concrete core thickness mm
B1	L.	8	8	230	230	2800	500	300
B2	J.	8	8	230	230	2800	500	300
B3	J.	4	8	155	230	2800	500	300
B5	L.	4	8	155	230	3000	500	300

Table 2. Dimensions and properties of push-out specimens.

No.	Dimensions mm			Shear connector type	Steel plate thickness mm	No. of shear connectors in each plate
	H	W	L			
P.L.8	600	300	500	L.	8	2
P.L.4	600	300	500	L.	4	2
P.J.8	600	300	500	J.	8	2
P.J.4	600	300	500	J.	4	2

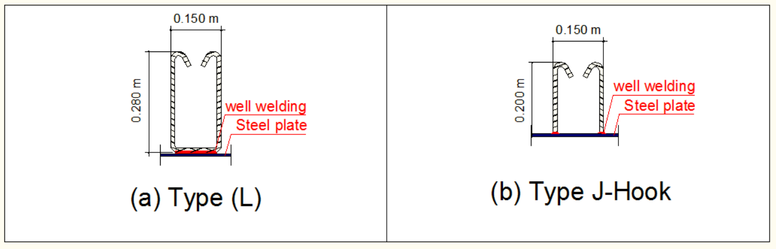


Fig. 2. Types and dimensions of shear connectors.

connectors can be calculated by the set of equations below (Abdul Razzaq, 2018):

$$N_{t,Rd} = A_{st} f_{yst} \tag{2}$$

$$n_c \geq N_{c,Rd} / P_{c,Rd} \tag{3}$$

$$N_{c,Rd} = A_{sc} f_{ysc} \tag{4}$$

Where: n_c and n_t = number of shear connectors in compression and tension steel plate, respectively.

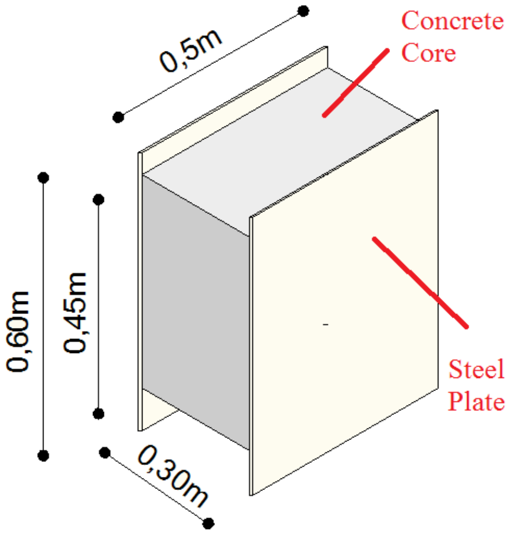


Fig. 3. The dimensions of push-out specimens.

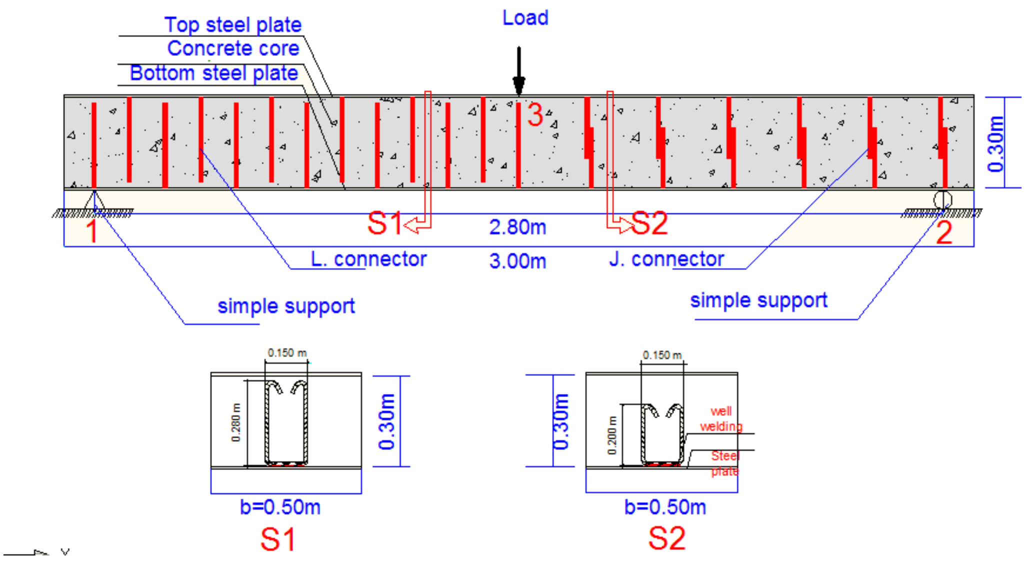


Fig. 4. Typical SCS beams.

$P_{c,Rd}$ and $P_{t,Rd}$ = shear resistance of the compression and tension shear connector, respectively.

f_{yst} and f_{ysc} = characteristic strength of compression and tension plates, respectively.

A_{st} and A_{sc} = area of tension and compression steel plates, respectively.

There is another parameter that limits the distance between the shear connectors, this is specified for preventing the buckling of compression steel plates (Abdul Razzaq, 2018).

$$ {}^{S_c}/_{t_c} \leq 40 \qquad (4) $$

where S_c is the distance between shear connectors of compression steel plate and t_c is the thickness of compression steel plate.

Table 1 shows the distance between the shear connectors used in the different SCS sandwich beams.

2.2. Material properties

Ordinary Portland cement (type I) was used to cast the specimens in this study. The ordinary Portland cement was manufactured by Al-Mabruka company (Produced in Basrah-Iraq). The cement control sample is tested in the labratories of Civil Engineering Department and Chemical Engineering Department at the University of Basrah. Crushed gravel from the Badra and Jassan quarry (Iraq-Kute) was used. Natural sand from Al-Romela region in Al-Basrah city was used in concrete mixes. The test results conform to ASTM C136-02, ASTM C117-02, ASTM C33-03 and Iraqi specifications No. 45/1984. Tables 3 and 4 show the grading and physical and chemical properties of coarse aggregate, respectively. The grading of fine aggregate is shown in Table 5. Table 6 shows the physical and chemical properties of the sand used for casting the push-out specimens and SCS sandwich composite beams.

2.3. Steel plates and reinforcement bar

Iranian steel plates were used in the manufacture of push-out specimens as well as the SCS sandwich beams. The steel plates were used with thicknesses of 4 and 8 mm. Three specimens from each thickness were tested to specify the properties of the steel plates. The dimensions of steel plate specimens are shown in Fig. 5. The test results conform to ASTM A36 and A572. Table 7 shows the properties of steel plates with thickness of 4 and 8 mm.

The deformed reinforcement steel bars were used in manufacturing the specimens. The bars are of diameter 12 mm. They were used as shear connectors. The tensile test was carried out according to ASTM standard (ASTM A615/A615 M-09) to determine the properties of reinforcement bars. Three samples with a length of 1 m were tested. Table 8 lists the results of the test.

Table 3. Sieve analysis for gravel.

Sieve size, mm	Passing material, (%)	ASTM C33-03, (%)
25	100	100
19	98	90-100
9.5	48	20-55
4.75	7	0-10
2.36	1.5	0-5
0.075	0.03	1≤

Table 4. Physical and chemical properties of gravel.

Properties	Test result	Iraqi specifications, No. 45/1984
Specific gravity	2.69	-
Sulfate content %	0.08%	≤ 0.1%
Absorption %	1.248%	-

Table 5. Grading of sand.

Sieve size, mm	Passing material, (%)	ASTM C33-03, (%)
9.5	100	100
4.75	`100	95-100
2.36	95	80-100
1.18	73	50-85
0.60	50	25-60
0.30	22	5-30
0.154	3	0-10
0.075	1	3% For concrete exposed to friction; 5% for another concrete type.

Table 6. Physical and chemical properties of sand.

Properties	Test result	Iraqi specifications, No. 45/1984
Specific gravity	2.63	-
Sulfate content %	0.31 %	≤ 0.50%
Absorption %	0.73%	-
Moisture content %	0.32%	-

2.4. Push out specimens

Table 2 lists the dimensions and properties of push out specimens. The dimensions of the push-out specimens have been chosen such that be similar to those of the SCS sandwich composite beams. Therefore, the dimensions of the push-out specimens are: 600*500*300 mm, see. All push out specimens were loaded with a static load in several increments and the slip displacement associated with each load increment was measured by dial gauges. Fig. 6 shows the test set up for the push-out specimens.

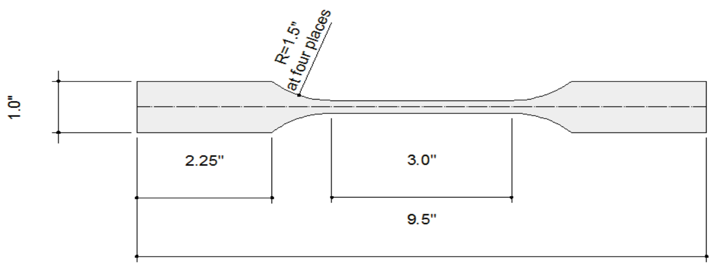


Fig. 5. Dimensions and details of steel plate's Specimen.

Table 7. Properties of steel plates.

Thickness of steel plates mm	Yield stress MPa.	Ultimate strength MPa.	Young's modulus of elasticity, MPa.
4	384	507	201000
8	381	518	203000

Table 8. Properties of reinforcement bar.

Diameter mm	Area mm^2	Weight g/m	Yield stress MPa.	Yield strain	Ultimate strength MPa.
11.8 deformed	109.4	885	571	.00278	668

Fig. 6. Test set up for the push-out specimens.

2.5. Procedure for push out test

1. Before testing, the push-out specimens are prepared in order to record the required measurements.
2. For specimens that having plate of 4 mm thickness, the plates are supported at bottom of specimen to prevent the buckling through testing process.
3. Three dial gauges were installed, two for measuring the side displacement and the third for measuring the slip.
4. The load is then applied gradually on the specimen and each load increment does not exceed 10% of the expected ultimate load. The load is increased until up to failure.
5. At each load increment all required measurements are recorded.

6. Six cylinders and six cube specimens are casted for the purpose of determining the concrete properties. Three cylinders and six cubes are tested to obtain the compressive strength, and three cylinders are tested to obtain splitting tensile strength.

2.6. SCS sandwich composite beams

The process of preparation, and casting of SCS sandwich beams is as follow:

1. Shear connectors are fastened by welding to the face of the steel plates at the pre determined positions.
2. A thick nylon layer is spread out on the laboratory floor.
3. The steel plates are placed vertically so that the distance between them is 300 mm, Fig. 7. They will be work as side formwork.
4. The ends of beams formwork are closed with timber.
5. Casting of concrete core is done. The specimens are casted into three layers and each layer is vibrated by an electric vibrator. The cubes and cylinders are also casted at the same time.
6. After a suitable period, the mold is opened so that the SCS sandwich beam is ready for water curing. The mold of cylinders and cubes are also opened. The SCS sandwich beams as well as cubes and cylinders are well covered with damp textile coverings and then are covered with a thick nylon layer to prevent the water evaporation.
7. After 28 days, the SCS beams is ready for final test.

2.6.1. **Procedures for SCS sandwich beam test**

The test of SCS sandwich beam is carried out according to the following stages:

1. The cubes specimens were tested to find the cube compressive strength of concrete (fcu).
2. Three cylinders are tested to find the cylinder compressive strength (f'c) as well as modules of elasticity (Ec).
3. The remaining cylinder specimens are tested to find the splitting tensile strength (ft).
4. The sides of the SCS sandwich beams are painted with non-plastic white color to reveal the hair cracks clearly.
5. The dial gauges are fixed in suitable position to measure deflection and slip between steel plates and concrete core and they were distributed as shown in Fig. 8.

6. The electrical strain gauges are used to measure strain in concrete core and steel plates. Ten electric strain gauges are fixed as shown in Fig. 9.
7. The load is applied in successive increments up to failure and each increment the required measurements are recorded.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. Push-out specimens

3.1.1. Load slip relation

Table 9 lists the experimental results for push out specimens. The mode of failure of each push out specimens was listed in Table 9. Fig. 10 shows the load slip relation of push-out specimens.

Fig. 7. The formwork of beams.

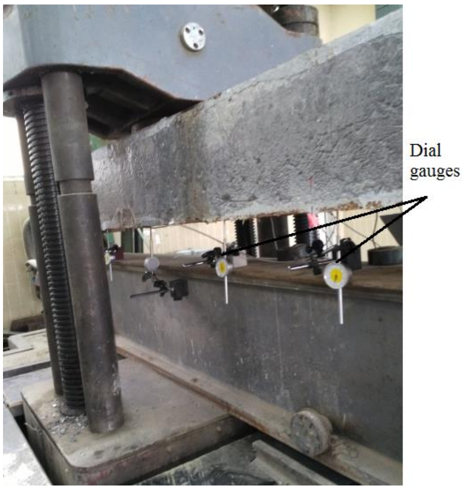


Fig. 8. Beam B3 at universal testing machine.

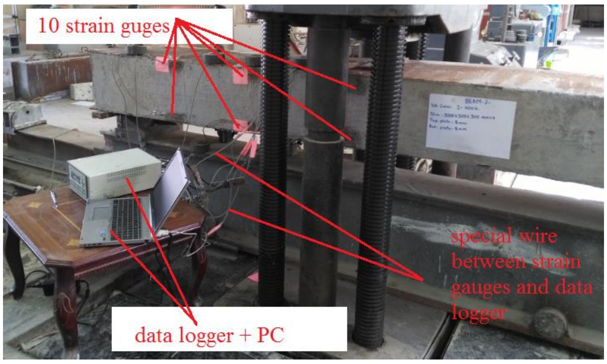


Fig. 9. The dial gauges used to measure deflection.

Table 9. Results of Push out specimens test.

Designation	Type of Shear connector.	No. of shear connectors	Yield stress of bar f_{by} MPa.	Cylinder compressive strength of concrete (f'_c) MPa.	Thickness of steel plate mm	Yield stress of steel plate f_{py} MPa.	Ultimate load P_u N	Ultimate shear strength of each connectors N++	Slip Associated with Ultimate load mm	Failure mode
P.L.8	Type L	4	420	26.4	8	381	300000	75000	4	Y.S.*
P.L.4	Type L	4	420	24.7	4	381	200000	50000	11	Y.S.+Bu.**
P.J.8	Type J	4	420	23.8	8	381	255000	63750	4.09	S.S.***
P.J.4	Type J	4	420	26.7	4	381	255000	63750	4.26	Bu.+S.S.***

++: Ultimate shear strength of each connectors = Ultimate load/ No. of shear connectors.

* Y.S.: Yield of shear connectors.

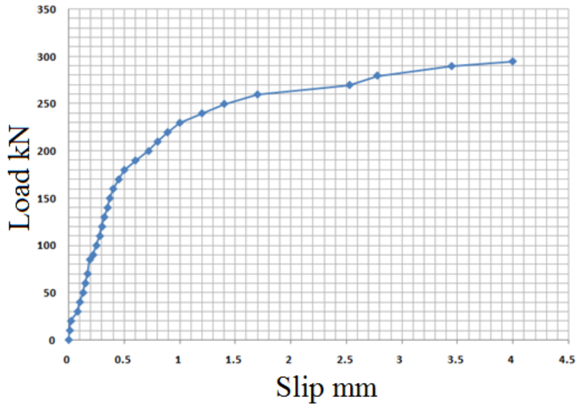
** Bu.: Buckling of steel plates.

*** S.S.: Shearing of shear connectors at welding area.

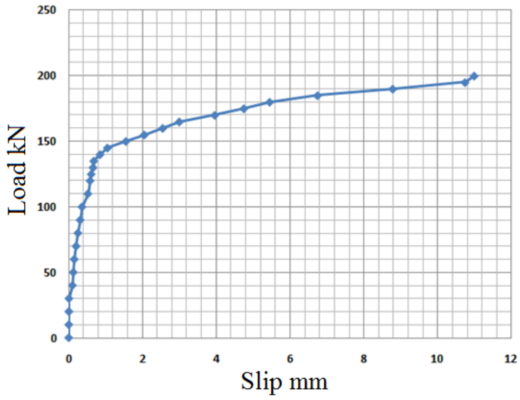
3.1.2. **Failure mode**

Examining the failure modes of push-out specimens, three main types of failure mode are observed and can be explained as follows:

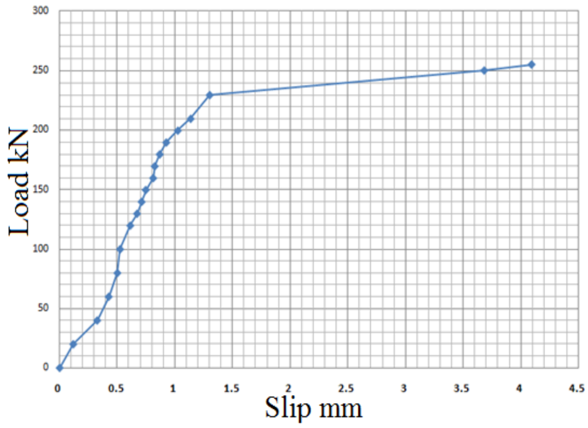
1. Yield of shear connectors: where shear connectors are failed before the concrete core and steel plates, Fig. 11. This mode of failure was happened in test of specimens P.L8 and P.L4.
2. Buckling in steel plate: This type of failure usually occurs in the case of the thin steel plates (4 mm thickness). In this study, this type of failure occurred in P.L4 and P.J4, Fig. 12.
3. Shearing of shear connectors: This type of failure occurred in PJ8 and PJ4 specimens, Fig. 13. In these specimens the connectors are subjected to cut near the welding region. This may be attributed to change in properties or area of connectors due to welding.



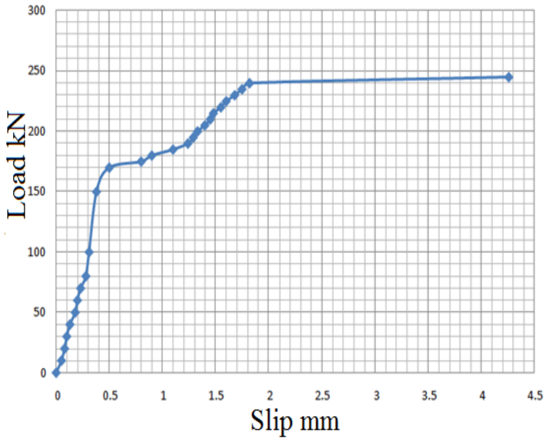
(a): Load-slip curve of specimens P.L.8.



(b): Load-slip curve of specimens P.L.4.



(c): Load-slip curve of specimens P.J.8.



(d): Load-slip curve of specimens P.J.4.

Fig. 10. Load slip curves of push-out specimens.

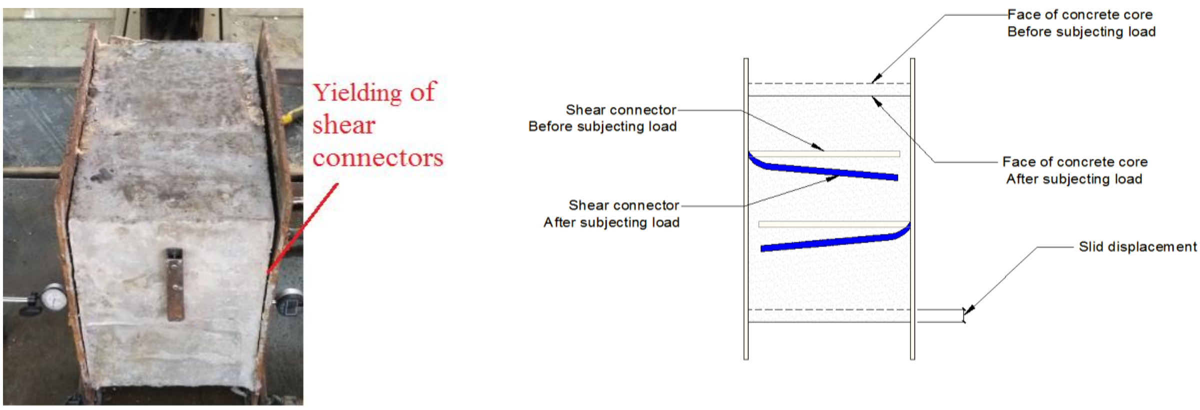


Fig. 11. Yield in shear connectors.

Fig. 12. Buckling of steel plate.

Fig. 13. Shearing of shear connector.

3.1.3. Analysis push out test results

1. The L. shear connector in specimen P.L.8 has the highest shear resistance, Table 9. This is due to two reasons: the first one, is the embedded length inside the concrete core. When the embedded length of the shear connectors increases, the resistance of the shear connectors to pull out increases too. The second reason, is the long length of the welding area of the shear connectors to the steel plate. For this type of connector the welding is along the horizontal part, which is in contact with the steel plate.
2. When comparing the behavior of models PL8, and PJ8, it is observed that the load slip relation are close to each other.
3. The failure mode for specimens PL8 due to yield in shear connectors, while the cause of the failure in the PJ8 specimen is the cut of the shear connector.
4. The shear strength of J-hook is the highest shear strength if the steel plate is 4 mm thick, as detailed in Table 9.
5. When comparing the behavior of PL4, and PJ4 specimens, it is noted that the load slip curves are close to each other.
6. The failure mode for PL4 is basically due to buckling of steel plates, while the cause of failure in the PJ4 is the cut of the shear connectors with the buckling of steel plates.

3.2. Steel-concrete-steel sandwich beams

Table 10 lists the experimental results for SCS sandwich beams. Fig. 14 shows the load deflection relationships of SCS sandwich beams. Figs.15 and 16 shows the load strain relations of top and bottom plates for beam B2 respectively. The variation of strain across the depth of beam B2 at the central section is shown in Fig. 17.

3.2.1 Modes of failure

There are four types of failure:

a- flexural failure, Where the middle crack occurs when the load reaches 110 kN, for beam B2, and as the load increases, the cracks become widen, as shown Fig. 18.

b- Shearing of shear connectors: Where cutting occurs in the shear connectors close to the welding area with the steel plates, as shown in Fig. 18. This failure occurs for beams B2 and B3.

c- Buckling in compression plate, Fig. 19. This mode may be seen in beam B3 and B5.

Fig. 20 displayes the mode for beam B5. SCS sandwich beam B5 is failed by flexural filure addion to significant alongation in shear connectors for bottom steel plates, as shown in Fig. 21.

3.2.2 Beams B1, B2:

Fig. 22a shows the comparison between the load deflection behavior of beams B1 and B2.

3.2.3 Beams B3 and B5

Fig. 22b shows the comparison between the load deflection behavior of beams B3 and B5.

3.2.4 Analysis of experimental results

From Table 10 and Fig. 14, and Fig. 22, the followings notes can be observed:

1. The ultimate load of the beam B1 is highest than the other beams. The ultimate load of beam B2 is less than the ultimate load of beam B1 by 0.125, Table 10.
2. The failure of beams B2 and B3 is suddenly occurs by shearing of shear connectors, while B1 and B5 showed more ductile behavior.
3. The relations of the load-deflection for beams B3 and B5 are almost identical in the linear phase.

Table 10. The test results of SCS beams.

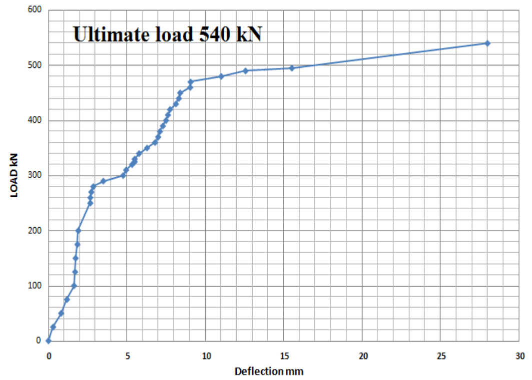
Type of beam	Ultimate Load kN	Load at first crack kN	Extrapolated deflection mm at ultimate load	Extrapolated strain/top plate X10^-5 at ultimate load	Extrapolated strain/bottom plate 10^-5 at ultimate load	Mode of failure
B1	540	135	28	/	/	F.F.*
B2	480	90	11.71	-66.255	139.305	S.S.**
B3	450	70	19.558	-210.149	154.494	S.S.+B.CP.***
B5	515	95	22.13	-128.44	138.416	F.F.+ E.S.

*F.F.: Flexural failure.

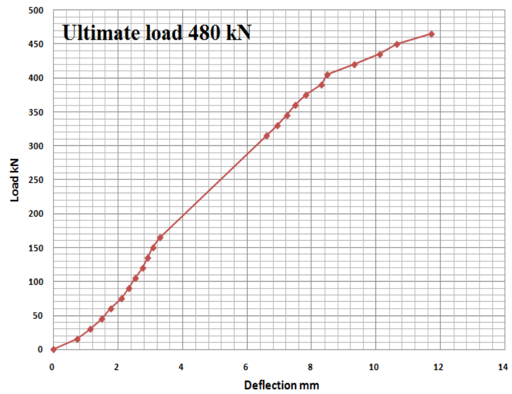
**S.S.: Shearing in shear connectors.

***B.CP.: Buckling of compression plate.

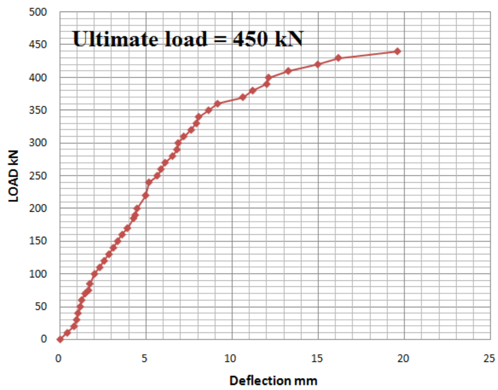
****E.S.: Elongation of shear connectors.



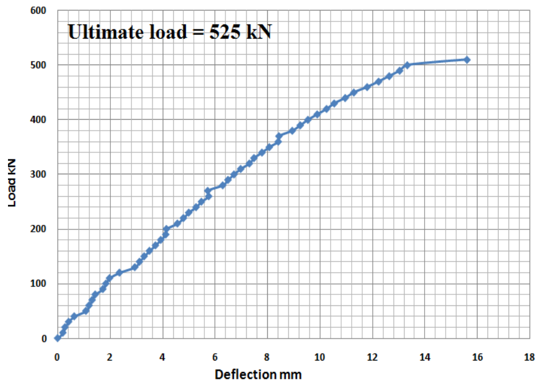
(a): Experimental load deflection relation



(b): Experimental load central deflection relation



(c): Experimental load central deflection relation for beam B3.



(d): Experimental load central deflection relation for beam B5.

Fig. 14. Experimental load central deflection relation of SCS beams B1,B2,B3 and B5.

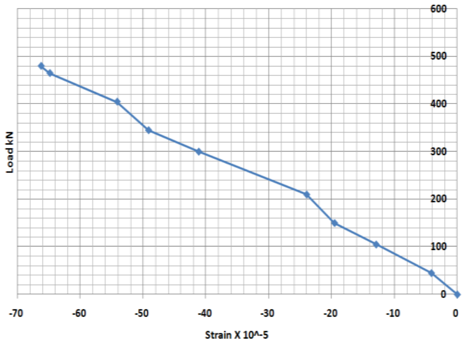


Fig. 15. Load strain relation for the top steel plate of beam B2.

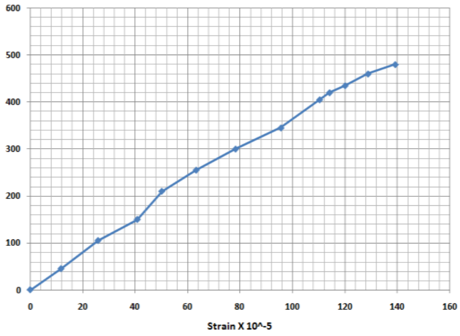


Fig. 16. Load strain relation for the bottom steel plate of beam B2.

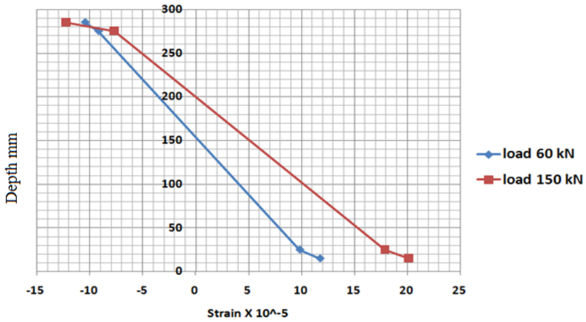


Fig. 17. The change of strain across the depth of beam B2, .

Fig. 18. Mode of failure for SCS sandwich beam, B2, shearing in shear connectors.

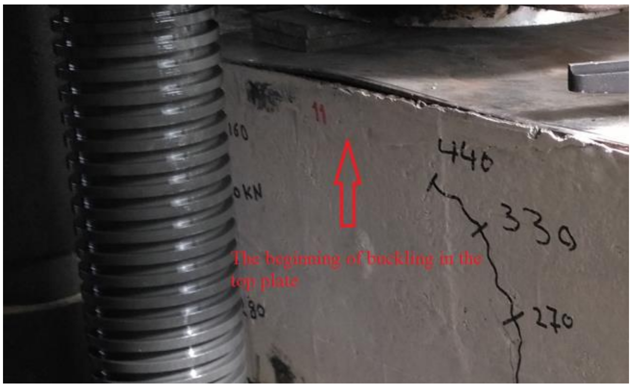


Fig. 19. Buckling in the top steel plate.

Fig. 20. Mode of failure for SCS sandwich beam, B5.

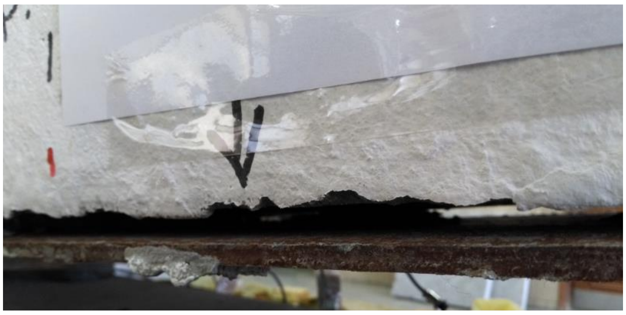
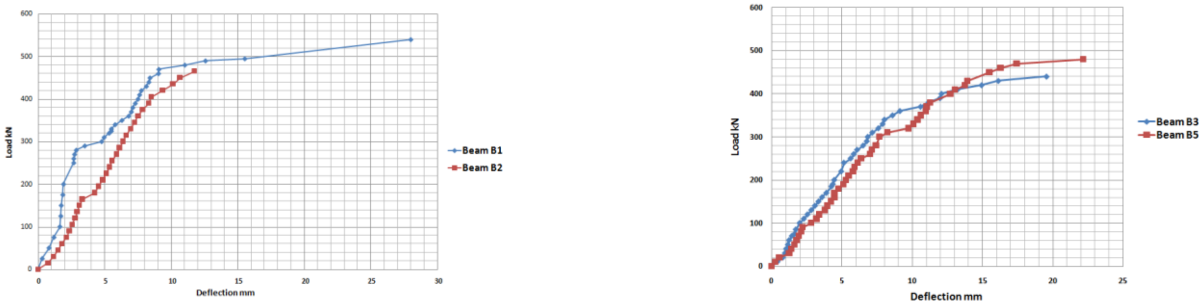


Fig. 21. Separation of bottom steel plate and elongation of shear connector.



(a):Comparison of load-deflection relations of SCS beams B1 and B2.

(b): Comparison of load-deflection relations of SCS beams B3 and B5.

Fig. 22.Comparison of load-deflection curves of SCS beams.

4. CONCLUSIONS

4.1. Push-out

1. It can be noted that the thickness of the steel plate has an effective influence on the shear strength of the shear connector. The ultimate load of specimen PL8 with 8 mm thickness is 48% greater than specimen PL4 with 4 mm thickness. This can be explained by the shear connectors are subjected to shear, tension or compression, and moment. The moment depend on the end fixity, which depend on plate thickness

2. The specimens manufactured from plates with thickness of 4 mm, failed as a result of the occurrence of buckling in the steel plates.

3. The long leg stirrups (L. shear connector) have the highest shear resistance.
4. All push-out specimens have ductile behavior except PJ8 and PJ4. This is because the failure of these two specimens occurs at the point of contact with steel plates by cut of connector.

4.2. Steel-concrete sandwich beams

From the experimental results the following conclusions may be drawn:

1. There are three main types of failure: a) flexural failure, b) buckling of compression plate, c) shearing or cut of the shear connectors.
2. All beams undergo significant flexural cracks. Most of the cracks in the concrete during the loading stages are confined to the middle third of the beam span.
3. The use of proposed shear connectors from deformed steel bars produces a good connection between steel plates and concrete core.
4. The SCS sandwich beams having L type shear connectors (B1) reveal better performance than the rest of beams. The behavior of these beams is ductile and before failure they show large deflection with many wide cracks.
5. The failure of SCS beams having J-type shear connectors (B2, B3), is a sudden failure by cut of connectors.
6. The cracks begin to appear in concrete when the load reaches 15-25% of the ultimate load.
7. The specimens manufactured by using top steel plate with thickness 4 mm undergo failure by buckling of this plate.

5. REFERENCES

Abdul Razzaq, H.A, "Analysis of Steel-Concret-Steel Sandwich Composite", PhD. thesis University of Basrah, June 2018.

Farhan, J.A. and Hussain, H.M., "Development of three-layer composite steel-concrete-steel beam element with applications", Eng. Tech. Journal, Vol. 28, No. 24, 2010, pp. 6970-6985.

Liew, J.Y.R. and Wang, T.Y. "Novel steel-concrete-steel sandwich composite plate subjected to impact and blast load", Advanced in structural engineering, Vol. 14, No. 4, 2011, pp. 673-687.

Mckienly, B. and Boswell, L.F., "Behavior of double skin composite construction", J. of constructional steel research No. 58, PP. 1347-1359, 2002.

Schalaseman, C. and Russell, J., "Application of advanced construction technologies to new nuclear power plants", M.P.R. 2610 revision 2, Sep. 24, 2004.

Solomom, S.K., Smith, D.W. and Cusens, A.R., "Flexural tests of steel-concrete-steel sandwiches", Magazine of concrete research: Vol. 28, No. 94, March 1976, pp. 13-20.

Roberts, T.M., Edwards, D.N. and Narayanan, R., "Testing and analysis of steel-concrete-steel sandwich beams", J. construct. steel Res., Vol. 38, No. 3, PP. 257-279, 1996.

Wright, H.D., Oduyemi Tos and Evans, H.R." The design of double skin composite elements", Journal of constructional steel research, Vol.19, 1991, pp.111-132.

Yan, J.B., Liew, J.Y.R., Zhang M.H. and Sohel, K.M.A. "Experimental and analytical study on ultimate strength behavior of steel-concrete-steel sandwich composite beam structures", Materials and structures (2015), 48:1523-1544.