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Experimental and numerical investigations of composite concrete steel flexural members with angle shear connectors under negative moment

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ABSTRACT

Experimental and numerical research has been conducted to investigate the role of using angle shear connectors as a replacement of headed stud (HS) on the performance of the composite beams under the effect of the negative bending moment (NBM). The replacement was done by using the same cross-section area for both connectors. A total of five specimens were fabricated and tested under the effect of NBM. Shear connector type, bond interaction (partial and full), and angle shear connectors arrangement were considered as the main parameters. A finite element model (FEM) was built using commercial software for modeling the composite beams. The experimental results, the ultimate strength decreased by 4.12% for single angle shear connectors, compared to the specimens with HS shear connectors. The numerical results showed a good agreement with the experimental results in terms of load-displacement relation and mode of failure.

Keywords: Bond interaction; Composite section; FEM; Shear connectors

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1. Introduction

Composite members are the two or more material combinations of different mechanical properties. The most important factor that controls the behavior of composite members is the physical interaction between the different elements, which is called a bond. Different techniques need to be used to ensure an acceptable interaction between components of the composite members. For steel-concrete composite members, shear connectors are used to transfer the longitudinal shear forces through the bond region. Therefore, the design of appropriate connectors to afford the shear stresses in composite members is controlled by the maximum shear force transfer.

Different shear connectors shapes have been used for this purpose. The most used ones are the angle shear connector. Different factors affect the performance of these connectors and control the alternately interactive response of the connector and the adjacent area of concrete.

Lam and El-Lobidy [1] described a finite element model (FEM) to investigate the role of headed stud (HS) shear connectors on steel-concrete composite beam performance. They employed the non-linear material properties and their results were validated with the experimental results. Wang and Chung [2] conducted an extensive numerical program to study the full range of composite beams performance with flexible shear connectors. They employed the nonlinearity interface with the nonlinearity material and geometric with two- and three-dimensional FEM in their study. Their results were compared with the experimental results and wer found to be highly satisfactory.

Stoy and Shima [3] studies the beam type specimens performance with L-shape shear connectors which is subjected to a strut compressive force and compared the results with FEM results. Different factors were studied using FEM such as the concrete strength, connectors size, and the strut angle. Shariati et al. [4]

conducted a push-out test to study the behavior of high strength concrete (HSC) slab with different shapes of embedded angle shear connectors. Mazoz et al. [5] conducted presented a push-out test on new types of shear connectors (I-shaped). Nouri et al. [6] investigated the behavior of a new shear connector (stiffened angle shear) at an elevated temperature using eight push-out specimens. Shariati et al. [7] studied and compared the results of the performance of using two types of shear connectors (channel and angle shear) embedded in HSC composites under static and cyclic loadings using push-out specimens.

Tahmasbi et al. [8] studied numerically using FEM the C-shaped and L-shaped angle shear connectors performance embedded in RC slabs using push-out tests and validate the results against the experimental data. Zhang and Zhang [10] conducted investigated experimentally the angle shear connectors capacity using push-out specimens. The connectors geometry (thickness and height) was considered in this study. Mansouri et al. [9] Predicted the angle shear strength based on several factors using FEM. The compressive strength of concrete, connectors length, thickness, and shear strength were included in their analysis. The analytical results were verified by the experimental results

Different experimental programs were employed in the evaluation of the strength design of the shear connector such as push-out test specimens as mentioned in the standard American Institute of Steel Construction (AISC) code [12] for some connectors. In the present work, an experimental and numerical study using FEM is adopted to investigate the using angle shear connectors effect instead of the HS based on equivalent cross-section area on the composite beam performance under the effect of negative bending moment (NBM).

2. Experimental program

In this program, five beams were fabricated and tested. The composite section included I-sections hot rolled steel beams with RC slab and various shear connectors types. The M4×3.2 steel I-section is selected according to AISC with an overall length of 1100 mm. The RC slab is (1100×400×80) mm. and it is reinforced by 8 φ10mm ordinary steel reinforcement top and bottom reinforcement and φ10mm @ 150 mm c/c closed stirrups reinforcement.
HS and angle shear connectors with an equivalent cross-sectional area were used. The shear connector type, concrete slab-steel beam interaction, and sitting arrangement of connectors were considered. Two proposal methods of connectors setting were included in this study to examine the composite section performance. Table 1 shows the description, designation, and geometrical details of steel beams that were used in this study. Figure 1 shows the steel beam preparation before slab casting.

Table 1. Composite beam matrix

Specimen Designation	Connector Type	Bond Interaction
S.P.HS1	HS	Partial
S.F.HS2	HS	Fully
S.P.A1	Angle	Partial
S.F.A21	Angle	Fully
S.F.A22	Angle	Fully

Two specimens were fabricated using HS shear connectors (S.P.HS1 and S.F.HS2). The letter (S) refers to the specimen, P and F indicate the use of partial or full interaction, respectively. HS1 or HS2 refers to the use of single or double connectors, respectively. Three specimens of angle shear connectors were fabricated (S.P.A1, S.F.A21, and S.F.A22), where the symbol (L1) means the use of single angle shear connector; (A21) and (A22) refers to pair of connectors with a different setting arrangement as shown in Figure 1. A single HS shear connector welded in the mid tension-steel flange was used to ensure the partial bond interaction, while a pair HS or angle shear connector was used to ensure the full bond interaction.

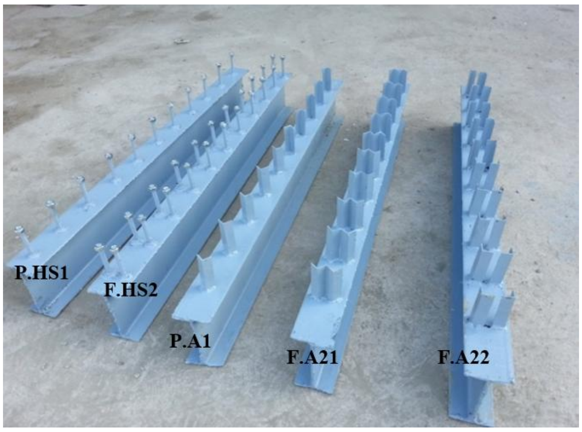


Figure 1. Preparation of composite beam

3. Experimental test

Figure 2 shows the loading details and support conditions for the composite beam. The effect of NBM results from the point load that was applied at the mid-span of the steel beam. The load was applied using load-controlled hydraulic jack with a capacity of 1000 kN with a constant loading rate of 0.2 kN/sec. A dial gauge was attached at mid span to record the mid-span displacement during the test as well as at the end of the RC slab to measure the slip.

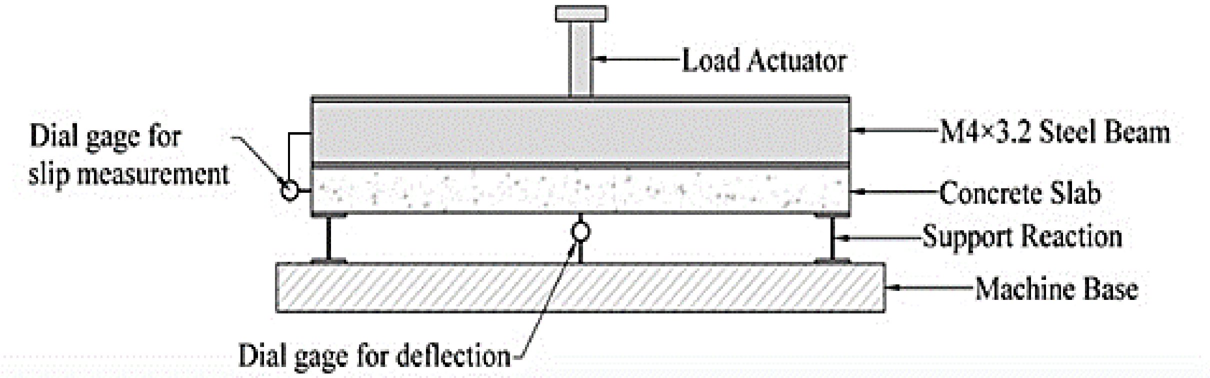


Figure 1. Loading details and support condition

4. Results and discussion

4.1. Load-displacement relationship

Load-displacement relationship, end slip, and composite steel plate failure pattern for all specimens are recorded and discussed. The load-displacement curve for all composite beams is shown in Figure 3. It can be observed that the recorded peak load for S.P.HS1 was 104.3 kN. The first recorded crack of the RC slab was mentioned at a load level of 75.1 kN while the measured slip at the peak load was 3.75 mm. The peak load for S.F.HS2 was 114 kN. The first recorded crack was observed at 71.4 kN while the end slip at the peak load was 0.08 mm.

For specimens with angle connectors, the recorded peak load for S.P.A1 was 100 kN. The first recorded crack was observed at a load of 50.5 kN. The end slip for this specimen was 0.03 mm at the ultimate level. For S.F.A21, the peak load was recorded to be 117.2 kN, while the crack was initiated at a load level of 57.2 kN. The end slip of the S.F.A21 specimen at the peak load level was 0.02 mm. For S.F.A22, the peak load of this specimen was recorded to be 107.3 kN and the crack initiations were observed at a load level of 57.2 kN. The recorded specimen’s end slip at the ultimate level was 0.07 mm. All specimen failed in same manner due the excessive cracks in the negative moment with different values of slip as mentioned above. Table 2 summarizes the cracking load, peak load, and mid-span deflection for all specimens.

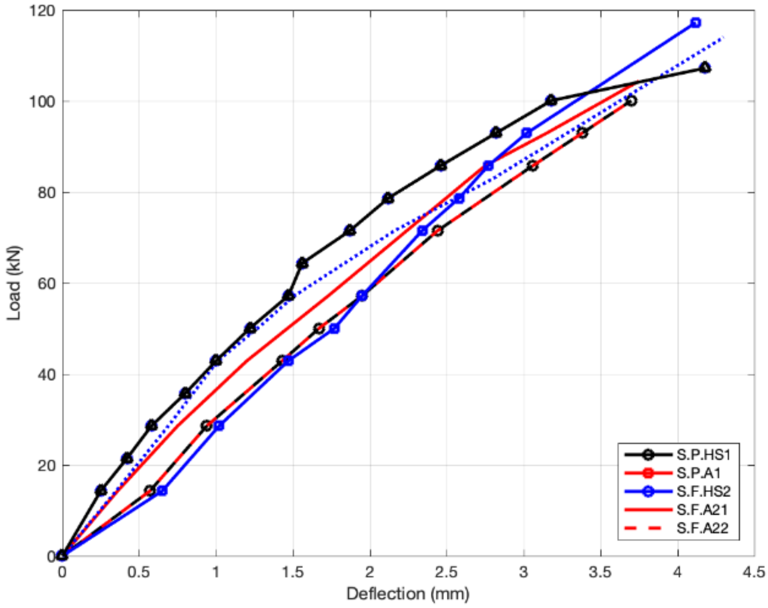


Figure 3. Load-displacement relationship of all specimens

Table 2. Cracking and peak load and corresponding midspan deflections

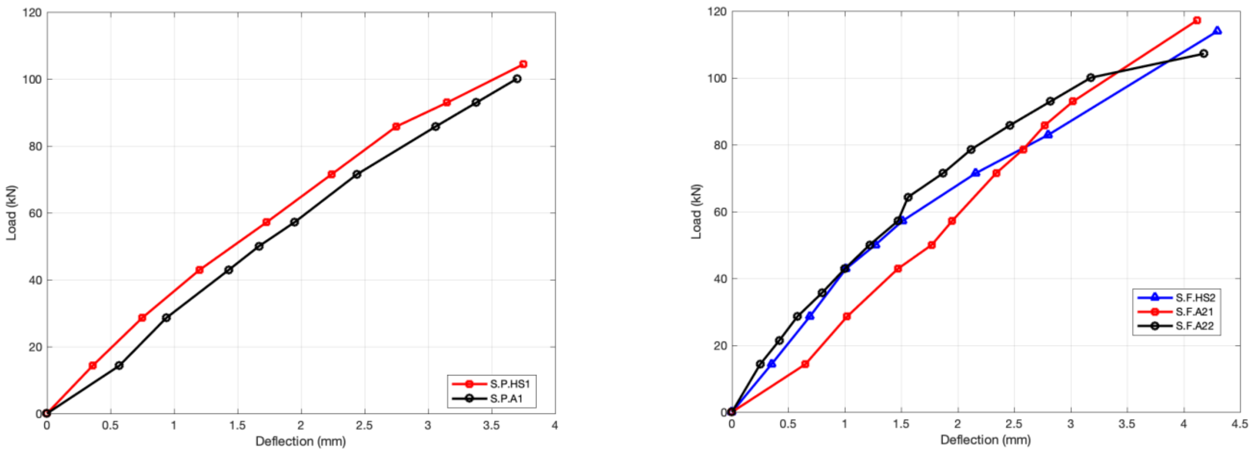
Specimen	First crack load (kN)	Peak load (kN)	Deflection at first crack load (mm)	Deflection at peak load (mm)
S.P.HS1	75.1	104.3	1.54	3.76
S.F.HS2	71.4	114	2.15	4.31
S.P.A1	50	100	1.68	3.71
S.F.A21	57.2	117.2	1.94	4.13
S.F.A22	57.2	107.3	1.48	4.19

4.2. Shear connectors type

An angle shear connector was used with the same section area to HS connectors. Figure 4 and Table 3 show the comparison in terms of load-displacement relationship and load at the peak load level of the adopted specimens, respectively. From experimental results, a decrease by a ratio of (4.12) % was observed in the peak load when the single angle shear (A1) connectors were employed as a replacement for HS. For S.F.A21, the peak load strength was increased by 2.8 % compared to double HS. However, for S.F.A22, a decreased in the peak load was observed by 5.87 % than the peak load of double HS.

Table 3. Connectors type effect

Specimen	Peak load (kN)	Difference (%)
single shear connector		
S.P.HS1	104.3	-
S.P.A1	100	-4.12
double shear connector		
S.F.HS2	114	-
S.F.A21	117.2	2.8
S.F.A22	107.3	-5.87



single shear connectors

double shear connectors

Figure 2. Comparison of shear connector type

4.3. Effect of connector arrangement

The arrangement of the angle shear connectors was an important factor that affects the composite section performance. Two arrangements were adopted as shown in Table 4 (S.F.A21 and S.F.A22). Figure 3 and Table 4 compare the load-displacement relationship between the two connectors arrangements.

Table 4. Connectors arrangement effect

Specimen	Peak load (kN)	Difference (%)
S.F.A21	117.2	9.32
S.F.A22	107.3	

The first arrangement of angle shear connectors (S.F.A21) showed a higher peak load strength compared to the second suggested (S.F.A22) by a ratio (9.32) %.

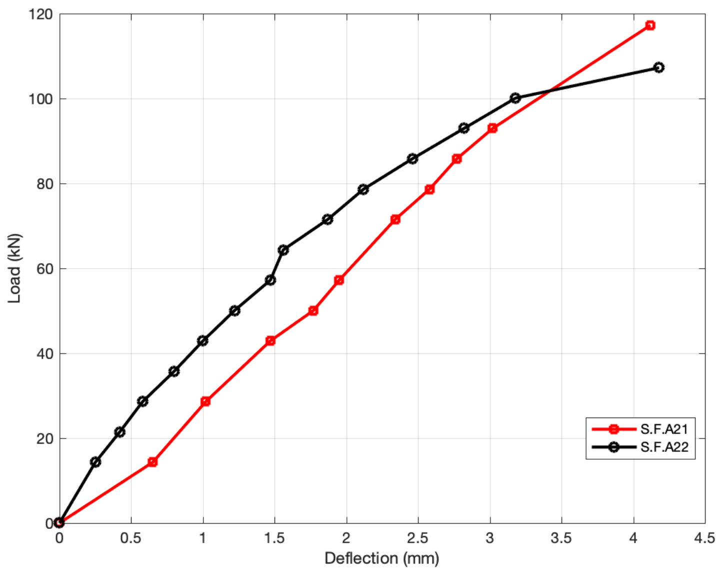


Figure 3. Angle shear connectors arrangement effect

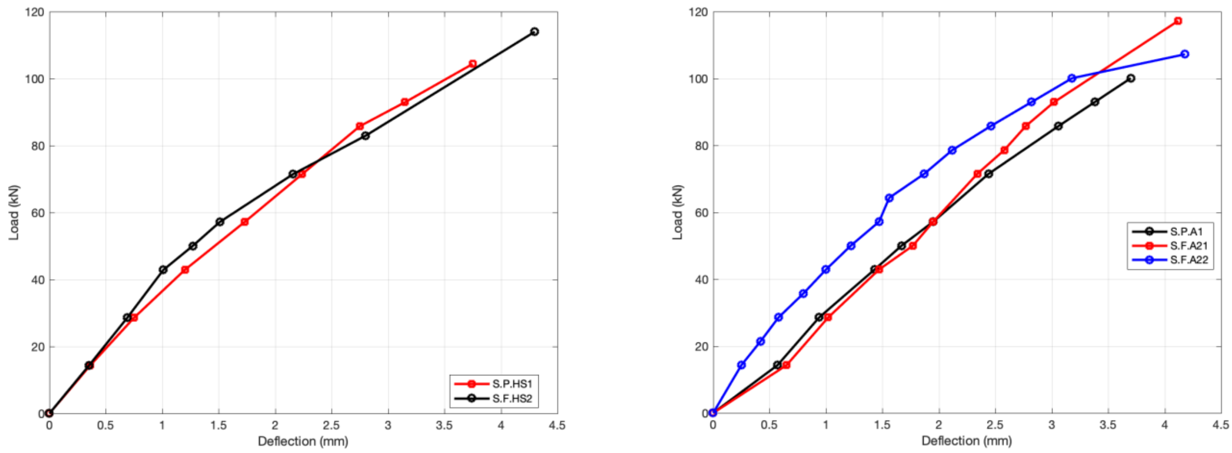
4.4. Bond interaction effect

In this section, the role of bond interaction for HS and angle connectors is studied. It is important to investigate the bond interaction effect on the performance of a composite steel beam under NBM. Table 5 and Figure 4 present a comparison between the full and partial interaction of the double HS and angle connectors.

Table 5. Bond interaction effect

Specimen	Peak load (kN)	Difference (%)
HS connectors		
S.P.HS1	104.3	-
S.F.HS2	114	9.2
Angle connectors		
S.P.A1	100	-
S.F.A21	117.2	17.2
S.F.A22	107.3	7.2

The load of the composite specimen with double HS (S.F.HS2) is greater than the specimen with the single HS (S.P.HS1) by about 10 kN. This difference can be related to the strong bond interaction. The same improvement was observed for the double angle connector (S.F.A21 and S.F.A22) instead of the single connector. The peak load was increased by 17.2 % and 7.2 % for S.F.A21 and S.F.A22 compared to S.P.A1, respectively.



HS connectors

Angle connectors

Figure 4. Bond interaction effect

5. Finite element analysis (FEA)

In this section, a three-dimensional FEA using commercial software was used to model the composite concrete steel and validate the experimental results and perform additional cases with new parameters. Different elements were used to model the different material of the composite beams in the FEM is shown in Table 6. The nonlinear solution algorithm used in this analysis was done using a full Newton-Raphson solver. The materials nonlinearity due to concrete cracking, concrete crushing, and reinforcement yielding were considered during the analysis. The typical mesh, loading arrangement, and boundary condition are shown in Figure 5 and the connector representation in the FEM is shown in Figure 6. The specimens with only angle shear connectors were used in FEM.

Table 6. Description of used elements

Used element	Element type	Modeled material
SOLID65	8-node brick element	concrete
SHELL181	4-node element	steel beam and angle shear connectors
LINK180	2-node element	steel reinforcement
CONTA178	2-node element	interface between steel beam and concrete slab
COMBIN39	2-node spring element	slip resistant between shear connectors in slab and compression steel flange of beam.

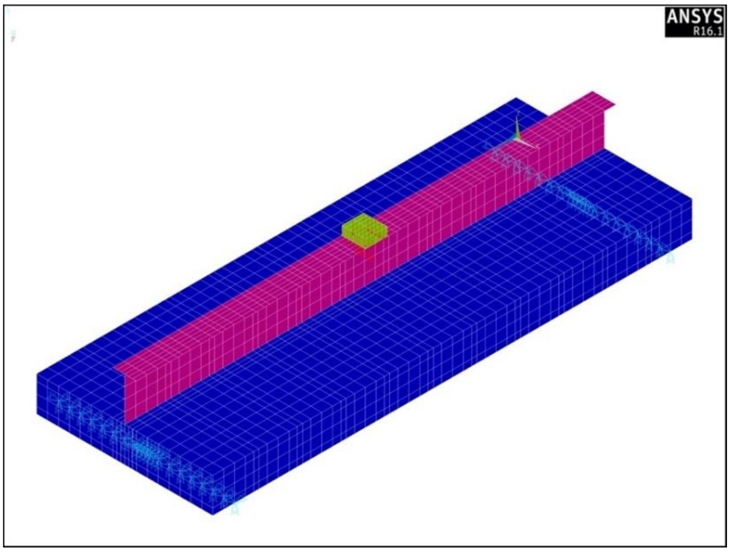
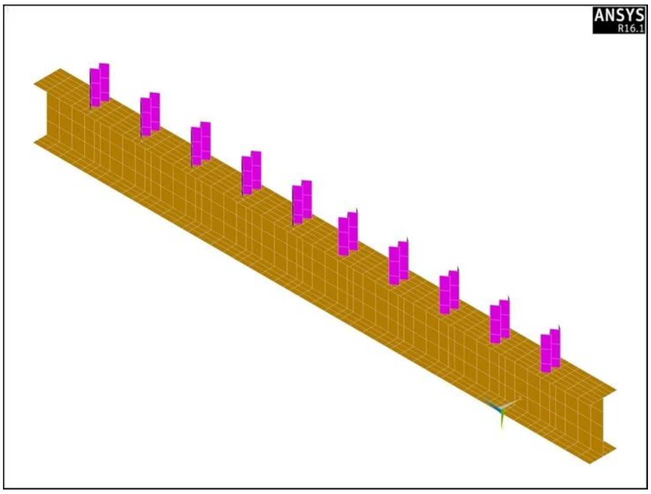
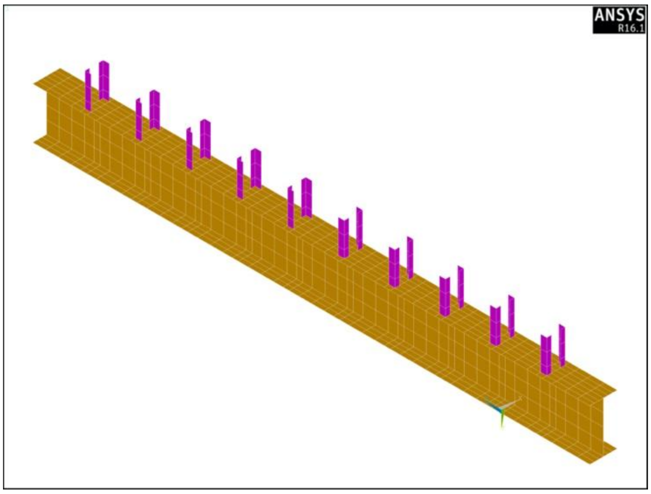


Figure 5. Mesh, loading arrangement, and boundary conditions



S.F.A21



S.F.A22

Figure 6. Representation of connector

The FEM for S.P.A1, S.F.A21, and S.F.A22 captured both the trends in initial stiffness and failure mode. Table 7 shows the comparison between FEM and experimental results in terms of load and displacement at peak load level. Figure 7 shows the comparison of load-displacement relationship between FEM and experimental results.

Table 7. Comparison of experimental and FEM results

Specimens	Peak load		Displacement at peak load		Slip at peak load	
	Exp. (kN)	FEM (kN)	Exp. (mm)	FEM (mm)	Exp. (mm)	FEM (mm)
S.P.A1	100	100.1	3.71	4.01	0.03	0.025
S.F.A21	117.2	117.26	4.13	4.32	0.02	0.015
S.F.A22	107.3	107.25	4.19	4.52	0.07	0.074

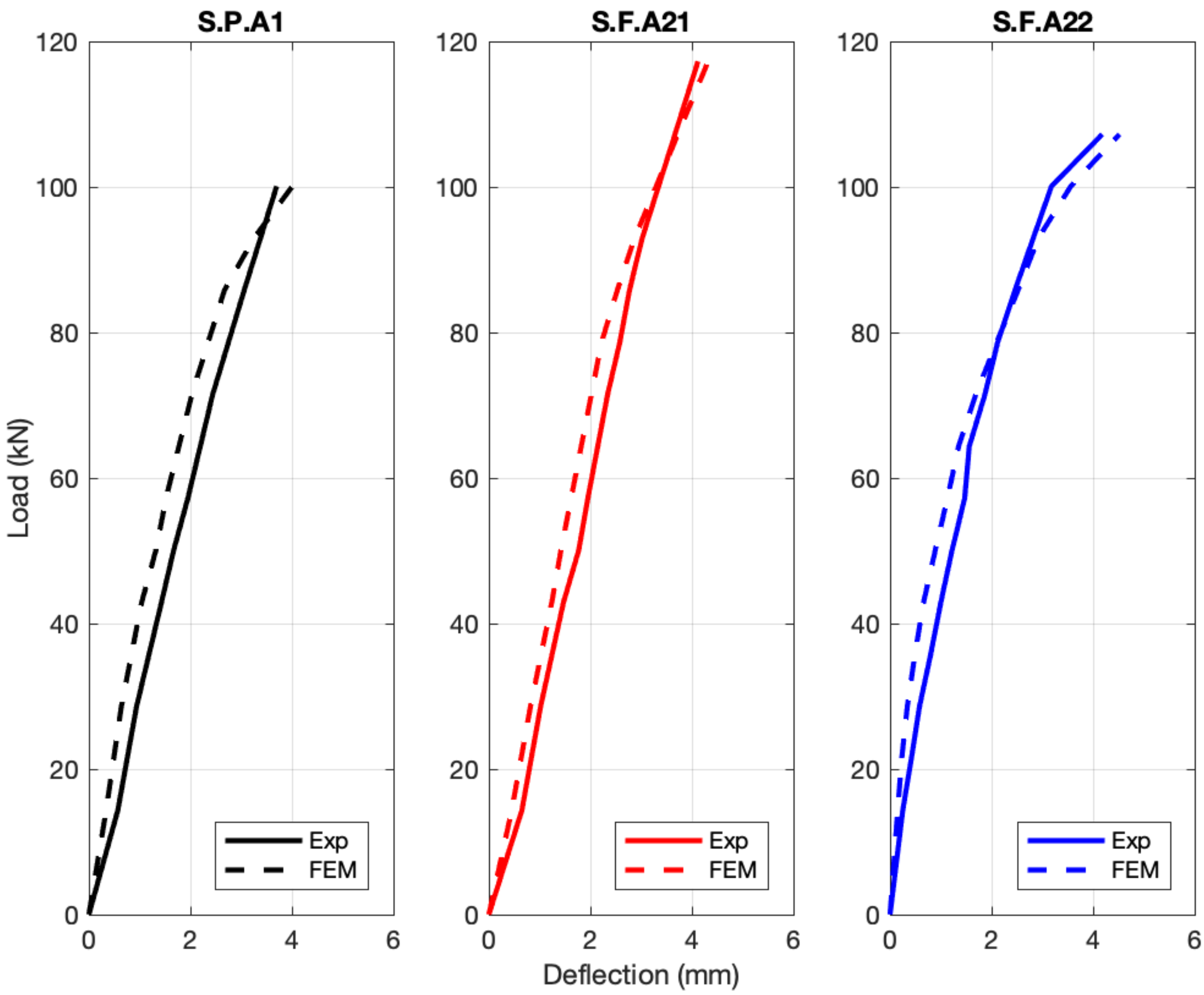
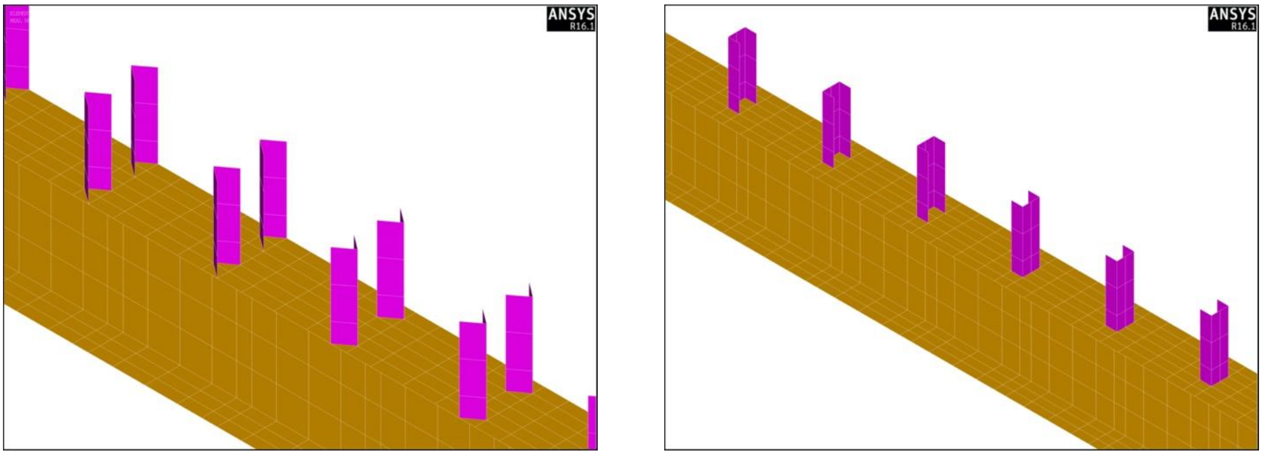


Figure 7. Experimental and FEM results comparison for all angle connectors specimens

The model was extended to better understand the limiting failure modes by including other factors that may control the overall behavior. The transverse distance between a pair of connector affects the bond strength. In the experimental program, the distance between the angle connectors was zero for S.F.A21 while it was 20 mm for S.F.A22 as shown in Figure 8. In FEM, this parameter was changed to be 20 mm for S.F.A21 and zero for S.F.A22 as shown in Figure 8. For S.F.A21, an increase in the peak load was achieved by about 6.3% compared to the experimental results. This increase in the specimen's capacity is related to the improvement in the bond strength. On the other hand, a decrease was observed in peak load for S.F.A22 by 6.6% compared to the experimental results. However, increasing or decreasing the distance between a pair of connectors does not affect the failure mode. However, a slight difference was observed in end slip of the specimen. The comparison results are shown in Figure 9 and Table 7.



S.F.A21 S.F.A22

Figure 8. Representation of new distance between connectors

Table 8. Effect distance between angle connectors

Specimens	Distance between connectors (mm)	Peak load		Displacement at peak load		Slip at peak load	
		Exp. (kN)	FEM (kN)	Exp. (mm)	FEM (mm)	Exp. (mm)	FEM (mm)
S.F.A21	0 mm	117.2	117.26	4.13	4.32	0.02	0.015
	20 mm	---	124.7	----	4.52	----	0.014
S.F.A22	20 mm	107.3	107.25	4.19	4.52	0.07	0.074
	0 mm	---	100.1	----	3.89	-----	0.076

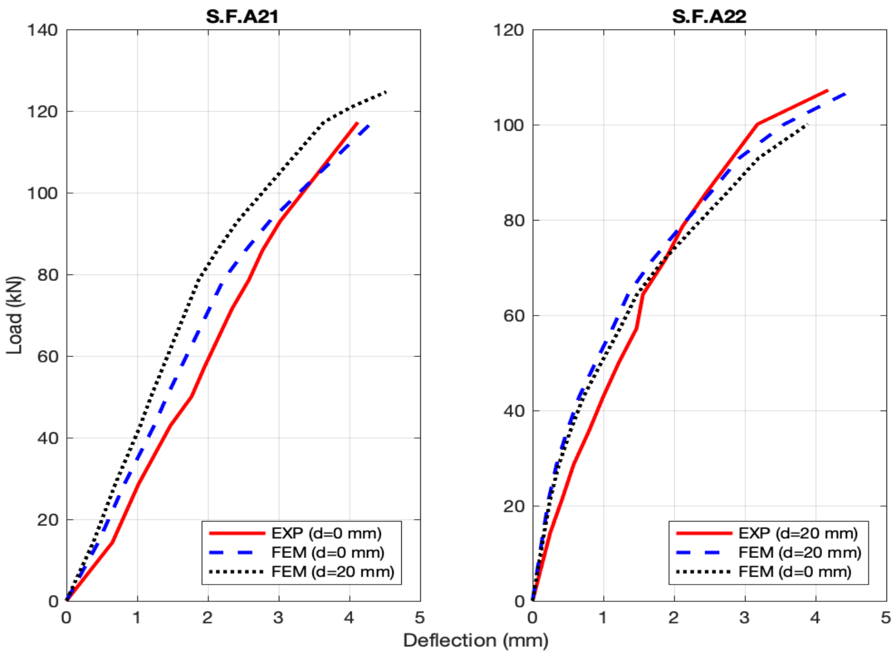


Figure 9. Effect of distance between pair of connectors

6. Conclusion

This research present and experimental and numerical study to investigate the performance of angle shear connectors as an equivalent for HS connector based on same cross-section area in the composite beam subject to NBM. The following major conclusions can be drawn:

1. A decrease in the ultimate capacity about 4.12% was observed when single angle connectors were employed compared to HS connectors.
2. An increase in the composite beam capacity was achieved when double angle connectors (S.F.A21) were considered as a replacement for the double HS connectors. This increase was about 2.8% of the peak load of S.F.HS2. However, a decreased in ultimate capacity by 5.87% when the second setting arrangement of angle connectors (S.F.A22) was used compared to S.F.HS2.
3. The setting arrangement of angle connectors has a significant effect on the performance of the composite section. The first arrangement of angle connectors (S.F.A21) was increased by 9.32% compared to the second sitting arrangement (S.F.A22).
4. An increase in the peak load of specimen with double HS was achieved by 9.2% compared to a specimen with single HS due to the improvement in the bond strength. On the other hand, an increase in the peak load of composite beam with double angle was achieved by a 17.2% and 7.2% compared to specimen with single angle connectors for the first and second setting arrangement (S.F.A21, S.F.A22), respectively.
5. The finite element analysis (FEA) results agree well with the experimental results in terms of peak load, stiffness, failure mode, and end slip of the beam.
6. Increasing the distance between the pair of connectors from 0 mm to 20 mm increase the peak load by 6.3% without changing the composite beam failure mode.

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