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Torsional Behavior of Steel-Concrete-Steel Sandwich Beams with Welded Stirrups as Shear Connectors

Samoel M. Saleh [1*], Fareed H. Majeed [1], Osamah Al-Salih [1], Haleem K. Hussain [1]

[1] *College of Engineering, University of Basrah, Basrah 61004, Iraq.*

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Abstract

The structural performance of a steel-concrete-steel sandwich beam (SCSSB) with welded stirrups to the steel skin plates as shear connections exposed to a pure torsion load was studied in this paper. Eight SCSSB specimens were fabricated and tested under pure torsion. The effects of the compressive strength of the concrete core, 26 and 35 MPa, the thickness of the top and bottom steel skin plates, 2 and 4 mm, and the degree of shear interaction, which represents the number of beam stirrups, between the steel skin plates and the concrete core are 75, 100, and 125%. The experiment beams revealed a similar mode of failure for all SCSSB specimens regarding all considered variables, which started with inclined cracks along the specimens' side faces and ended with local separation between one of the steel skin plates (top or bottom) and the concrete core. In addition, the experiment results showed an increase in the torsional strength with the increase in the shear connection ratio and the thickness of the steel skin plate, as well as with the increase in the strength of the concrete core. However, it was observed that the torsional ductility of the tested beams is proportional directly to the steel skin plate thickness and degree of interaction and inversely with the concrete compressive strength. The results showed that the use of steel skin plates with welded stirrups as a shear connection could reduce the negative effect of increasing the compressive strength of the concrete core on the torsional ductility of SCSSB.

Keywords: Sandwich Beam; Shear Connection; Torsional Strength; Torsional Ductility; Pure Torsion.

1. Introduction

Nowadays, the use of steel-concrete-steel sandwich beam (SCSSB) has become popular in the construction of infrastructure as well as other types of concrete structures, especially those subjected to blast or impact loads. This type of structure is made from a concrete core sandwiched between two steel plates. However, the efficiency of such composite beams depends primarily on how the developed forces between the concrete core and steel skin plates are transferred. In order to ensure a proper connection between steel plates and concrete cores, interrelated materials or shear connectors are commonly used. Besides, the use of shear connectors demonstrated the superior performance of SCSSB compared with traditional concrete beams in applications requiring high ductility, strength, impact resistance, or blast resistance [1-4].

Extensive previous experimental and analytical studies have been conducted to investigate the behavior of SCSSB through the examination of different proposed kinds and configurations of shear connections. Leng & Song [5] investigated the shear performance of SCSSB by using round steel bars to connect the skin plates together and the concrete core in addition to headed studs. Nine slender beams with different shear span-to-depth ratios were tested under the action of static loads. It was found that the shear resistance of such beams is dependent on the strength of the steel plate, vertical reinforcement, and stud connectors. Experimentally, Wang et al. [6] examined the structural behavior of

* Corresponding author: samoel.saleh@uobasrah.edu.iq

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SCSSB with bolt shear connectors under the effect of off-center drop hammer loading. Several parameters were considered in this study, including the depth of the concrete core, the thickness of the steel plates, and the location of impact loads. A variety of failure modes were observed, including flexural failures, shear failures, and fractures of bottom steel plates. The experimental results show that the tested beam specimens with the adopted shear connections exhibit a desirable structural resistance under impact loads. Zhang et al. [7] examined the shear resistance of SCSSB by testing eight specimens having overlapped headed studs and J-hooks hybrid shear connections with different degrees of shear interaction. The effect of shear span-to-depth and the steel reinforcement ratios were also considered in this investigation. It was observed that the shear resistance of the tested SCSSB is inversely related to the degree of shear interaction, as well as the spacing and type of shear connectors. Yan et al. [8] studied the flexural behavior of SCSSB with enhanced C-channels as shear connectors. Six specimens were tested under bending loads considering the effect of concrete type, shear span-to-depth ratio, thickness of skin steel plates, and the spacing of shear connectors. It was found that with a proper selection of shear connectors spacing and shear span, such sandwich beams with the suggested shear connections show good ductility with flexural failure. Moreover, the flexural resistance of tested specimens was improved with the increase of skin plate thickness and/or strength of the concrete core.

The structural behavior of SCSSB made with J-hook shear connectors has been investigated numerically by Yan et al. [9]. A three-dimensional finite element model was developed and verified by six experimentally tested beams. Through the validation of the finite element analysis, it was found that the finite element model might offer a good means of estimating ultimate strengths, modes of failure, and shear cracks in the concrete core. Wang et al. [10] investigated experimentally, analytically, and numerically the dynamic response of a proposed stiffener-enhanced SCSSB under the action of low-velocity impact loading. It was observed that the tested specimens failed in a flexural mode, while their impact resistance was significantly improved with the use of stiffeners in the tension plate. In addition, a finite element analysis and an analytical analysis were proposed and validated by the experimental results. Karimipour et al. [11] tested twenty-four sandwich panels made from a low-strength and moderately low-density concrete core sandwiched by two high-strength thin steel plates using a proposed stud-bolt shear connection. Normal strength and fiber-reinforced concrete were adopted in this study. It was found that the shear strength and ductility of the tested specimens were significantly improved with the increased stud-bolt diameter and fiber reinforcement ratio. An experimentally validated numerical study of SCSSB behavior with new X-form shear connectors was presented by Ilango & Anandavalli [12]. The thickness of steel skin plates and the diameter and spacing of shear connectors were the main parameters considered in this work. As a result of this investigation, the proposed X-shear connectors were able to improve the load-carrying capacity and the ductility of these composite beams.

In contrast, a number of earlier studies looked at the impact of the strength and type of the concrete core as well as steel skin plates on the structural behavior of steel-concrete-steel sandwich structures. Liew & Sohel [13] examined the behavior of SCSSB with a lightweight concrete core. Twelve beam specimens have been tested to evaluate bending and shear resistance under the action of a static load. The degree of shear interaction and the strength and type of the concrete core—normal concrete and fiber-reinforced concrete—were the main parameters considered in this study. It was observed that the presence of about 1% volume fraction of fibers in the concrete core of the tested SCSSB specimens improved the beams’ flexural resistance and ductility. Yan et al. [14] studied experimentally and analytically the effect of different types of concrete core on the behavior of SCSSB. Twenty-two beam specimens were tested in this investigation. It was concluded that the increase in concrete strength improved the composite action and the ultimate carrying capacity of the tested SCSSB specimens. In addition, the sandwich beams' carrying capacity can be improved by adding fibers to their concrete cores. The shear-tension interaction strength of SCSSB with an ultra-lightweight concrete core has been studied by Yan et al. [15]. This study was based on the experimental results of thirty push out tests and eighteen tensile tests on sandwich beams with different types of concrete cores sandwiched by steel skin plates connected together by J-hook connectors. Design equations were proposed to evaluate the tensile strength of J-hook connectors in different types of concrete, which were validated by the experimental test results. The flexural behavior of a new SCSSB using enhanced C-channels as shear connectors and an ultra-high performance concrete core was examined by Yan et al. [16], considering the effect of shear span-to-depth ratio, the thickness of skin steel plates, and the strength of the concrete core. It was observed that the stiffness and strength of the tested beam specimens increased with the increase in skin plate thickness. However, the improvements from increasing the thickness of the skin plates on the cracking strength of the tested beams are less than those on yield and ultimate strength.

Experimental tests were carried out on SCSSB infilled with an ultra-lightweight cement composite by Sohel et al. [17]. Headed stud and J-hook connectors were used in the fabrication of the tested beam specimens for comparison. It was found that both beams with headed studs and those with J-hooks exhibited the same load-deflection behavior and ultimate strength. Alawsi et al. [18] investigated the effect of concrete core depth on the behavior of SCSSB. Four SCSSB specimens with different depths were fabricated and tested under the effect of three-point loading. A truss configuration with 10 mm steel bars was adopted as a shear connection. The experimental results showed that the increase in SCSSB depth from 150 mm to 300 mm improved their cracking and ultimate strengths by about 34% and 59%, respectively. In addition, the flexural toughness of the tested specimens was increased by a ratio of about 100% with the addition of 25% to the beams’ depth.

The use of SCSSB in a wide range of construction applications, especially in infrastructure meant for nuclear or military purposes, may result in these components being subject to various types of forces [19]. However, the review of previous studies shows that the structural behavior of SCSSB subjected to shearing and bending forces has been extensively investigated, while the torsional effect on the behavior of such composite beams has yet to be reported. Hence, the present study was undertaken to investigate the structural behavior of SCSSB under the effect of pure torsion. Eight SCSSB specimens were fabricated to study the effect of skin plate thickness, concrete compressive strength, and the degree of shear interaction between the skin plate and concrete core on the torsional behavior of such composite beams. The uniformly distributed transverse steel reinforcement (stirrups) was adopted in the present study as a shear connection by welding it to the top and bottom steel skin plates and embedding it in the concrete core of the beam specimens.

2. Materials and Methods

2.1. Material Properties

In order to achieve the present work's goals, the normal weight concrete, carbon steel plates, and steel reinforcement stirrups (as shear connectors) were utilized for the fabrication of the tested SCSSB specimens. Two different concrete mixes with design compressive strength equal to (25 and 35 MPa) were adopted in the present experiments, using ordinary Portland cement (OPC), natural crash stone as coarse aggregate (gravel) with a maximum size of about 19 mm, and natural river sand with 2.36 mm maximum size as fine aggregate (sand). According to ASTM standards [20, 21], the evaluated physical properties of the adopted OPC are listed in Table 1, while the properties and particle size distribution of fine and coarse aggregates are shown in Tables 2, and Figure 1, respectively.

Table 1. Physical properties of ordinary Portland cement according to ASTM C150/C150M-18 [20]

Standard Test	Test Specification	Test Result
Fineness (m^2/kg)	Blaine air permeability	305
Setting time (minute)	Initial	135
	Final	265
Compressive strength (MPa)	3 days	15.7
	7 days	21.8

Table 2. Physical properties of coarse and fine aggregates according to ASTM C33/C33M-18 [21]

Material	Gravel	Sand
Maximum size (mm)	19.0	2.36
Specific gravity	2.62	2.66
Absorption (%)	1.34	1.12
Loose bulk density ((kg/m^3)	1520	1580

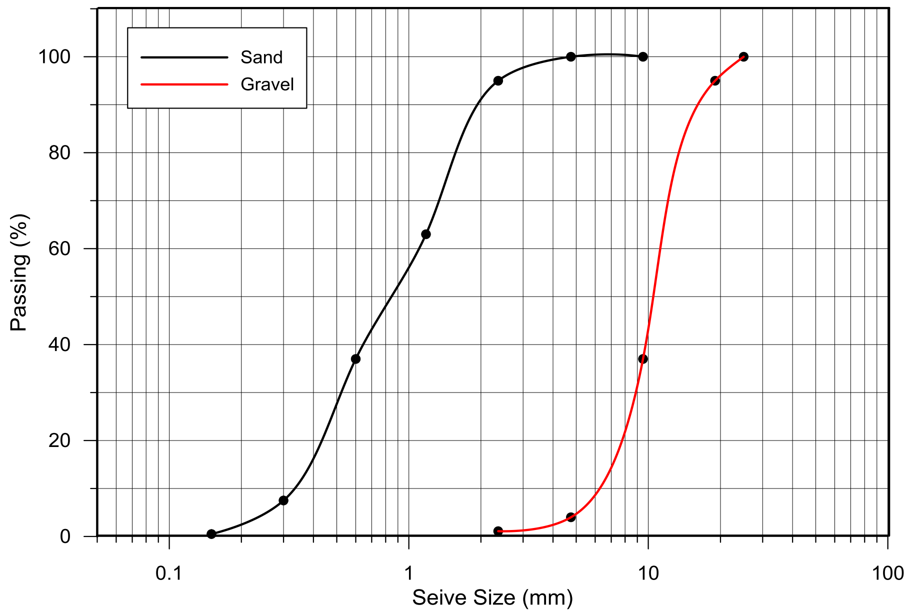

Figure 1. Particle size distribution of fine and coarse aggregates

At the time of fabricating the SCSSB specimens, a slump flow test was used according to ASTM C143/C143M-20 [22] in order to examine the fresh properties of the concrete used. Moreover, and in order to evaluate the mechanical properties of the hardened concrete of the specimens' cores, six 150 mm dia.×300 mm standard cylinders for each concrete mix were casted. A moist cure was performed on the cylinders as well as the beam specimens for seven days and then air-cured for twenty-one days until the testing time at the age of 28 days. The details of the adopted design concrete mixes as well as the concrete compressive strength ($f_c^/$) and the splitting tensile strength (f_t), which evaluated according to ASTM C873/C873M -15 [23] and ASTM C496/C496M -17 [24], respectively, are shown in Table 3. In addition, the mechanical properties of steel plates and steel reinforcement bars are shown in Table 4.

Table 3. Details and properties of adopted concrete mixes

Design compressive strength (MPa)	25	35
Water cement ratio	0.48	0.45
Cement (kg/m^3)	383	420
Coarse aggregate, gravel (kg/m^3)	1225	1255
Fine aggregate, sand (kg/m^3)	615	566
Slump test value (mm)	200	180
Compressive strength, $f_c^/$ (MPa)	26.8	35.7
Splitting tensile strength, f_t (MPa)	2.9	3.4

Table 4. Mechanical characteristics of steel

Steel type	Yield strength, f_y (MPa)	Ultimate strength f_u (MPa)	Specification
Reinforcement (Φ10)	460	720	ASTM A615/A615M-18 [25]
Steel plate (thickness 2 mm)	270	495	ASTM A370-18 [26]
Steel plate (thickness 4 mm)	270	505	

2.2. Specimens under Investigation

Eight SCSSB specimens were adopted in the present experimental program for a pure torsion test. The designation and details of SCSSB test specimens are shown in Table 5, where the total width and length were 250 mm and 2400 mm, respectively. The depth of the specimens' concrete core is equal to 150 mm, therefore, the total depth of the tested specimens is varied according to the thickness of top and bottom steel plates. Two thicknesses (2 mm and 4 mm) of the steel skin plates were used in this study. As well as serving as shear reinforcement, closed stirrups of 10 mm deformed rebar was employed to play the role of shear connectors by welding them to the top and bottom of skin steel plates of the tested SCSSB. A full length, double sides flare bevel groove weld type with an effective throat of about 2 mm was adopted to connect the steel skin plates with the stirrups. These stirrups were distributed uniformly along the torsion span of the tested beams. The number and spacing of the stirrups were estimated according to the following formula [27], in order to provide different degrees of shear interaction between the skin plates and the concrete core ranging from 75 to 125%. However, an excessive amount of stirrups were present in the support regions of the tested beams in order to prevent failure at these areas. Figure 2 shows the details and geometry of a typical test specimen, while Figure 3 depicts the adopted experimental program in the present work.

$$n_s = \frac{A_p \cdot f_y}{v_s} \tag{1}$$

where n_s is number of stirrups to provide full shear interaction, f_y is yield stress of transverse reinforcement (MPa), A_p is cross sectional area of top or bottom steel skin plate (mm^2), and v_s is shear strength of two legs stirrup (N).

Table 5. Details of steel-concrete-steel sandwich beam specimens

Specimen	B1	B2	B3	B4	B5	B6	B7	B8
Total length (mm)	2400	2400	2400	2400	2400	2400	2400	2400
Torsional span (mm)	1800	1800	1800	1800	1800	1800	1800	1800
Cross section depth (mm)	154	154	154	154	158	158	158	158
Cross section width (mm)	250	250	250	250	250	250	250	250
Thickness of top plate (mm)	2	2	2	2	4	4	4	4
Thickness of bottom plate (mm)	2	2	2	2	4	4	4	4
Longitudinal spacing of stirrups (mm)	200	150	200	150	200	150	200	150
Degree of interaction (%)	100	125	100	125	75	100	75	100
Concrete compressive strength, $f_c^/$ (MPa)	26.8	26.8	35.7	35.7	26.8	26.8	35.7	35.7
Splitting tensile strength, f_t (MPa)	2.9	2.9	3.4	3.4	2.9	2.9	3.4	3.4

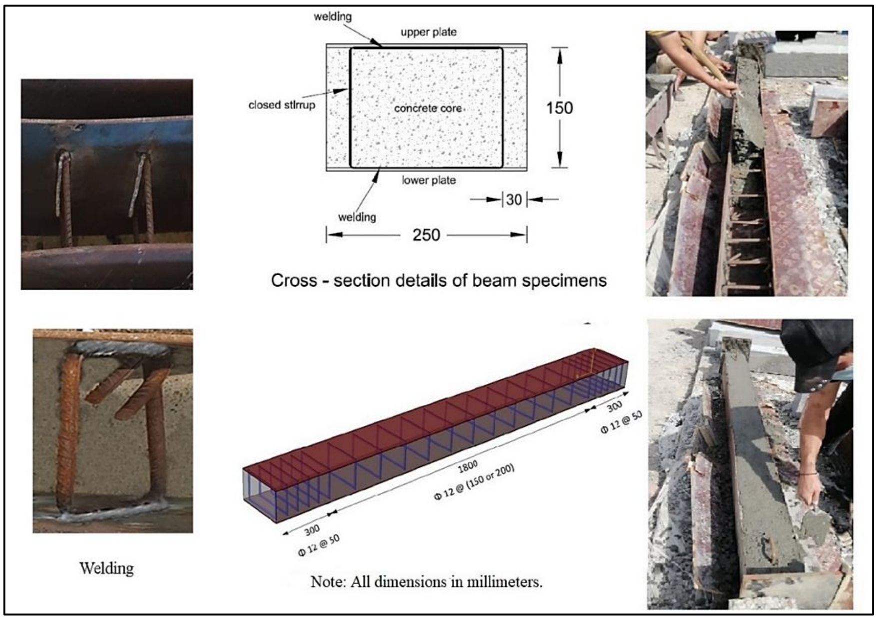

Figure 2. Geometric details of tested beam specimens

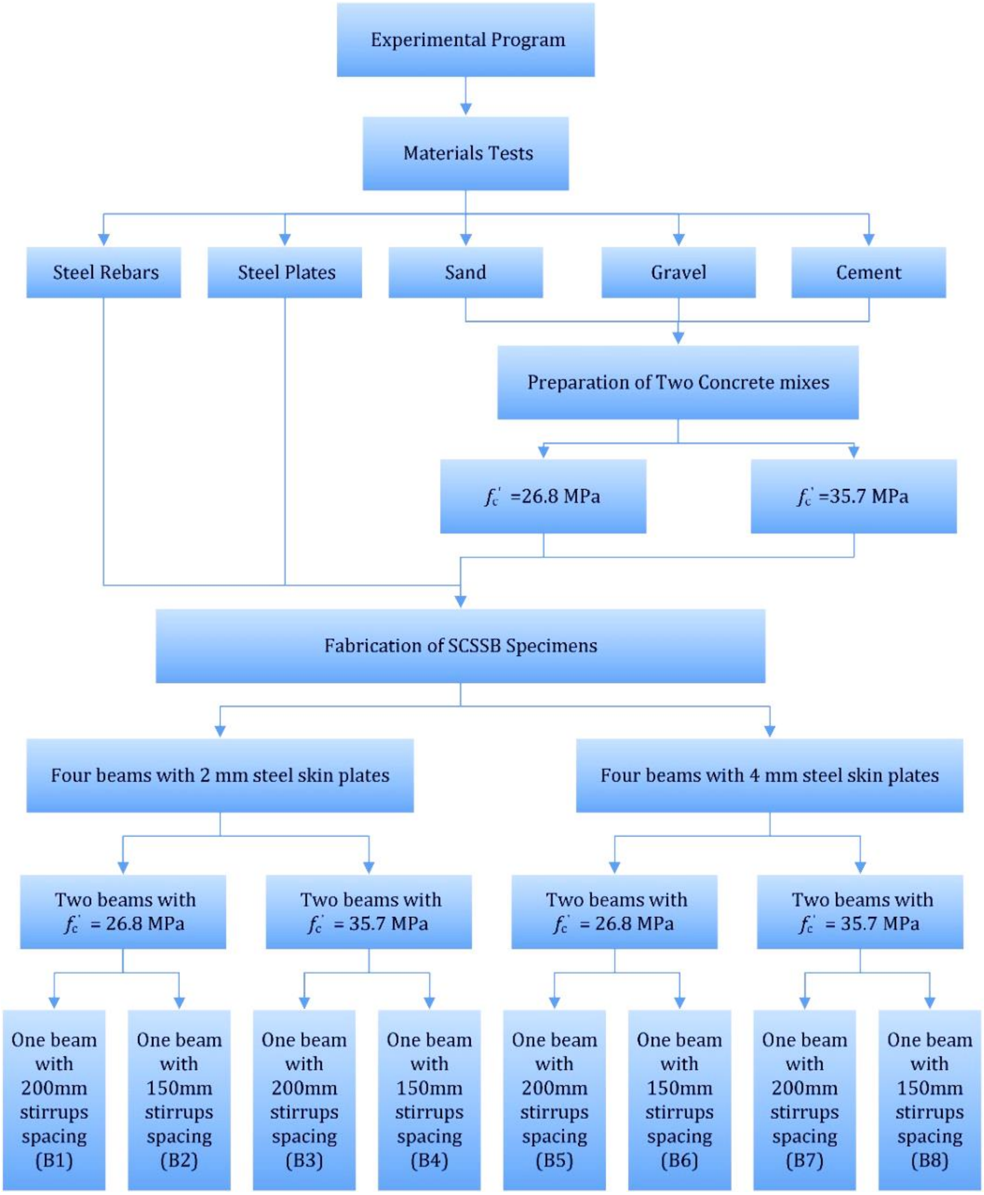

Figure 3. Experimental program flow chart

2.3. Test setup and Instrumentation

Figure 4 shows the experimental test set-up, where all the specimens were tested under pure torsion. Under the applied end torques, all SCSSB specimens were supported by two supports 1.8 m apart designed to allow free twisting. The end torques were developed by using two rigid steel arms fixed at the specimens' ends and loaded monotonically by a 50-ton universal testing machine through a diagonally placed rigid steel beam. As previously noted, to ensure that the tested specimen's regions at the end supports would not fail under the applied load, they were reinforced with high amounts of stirrups. A 50-ton load cell was used to measure the applied loading, while the angle of twist was measured using two linear variable differential transducers (LVDTs) fixed at the steel arms and 500 mm away from the tested specimens' centerline. A monotonic loading with a rate of about 4.0 kN/min. was applied to all tested beam specimens. The mode of failure, crack propagation with the applied loading, applied torque-angle of twist relation, and the corresponding cracking and ultimate torques were recorded for each tested specimen.

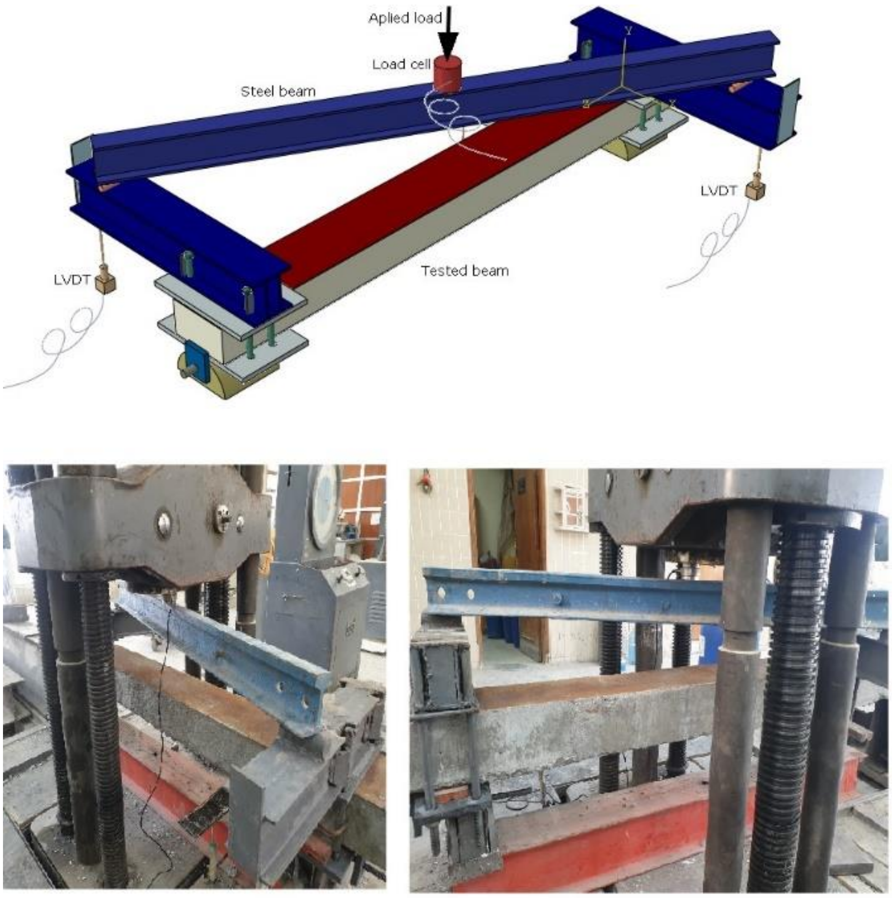

Figure 4. Test set up of beam specimens

3. Results and Discussion

3.1. Failure Modes and Torsional Strength

Actually, the experiments of SCSSB specimens revealed only one mode of failure. This mode of failure, as shown in Figure 5, began by developing inclined cracks in the side of beams with an angle of inclination of about 40°, which started from the bottom toward of top of specimens in one side and vice-versa in the other side. The developed crack patterns in the tested SCSSB specimens are approximately similar to those observed in previous studies considering the torsional behavior of traditional reinforced concrete beams, where the initial cracks were developed as inclined rings around the tested beams [28-30]. However, the presence of steel skin plate delayed the cracks from developing at the bottom or top face of the tested specimens at the first stages of the applied loading. The tested beams were failed after an excessive increase in the length and width of the cracks, which followed by local separation in the bottom or top steel skin plates from the concrete core with the applied loadings reaching the ultimate ones. Unlike the other tested SCSSB specimens, the tested beams (B3 and B4) were subjected to local uplift for the bottom skin plate, as shown in Figure 6. It was noted that the beam specimens that had 4 mm steel plate thickness were subjected to wider cracks comparing with those having 2 mm steel plates. This is because that the specimens with 4 mm steel plates were subjected to higher torsion until failure. A global separation between the concrete core and the top or bottom steel skin plate was not observed in all tested specimens. This may relate to the efficiency of the suggested type of shear connectors.

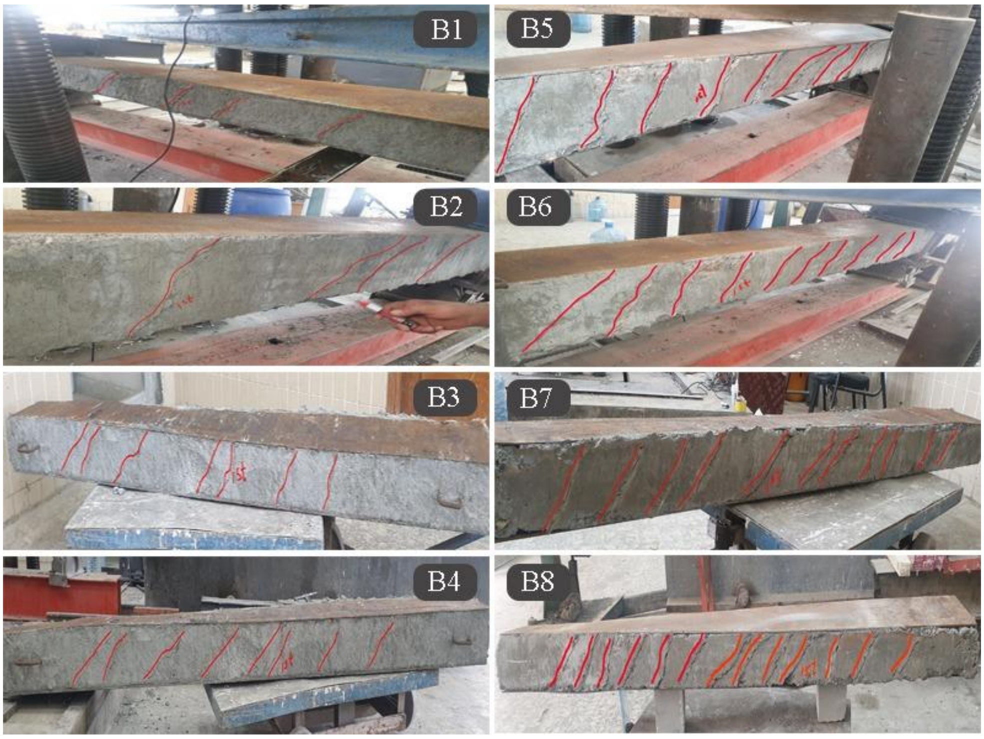

Figure 5. The mode of failure of tested beam specimens

Figure 6. Separation of steel skin plate from the concrete core of tested specimens

The cracking and ultimate torsional capacities of tested SCSSB specimens were evaluated based on three parameters: the thickness of steel skin plates, concrete compressive strength, and degree of shear interaction between the concrete core and the steel skin plates, where the experimental results are listed in Table 6. It was observed that the increase of steel skin plates from 2 mm to 4 mm enhanced the cracking and torsional capacities of SCSSB specimens by a ratio of about 29% and 32%, respectively, for specimens having a concrete compressive strength of about 26.8 MPa (B1 and B5). However, the role of this parameter (thickness of steel skin plate) may hold back with the increase of concrete compressive strength as observed in the results of (B3 and B7) specimens. Where, the increase in the thickness of steel plate from 2 mm to 4 mm with a concrete compressive strength of about 35.7 MP improved the cracking and torsional capacities of SCSSB specimens by only a ratio of about 15% and 22%, respectively. It should be noted that the above measured values were derived from the tested specimens with stirrups spacing of 200 mm.

Furthermore, the same results were listed for the tested specimens with stirrups spacing of 150 mm, in which the cracking and torsional capacities were increased by 39% and 28% in specimens with concrete compressive strength of 26.8 MPa, and by 11% and 15% in specimens with concrete compressive strength of 35.7 MPa, respectively, when the steel skin plate increased from 2 mm to 4 mm. According to these results, it can be concluded that the use of thicker steel plate improves both cracking and ultimate torsional capacities of SCSSB even when different levels of shear interaction are used. The analysis of the results showed that the effect of increasing the thickness of steel skin plates on the torsional capacity of SCSSB would reduce with the increase of concrete core compressive strength and/or the degree of shear interaction (number of stirrups). On the other hand, it was noted that the values of cracking torque and torsional capacity of the tested beams were significantly proportional to the compressive strength of the tested specimens' concrete core. For beam specimens with 2 mm steel skin plates, cracking torque increased by an average ratio of about 57% when concrete compressive strength increased from 26.8 MPa to 35.7 MPa, while it was only 34% for beams with 4 mm steel skin plates. It can be seen that the torsional rigidity of the tested SCSSB specimens was proportional to all parameters considered, but the thickness of steel plate was the main influenced factor.

Table 6. Test results of SCSSB specimens

Item	B1	B2	B3	B4	B5	B6	B7	B8
Cracking torque, T_{CR} (kN.m)	11.3	12.4	17.7	19.6	14.6	17.2	20.4	21.8
Cracking angle of Twist, ψ_{cr} (rad.)	0.006	0.007	0.033	0.035	0.017	0.021	0.042	0.046
Torsional rigidity (kN.m/rad)	1168.0	1199.3	1336.0	1363.3	1483.3	1657.9	1700.4	1860.7
Ultimate torque, T_{CR} (kN.m)	14.5	17.0	18.3	20.5	19.1	21.7	22.3	23.2
Ultimate angle of twist, ψ_u (rad.)	0.058	0.059	0.048	0.058	0.061	0.098	0.093	0.094
Torsional ductility Index	6.4	8.4	3.9	5.6	8.2	11.3	5.3	7.7

3.2. Behavioral Curves and Torsional Ductility

Figures 7 and 8 show the applied torque versus twisting angle of the tested SCSSB throughout the loading process until failure resulted from the experiments. All the tested specimens demonstrated a linear elastic response with significant torsional rigidity. It can be noted that the range of the elastic stage differed with the increase in concrete compressive strength and steel skin plate thickness. After concrete cracking, the tested beams were subjected to a rapid reduction in their torsional rigidity with a nonlinear relation between the applied torque and the developed twisting angle until the ultimate torque, where the specimens exhibited a reduction in their torsional capacity with the increase of the twist angle. As expected, it can be seen from Figure 9 that the use of a thicker skin steel plate improved the torsional strength as well as the torsional ductility of the tested SCSSB specimens.

The torsional ductility can be evaluated as the ratio of the peak twisting angle to the yielding twisting angle, which is indirectly related to how well the specimen can absorb energy during plastic deformations [31]. It was observed that the ductility of the tested SCSSB specimens improved significantly with the increase in skin steel plate thickness and degree of shear interaction (number of stirrups), but that it was inversely proportional to the concrete compressive strength (see Figure 10). Upon doubling the skin plate thickness, the tested specimens showed an increase in the torsional ductility of about 37%, while it was improved by an average ratio of about 42% with increasing the degree of shear interaction from 75% to 100%. As the concrete core's compressive strength was increased from 26.8 MPa to 35.7 MPa, SCSSB specimens lost approximately 35% of their torsional ductility.

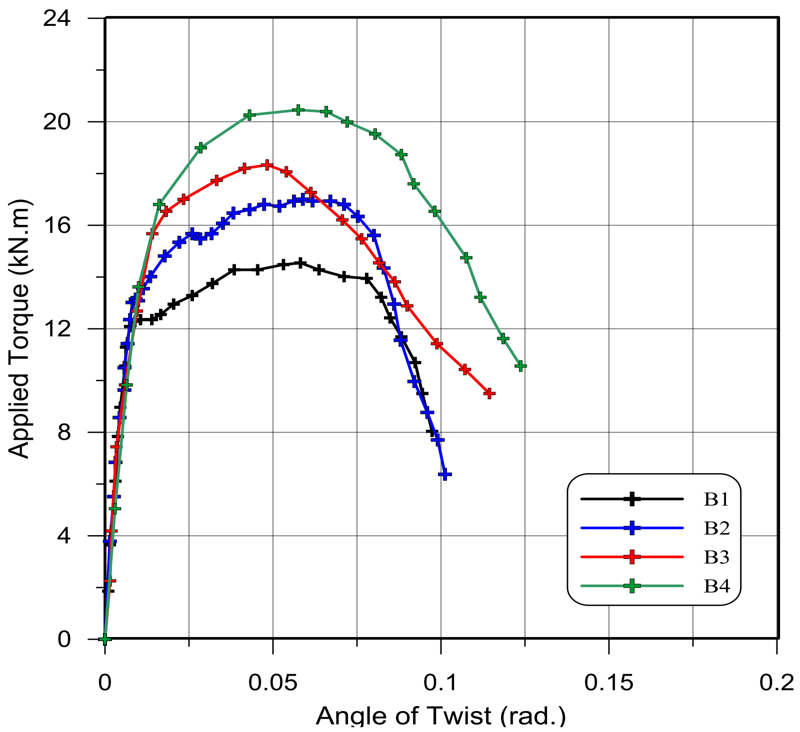

Figure 7. Behavioral curves of SCSSB tested specimens with 2 mm steel skin plates

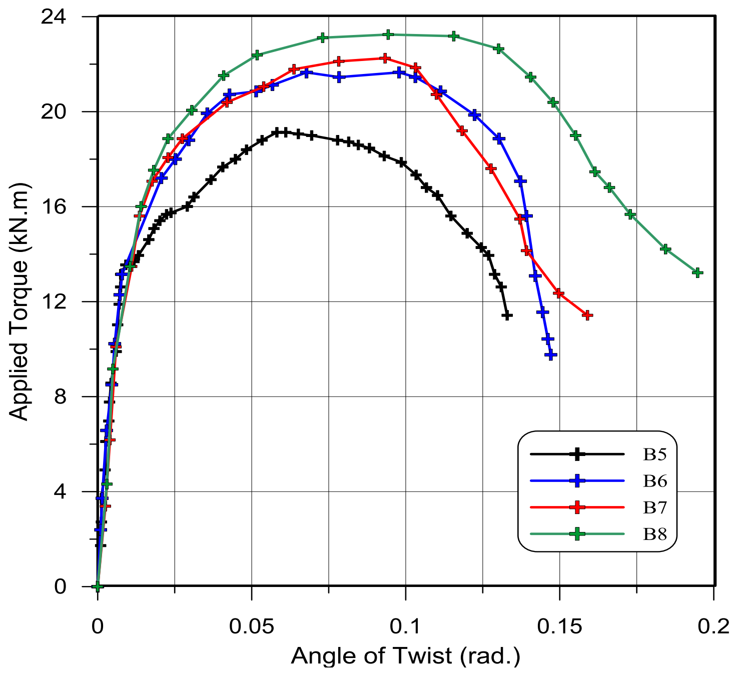

Figure 8. Behavioral curves of SCSSB tested specimens with 4 mm steel skin plates

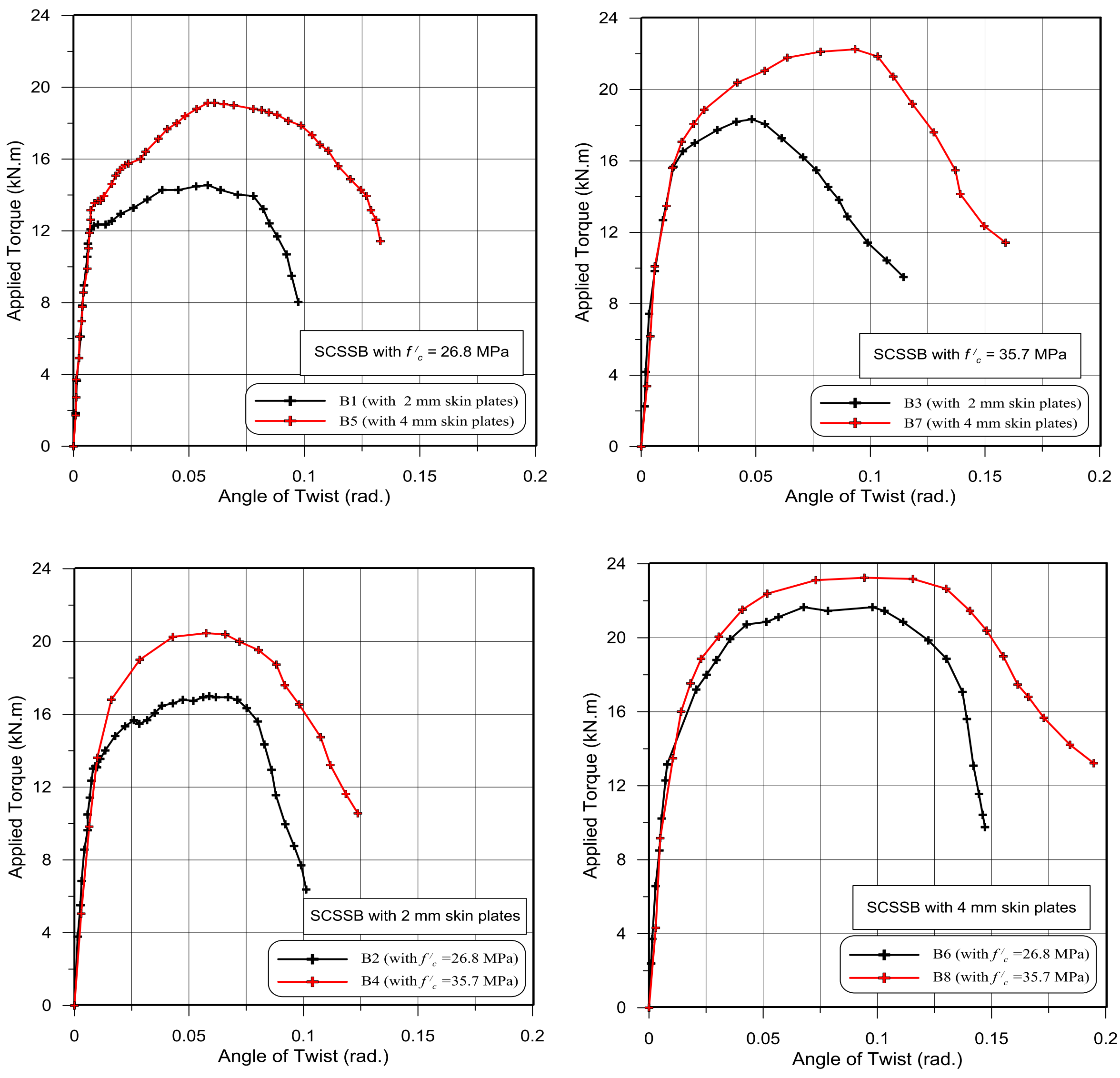

Figure 9. Effect of skin plate thickness and concrete compressive strength on SCSSB behavior

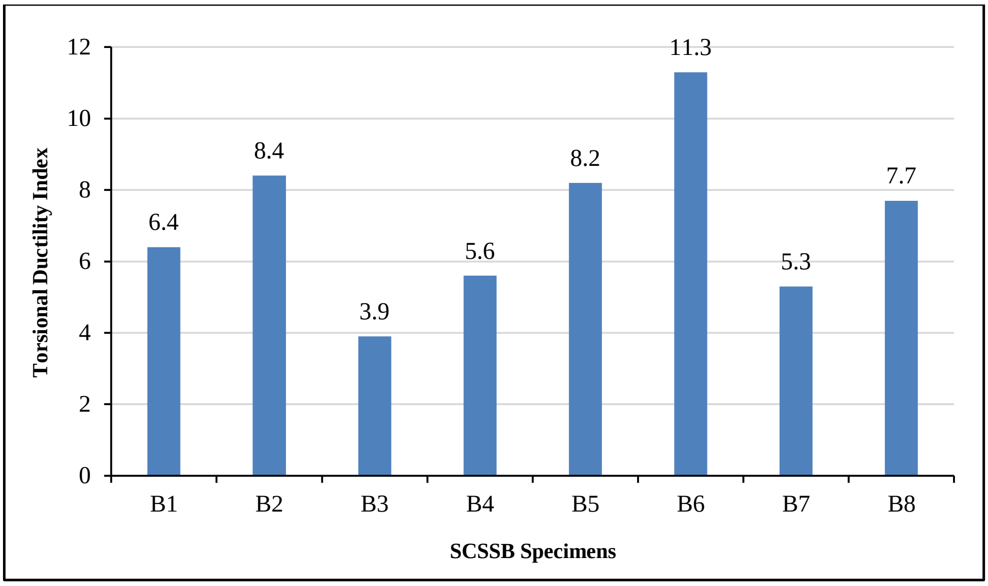

Figure 9. Variation of torsional ductility index of tested SCSSB specimens

4. Conclusions

In the present experimental investigation, eight SCSSB specimens were fabricated and tested under the effect of pure torsion in order to evaluate the structural performance of a steel-concrete-steel sandwich beam with welded stirrups to the skin plates as shear connections. The effects of the compressive strength of the concrete core, the thickness of the top and bottom steel skin plates, and the degree of shear interaction were considered the experimental parameters. The following points can be concluded from the analysis of test results:

- All the tested specimens exhibited approximately the same mode of failure by developing inclined side cracks followed by local separation of the skin plates from the concrete core;
- The adopted shear connection (welded stirrups) improved the torsional strength and ductility in addition to its essential function of providing adequate shear strength and interaction between the skin plates and concrete core of the tested SCSSB specimens;
- As expected, the torsional strength of the tested specimens increased with the increase in thickness of the steel skin plate, the concrete core's compressive strength, and the degree of shear interaction (number of stirrups);
- Among all the examined parameters, the increase in skin plate thickness showed excellent improvement in the torsional strength and ductility of the tested specimens;
- As expected, the torsional strength of the tested specimens increased with the increase in thickness of the steel skin plate, the concrete core's compressive strength, and the degree of shear interaction (number of stirrups).

5. Declarations

5.1. Author Contributions

Conceptualization, S.M.S.; methodology, S.M.S. and F.H.M.; investigation, F.H.M.; resources, S.M.S. and O.A.S.; data curation, F.H.M.; writing—original draft preparation, S.M.S. and F.H.M.; writing—review and editing, S.M.S. and H.K.H.; visualization, O.A.S. and F.H.M.; supervision, S.M.S. and F.H.M.; project administration, O.A.S.; funding acquisition, S.M.S., F.H.M., O.A.S. and H.K.H. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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