Numerical modeling of inverted-U-shaped connectors to enhance the performance of composite beams

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- Composite beams using reinforced concrete slabs connected to steel beams with shear stud connectors are a common element in modern building construction.

- Inverted-U-shaped connectors were initially developed to improve punching shear resistance in post-tensioned concrete slabs.

- This study uses finite element analysis modeling to investigate the use of inverted-U-shaped connectors to transfer horizontal shear in composite beams.

- The study concludes that inverted-U-shaped connectors can enhance composite beam performance and recommends areas for further study.

Shear connectors are often used to create composite sections by joining reinforced concrete sections with steel sections. The *Eurocode 4: Design of Composite Steel and Concrete Structures* recommends achieving this type of connection by welding headed studs, semiautomatically, to steel beam flanges.[1] In the United States, both the American Institute of Steel Construction's *Load and Resistance Factor Design Specification for Structural Steel Buildings*[2] and the American Association of State Highway and Transportation Official's *LRFD Bridge Design Specifications*[3] address the strength design of shear connectors for composite beams. According to these specifications, a beam must have enough shear stud connectors to achieve its full composite strength.

Literature review

Hicks et al.[4] studied the cost variation in modern skyscraper construction because composite steel and concrete structures are used widely in such buildings. The type of shear connectors used, the thickness of the concrete slabs, and the dimensions of the formed steel deck were all found to affect the capacity of steel–concrete composite slabs.

Hechler et al.[5] emphasized the benefits of composite action when steel and concrete work together to withstand imposed loads. They also explained how this composite behavior outperforms concrete and steel when used independently in various types of construction and construction phases.

Nie et al.[6] performed a load capacity study for prestressed continuous steel–concrete composite beams. Formulas for determining the characteristic loads (cracking, yield, and ultimate loads) of two-span prestressed continuous composite beams under symmetric applied loads were recommended for general cases based on the basic theoretical model for externally unbonded prestressed structures. In addition, a finite element simulation was suggested for modeling the system's nonlinear behavior. Comparisons of analytical, numerical, and experimental data revealed that the analytical technique and finite element analysis (FEA) model give an effective simulation of the nonlinear behavior of prestressed continuous composite beams.

Baran and Topkaya[7] developed an equation that predicts the ultimate resistance of channel connectors with reasonable accuracy and carried out an experimental study on channel-type shear connectors.

In addition, Wang et al.[8] carried out an experiment to examine how the degree of shear connection influences the behavior of steel–concrete composite beams. Composite beams with mild (low-stiffness) shear connectors have a lower ultimate capacity and ductility coefficient compared with rigid (high-stiffness) shear connectors. The failure mechanism of the composite beam moves from the concrete to the shear connector when the degree of shear connection decreases, according to Wang et al.[8]

Another experimental study was conducted by Yang et al.[9] on multiple-bolt shear connectors of prefabricated steel–concrete composite beams. In this study, the influence of the layout form of multiple-bolt connectors, the row spacing of bolts, and the strengthening effect of reinforced concrete slabs on the shear performance were evaluated using 10 push-out specimens of bolt shear connectors.

Mirza and Uy[10] numerically studied the modeling of short- and long-term performance of headed stud shear connectors in composite steel–concrete beams. Bavan et al.[11] numerically predicted the failure of composite beams subjected to combined negative bending moment and axial tension force. Wang and Chung[12] designed and numerically analyzed composite beams with shear connectors of realistic deformation characteristics. Mirambell et al.[13] numerically studied the deflections of steel–concrete composite beams with partial interaction.

Research by Khatib et al.[14] investigated punching shear reinforcement as an option for increasing the deformation and capacity of flat slabs. The research numerically studied the characteristics of a post-tensioned slab (unbonded) subjected to punching stress and reinforced with inverted-U-shaped reinforcement. The results were compared with an experimental examination using finite element software and the punching shear strength requirements from the American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14)*.[15] There was a high correlation among all the obtained results.

Kalibhat and Upadhyay[16] investigated the deformation behavior of steel–concrete composite beams with partial interaction, taking into account numerous aspects such as cross-section geometry, shear connection degree, length, and shear stud connector arrangement. The conclusions, however, were predicated only analytically and numerically, with no experimental confirmation.

The numerical behavior of externally post-tensioned steel–concrete composite girders was investigated by Alsharari et al.[17] The numerical model was generated and verified using experimental test data and an existing analytical model. The influence of different variables on the monotonic behavior of composite girders reinforced using external post-tensioned tendons was investigated in a numerical model to validate the results. The numerical model improved knowledge of the influence of these factors on the behavior of the reinforced beams. The parametric analysis findings demonstrated that as the percentage of shear connection decreased, stud stresses increased, and sliding between both the concrete surface and steel beam increased.

Previous research has shown that, compared with closed stirrup reinforcement, inverted-U-shaped reinforcement enhances flat-slab efficiency in terms of load capacity and failure mode.[18] The research studied the numerical benefit of using inverted-U-shaped reinforcement instead of stirrup reinforcement in strengthening two different types of post-tensioned beams. The findings were compared with ACI 318-14[15] and the computational results suggested that the ACI 318-14 limits on the minimum of shear reinforcement for prestressed concrete beams (bonded) were overly conservative. There was a strong connection between the numerical and experimental outcomes.

Shear connectors offer the required connection between materials for composite beams to perform to their full composite capacity. Slip at the interface between materials is dependent on the type of interaction between the steel beam and the concrete slab. Based on the types, spacing, arrangement, and behavior of the shear connectors, some relevant theoretical models have been developed that may be used to forecast the section response of a composite beam.[19,20]

In research by Daou et al.,[21] the shear connection degree in steel–concrete composite beams was investigated based on the type of shear connectors used. A nonlinear numerical study supported by testing revealed that the capacity and deflection of composite beams are dependent on the arrangement and mechanical characteristics of the shear stud connectors. Furthermore, a simpler model for predicting shear stud connector degree and composite beam capacity was presented.

Building on the previous research, this study presents an analytical study that demonstrates the effect of using inverted-U-shaped connectors instead of shear stud connectors on the behavior of steel–concrete composite beam sections. Two types of inverted-U-shaped connectors were investigated: mild (low stiffness) and rigid (high stiffness).

Shear connector types

Several types of shear connectors can be used in composite beams, as discussed by Shariati et al.[22] This research discusses two types of shear connectors and investigates the efficiency of using the proposed inverted-U-shaped shear reinforcement systems compared with using shear stud-type connectors in composite beams.

Stud-type connector

Welded shear studs were tested for the first time at the University of Illinois, which led to the first use of shear studs in bridges and building projects in 1956.[23] This type of stud shear connector was introduced because the studs could be semiautomatically welded to the steel beam flange to construct the composite section. The degree of interaction of the composite beam depends mainly on the degree of shear connection used.

Inverted-U-shaped connector

Inverted-U-shaped connectors were first developed as a solution for punching shear failure in structural concrete members such as slabs, beams, footings, flat foundations, and other reinforced concrete structures by Abou Saleh and Suaris.[24] The patented strengthening assemblies, which include hairpin (or inverted-U) shaped reinforcing bar elements attached to a support base, were used to improve punching shear strength in structural concrete members (**Fig. 1**).[25] Later, these reinforcement assemblies were investigated for other uses.[14,18,26,27] The use of inverted-U-shaped reinforcement assemblies has been shown to be an important enhancement in the cited research by reducing punching shear, increasing shear capacity, and reducing deflection in the tested beams.

Research significance and objectives

The effectiveness of composite structural behavior is optimized when both the concrete slab and steel component function compositely for all loading scenarios. All loads, including the structure's dead weight, should be resisted by the proposed composite section.

This study investigates the advantages of using inverted-U-shaped connectors instead of shear stud connectors. The primary goal of this research was to evaluate the behavior of composite beams with inverted-U-shaped connectors and check the predicted enhancement using finite element software. Daou et al.[21] conducted experimental and computational studies on composite beams with two types of shear stud connectors. A numerical investigation was carried out as part of this study based on the data from Daou et al. The numerical model was compared with the previous research results to validate the model.

Previous experimental testing

Experimental investigations by Daou et al. were carried out on two series of simply supported composite beams that were 1700 mm (67 in.) long with a 120 × 300 mm (4.7 × 12 in.) reinforced concrete section connected to a 140 mm (5.5 in.)

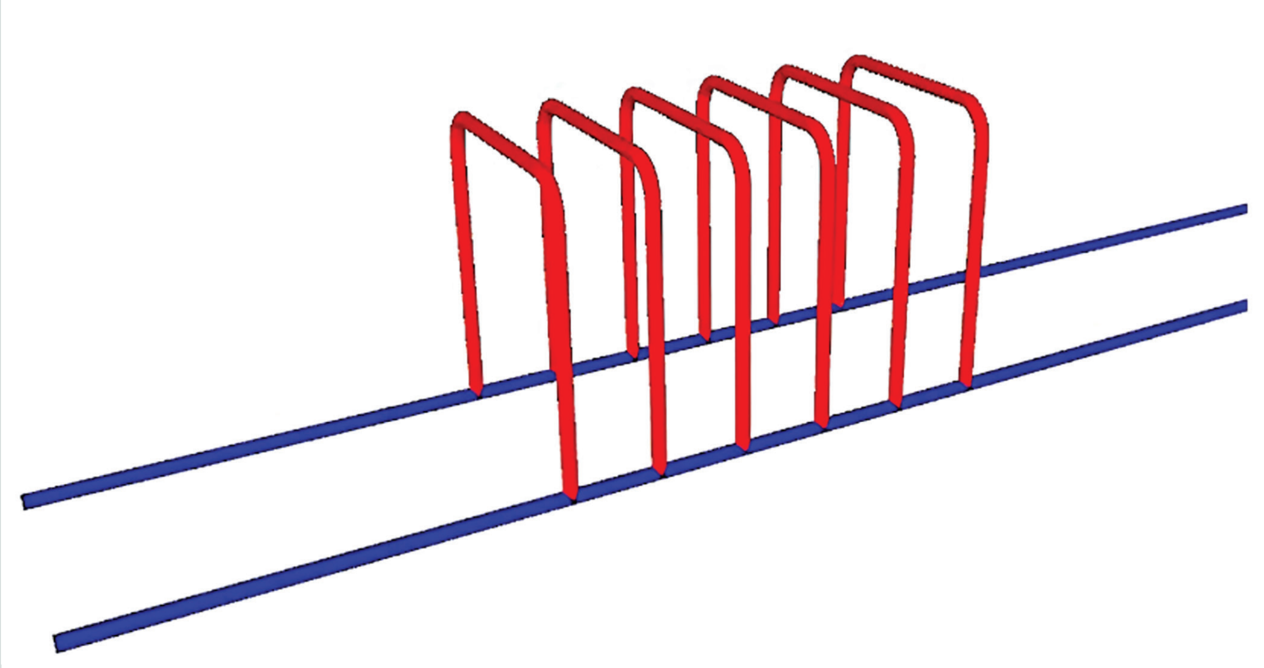

Figure 1. Inverted-U-shaped reinforcement.

deep steel beam (HEB 140). The beams spanned 1400 mm (55 in.) with 150 mm (6 in.) overhangs at each end. The reinforced concrete sections were connected to the HEB 140 sections by shear stud connectors with different stiffness, spacing, and arrangement in rows (two studs per row). Three beams were tested in each series; the first series used rigid shear stud connectors (yield strength f_y of 410 MPa [60 ksi]) and the second series used mild shear stud connectors (f_y of 275 MPa [40 ksi]).

The spacing between the connectors was determined as follows. The overhanging lengths (2 overhangs × 150 mm [6 in.]) were subtracted from the beam total length (1700 mm [67 in.]). The resulting span length was then divided by the number of shear connector rows to provide equal spacing across the span. All reinforced concrete sections had three 10 mm (0.40 in.) diameter reinforcing bars for longitudinal reinforcement and nine 6 mm (0.20 in.) diameter bars for transverse reinforcement (**Fig. 2**). Details of the test program are shown in **Table 1**.[21]

The composite beams were tested under static loading using two equal concentrated loads centered at the beam mid span and spaced 300 mm (12 in.) apart. The testing machine had a maximum capacity of 1000 kN (225 kip). Both ends of the beams were free to rotate, with one end allowed to translate horizontally under load (**Fig. 3**).[21]

Displacement and load readings were measured and collected using a data acquisition system. The concrete compressive stress was equal to 32 MPa (4.6 ksi). The mean measured yield stress of steel was 240 MPa (35 ksi). Mild and rigid connectors of low and relatively high stiffness, respectively, 10 mm (0.40 in.) in diameter, were used. They were arranged similarly to those in the composite beam tests.[21]

During testing, the beams' crack patterns were nearly identical. Cracks first appeared in the concrete slab, either vertically or inclined, near the point of greatest moment. Flexural cracks in the loaded section propagated from the tension zone to the compression zone in the concrete. As the applied load increased, the cracks widened. A minor reduction in load was seen when the cracks initiated, which was easily detected using the testing machine's readout. A small load reduction also occurred because of the failure of several connections in the beams with mild shear stud connectors.[21]

For the first series of beams with mild shear stud connectors, beam failure occurred due to a combination of shear stud connector and concrete failure related to the fracture of some

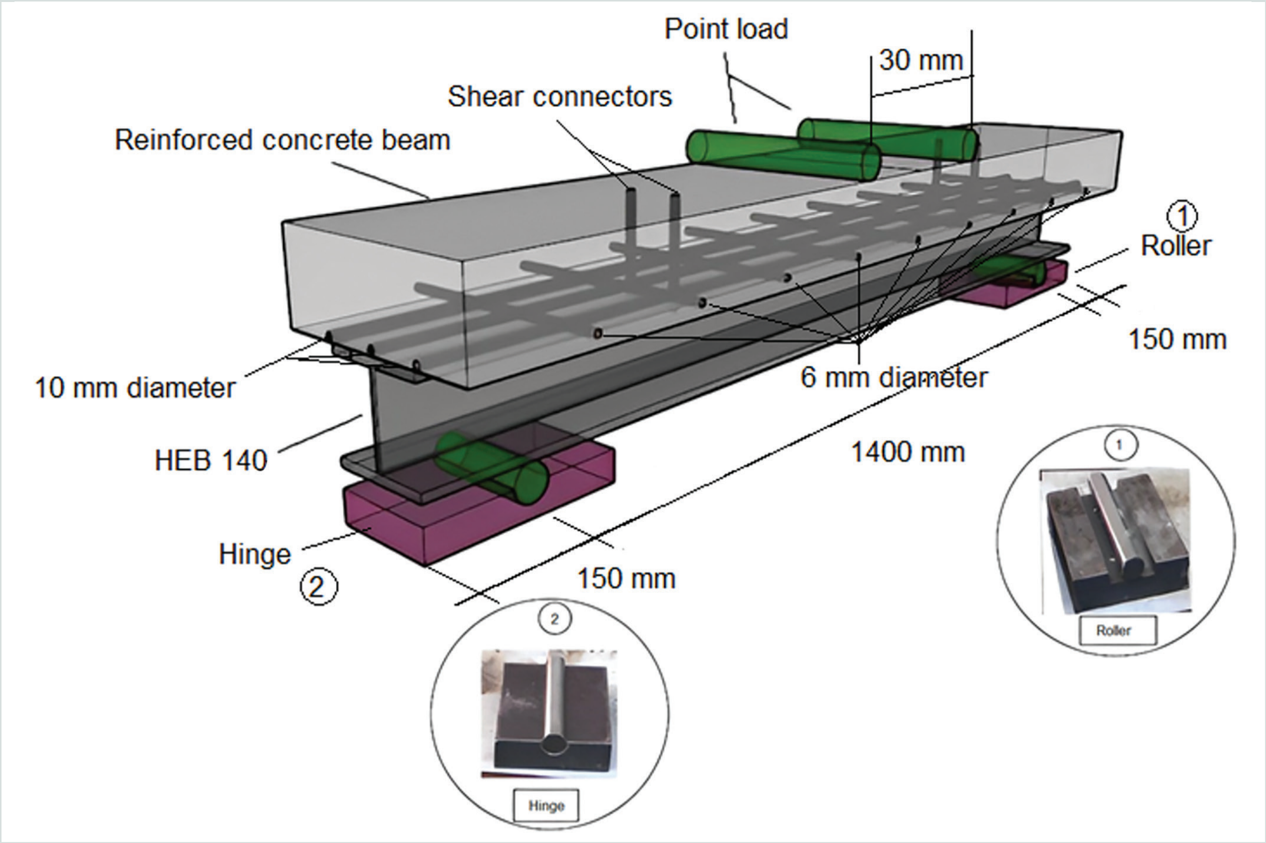

Figure 2. Details of the beam instrumentation, supports, and testing machine. Source: Reproduced with permission from Daou et al. (2021). Note: HEB 140 = 140 mm deep steel I-beam. 1 mm = 0.039 in.

Table 1. Composite beam test results

Number of connector rows	Shear stud type	Beam designation*	Maximum load, kN	Failure load, kN	Stress per shear stud, MPa	Type of failure
4	Mild	R4 H	327.57	274.73	552.62	CSF†
	Rigid	R7 H	350.28	324.73	847.13	CF‡
7	Mild	R10 H	364.32	282.470	315.78	CSF
	Rigid	R4 M	374.91	341.96	484.07	CF
10	Mild	R7 M	375.80	309.32	221.05	CSF
	Rigid	R10 M	385.61	348.01	338.85	CF

Source: Data from Daou et al. (2021).

Note: 1 mm = 0.039 in., 1 kN = 0.225 kip; 1 MPa = 0.145 ksi.

* R4 H, R7 H, and R10 H indicate the number of shear stud rows per specimen (4, 7, and 10, respectively) with shear connectors designated as rigid (high stiffness). R4 M, R7 M, and R10 M indicate the number of shear stud rows per specimen (4, 7, and 10, respectively) with shear connectors designated as mild (low stiffness).

† Indicates combination of concrete and shear connector failure.

‡ Indicates concrete failure only.

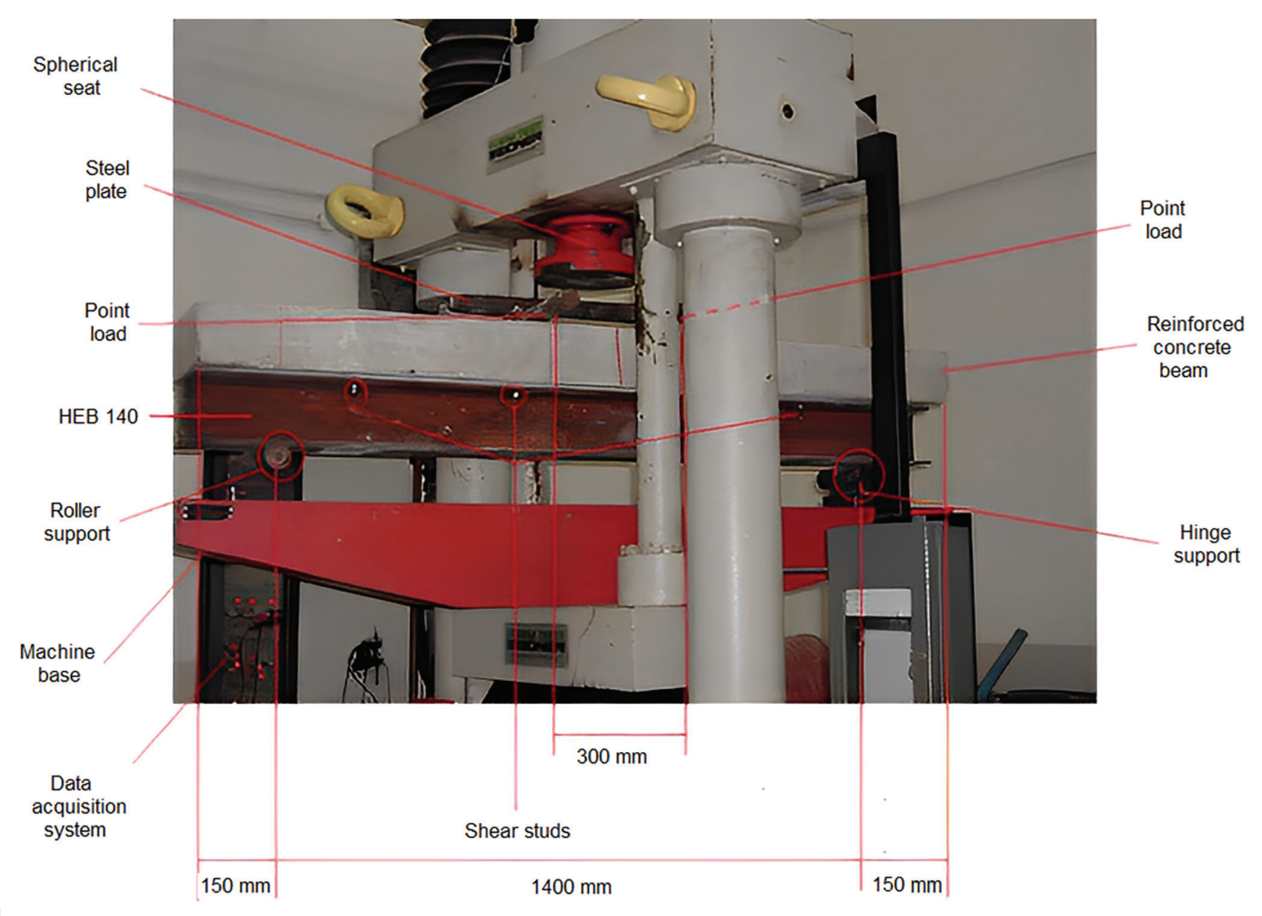

Figure 3. Details of composite beam mounted on testing machine. Source: Reproduced with permission from Daou et al. (2021). Note: HEB 140 = 140 mm deep steel I-beam. 1 mm = 0.039 in.

connectors, which was accompanied by concrete crushing at the point load. The composite beams with rigid shear stud connectors failed abruptly with a substantially inclined propagation of cracks between the concrete slab and the steel beam. This phenomenon was accompanied by the loss of concrete cover due to horizontal cracking at the concrete surface, the yield of reinforcing bars, and the fracture of shear stud connectors.[21]

The goal of the experimental testing was to evaluate the composite beam shear capacity only (and not the flexural capacity), clarify the effect of connector stiffness on composite behavior, and determine how the shear stud connector distribution affects full or partial composite action. To achieve this goal, the composite beams were designed so that failure would occur either in the concrete section only, or in the concrete section and shear studs.[28] The experimental maximum load capacity, the failure load, and the type of failure for each composite beam provided with mild and rigid shear stud connectors are presented in **Table 1** and **Fig. A.1** and **A.2**.[21] (For appendix figures, go to https://www.pci.org/2023May-Appx.)

Previous numerical modeling

In previous research by Daou et al., numerical models were constructed to imitate the behavior of the composite beams. The steel–concrete composite beam was modeled using FEA modeling software to account for the components' nonlinear behavior. The model was built using the characteristics of the materials from the experimental test program. Isotropic elements, which included eight nodes, each one with three degrees of freedom (translations in x, y, and z dimensions), were used to simulate the concrete. This element type may deform plastically, crack in the three orthogonal directions, and crush. A stiffer element type was chosen to model the steel I-beam. This element type also includes eight nodes, with three degrees of freedom in x, y, and z directions for each node. Steel reinforcement was modeled using a three-dimensional element with two nodes and three degrees of freedom (translations in x, y, and z directions). This element type may also deform plastically.[21]

The composite beam model was generated using material properties that were similar to those used in the experimental testing, and then the overall geometry was meshed. Because the reinforced concrete included multiple steel elements (main reinforcing bars, secondary reinforcing bars, shear stud connectors), the mesh was refined to ensure accuracy without dividing the model into different parts (which would take more time to model and run). The findings for the composite beams were generated in the form of tables containing node displacements, forces, and moments. The results, such as deflection charts and stress contour diagrams, were also presented in graphical form.[21]

A representative comparison of the results obtained from the numerical model with those from the tested beams with mild and rigid shear stud connectors is represented in **Fig. 4** and **5**, respectively. The comparison of the data obtained from the model with those from the tested beams with rigid and mild shear studs showed nearly identical results. The validity of this study was established by correlation of the numerical model findings produced from the finite element program with the experimental test evidence.[21]

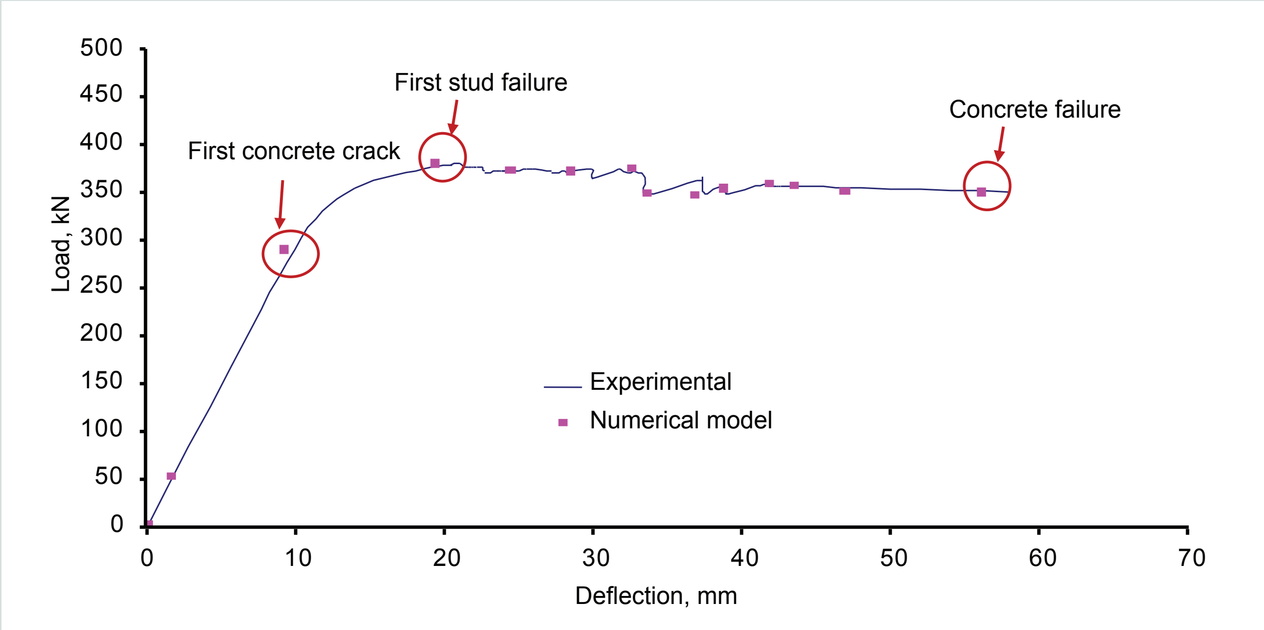

Figure 4. Comparison results for 10 mild (low-stiffness) shear stud rows. Source: Reproduced with permission from Daou et al. (2021). Note: 1 mm = 0.039 in.; 1 kN = 0.225 kip.

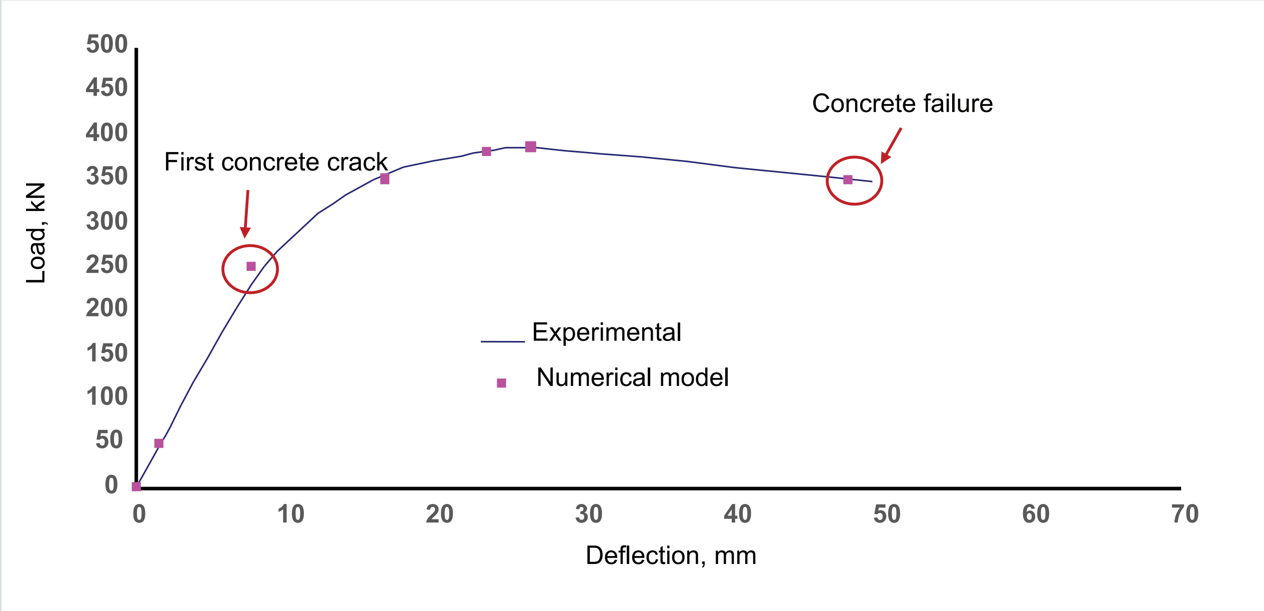

Figure 5. Comparison results for 10 rigid (high-stiffness) shear stud rows. Source: Reproduced with permission from Daou et al. (2021). Note: 1 mm = 0.039 in.; 1 kN = 0.225 kip.

The HEB 140 displayed substantial displacement at mid span before concrete failure in all tested beams. Furthermore, the final failure of the composite beams using mild shear stud connectors occurred as a mixture of concrete and shear stud connector failure, whereas the final failure of specimens with rigid shear stud connectors occurred in the concrete section. When a mild shear stud connector cracked, the load on the composite beams dropped noticeably. The arrangement of the shear stud connectors had a considerable impact on the composite beam's behavior. Decreasing the amount of shear stud connectors increased the deflection of the composite beams, while the type of shear stud connector had little effect on the beams' capacity. Finally, all beams with rigid shear stud connectors exhibited strong composite performance, whereas those with mild shear stud connectors exhibited partial composite action. It should be emphasized that the accuracy of analytical models was demonstrated by the correlation with the findings from the experimental test results. The increase in displacement may be viewed as a benefit over regular reinforced concrete beams for construction subjected to seismic load effects, where the ductility requirement is an essential feature to absorb the produced energy due to seismic activities.

The test results also revealed that the maximum increase in the capacity of composite beams provided with 10 rigid connectors was 10%; however, the capacity of the composite beams provided with 10 mild connectors reached up to 14.7%.[21]

Numerical models for composite sections in this study

Based on the previously mentioned experiments and numerical studies, a new connector shape was proposed that would be checked using a numerical model to determine whether it could enhance the performance of composite beams when compared with shear stud connectors. To provide relevant results, the dimensions of stud shear connectors were checked using the AASHTO LRFD specifications.[3] According to the AASHTO LRFD specifications, stud shear connector's height-to-diameter ratio should not be less than 4.0. In this study the height of 12 mm (0.5 in.) is divided by the diameter of 10 mm (0.40 in.) for a ratio of 1.2, which is less than 4. In addition, stud shear connectors ought to penetrate the concrete deck by at least 50 mm (2 in.). All these conditions and requirements were satisfied.

Twelve models for composite beams were built using a finite element program: six with shear studs, to replicate the results of Daou et al., and six with inverted-U-shaped connectors instead of shear studs. To model any structure using finite element software, several steps should be followed: first, drawing and defining the proper elements; then inserting loads, properties, and constraints; and then meshing it. The main components of the composite beam (including the concrete, steel beam, and reinforcement) were inserted in the x-y plane, and then were joined by lines to generate the cross-sectional area of the composite beam. This region was extruded along the z axis to form the overall volume of the composite beam. Then, the placement and geometry of the shear studs or inverted-U-shaped connectors were defined and inserted in the correct positions. Both supports were attached to the lower face of the HEB 140 profile directly.

A solid element represented the reinforced concrete beam material; each node had three degrees of freedom as well as the condition of translation in the x, y, and z directions. This element can also deform plastically, causing cracks in all three directions until the concrete fails. The normal strength performance of the concrete was modeled for multilinear kinematic hardening, using compression stress-strain curves for unconfined concrete provided by Kent-Park, and the tensile stress was f_t equals $0.3 f_c'^{2/3}$, where f_c' is the concrete compressive strength. The application of the solid element in concrete material modeling can produce results that reflect the nonlinear behavior of the reinforced concrete beams (**Table A.1**).[29] (For appendix tables, go to https://www.pci.org /2023May-Appx.)

The HEB 140 steel profile (**Table A.2**) was modeled using a quadrilateral shell element having four nodes and six degrees of freedom per node (x, y, and z translations and rotations), taking membrane and bending stiffness into account. The shell elements' formulation, which employs Reissner-Mindlin's first-order shear-deformation theory, was based on the work of various writers, notably Bathe and Dvorkin,[30] as well as MacNeal and Harder.[31] This shell element type may be used to solve linear and nonlinear problems and can accommodate massive deformations and rotations. The material properties used in the previously described experimental test program were used in the model, taking into account the nonlinear behavior of the components.[21]

Due to the mechanical properties of steel reinforcing bars, shear studs, and inverted-U-shaped connectors, another element type was added to the models. Because the different steel components are similar to truss members in terms of modeling, the convenient element to use was the three-dimensional spar element, which has two nodes with three degrees of freedom (translations in the nodal x, y, and z dimensions) (**Table A.3**). This element type can support both large displacement and large strain. Steel reinforcement, stud connectors, and inverted-U-shaped connectors were optimized to be completely elastoplastic.

The link between both reinforcement and connectors with concrete has full interaction, and the concrete nodes, at the contact to reinforcement, are the same nodes. There is no relative movement between the reinforced concrete section and the HEB 140 steel beam element because of their perfect connection. In addition, the surface between reinforcing bars and connectors was fully bonded. As a result, the concrete surface was fully bonded with the reinforcement and had complete contact, so that there was no relative movement along the interface.

The load was applied at the mid span of the composite beam using two separated concentrated loads. **Figure 6** shows the point loads and an internal cross-section mesh. The observed load, deflection, and concrete stress that developed beginning with the cracking load up to beam failure were recorded.

Several numerical and experimental studies report that inverted-U-shaped connectors enhance the behavior of both unbonded[14,24] and bonded post-tensioned slabs[27] and post-tensioned beams,[18,26] which encouraged this paper's authors to study its effects on composite structures.

Analysis of results and discussion

Through numerical simulation, it is possible to demonstrate how the stresses are distributed among the various components of the two-point load test for composite beams, enabling a deeper comprehension of the internal behaviors. The FEA beam models were solved. Tables containing nodal displacements, element forces, and moments for the composite beams were produced. As illustrated in **Fig. 7**, the results were also presented in a mapping format, such as deflection plots and stress contour diagrams. The nodal displacements (deflection) for the numerical model of the composite beams with inverted-U-shaped connectors (mild and rigid) are presented in **Fig. 8** through **11**.

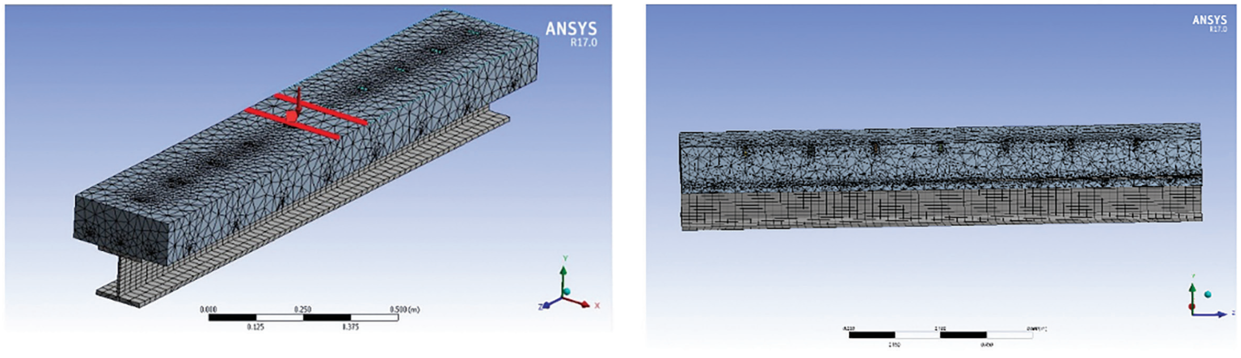

Figure 6. Numerical model of composite beam.

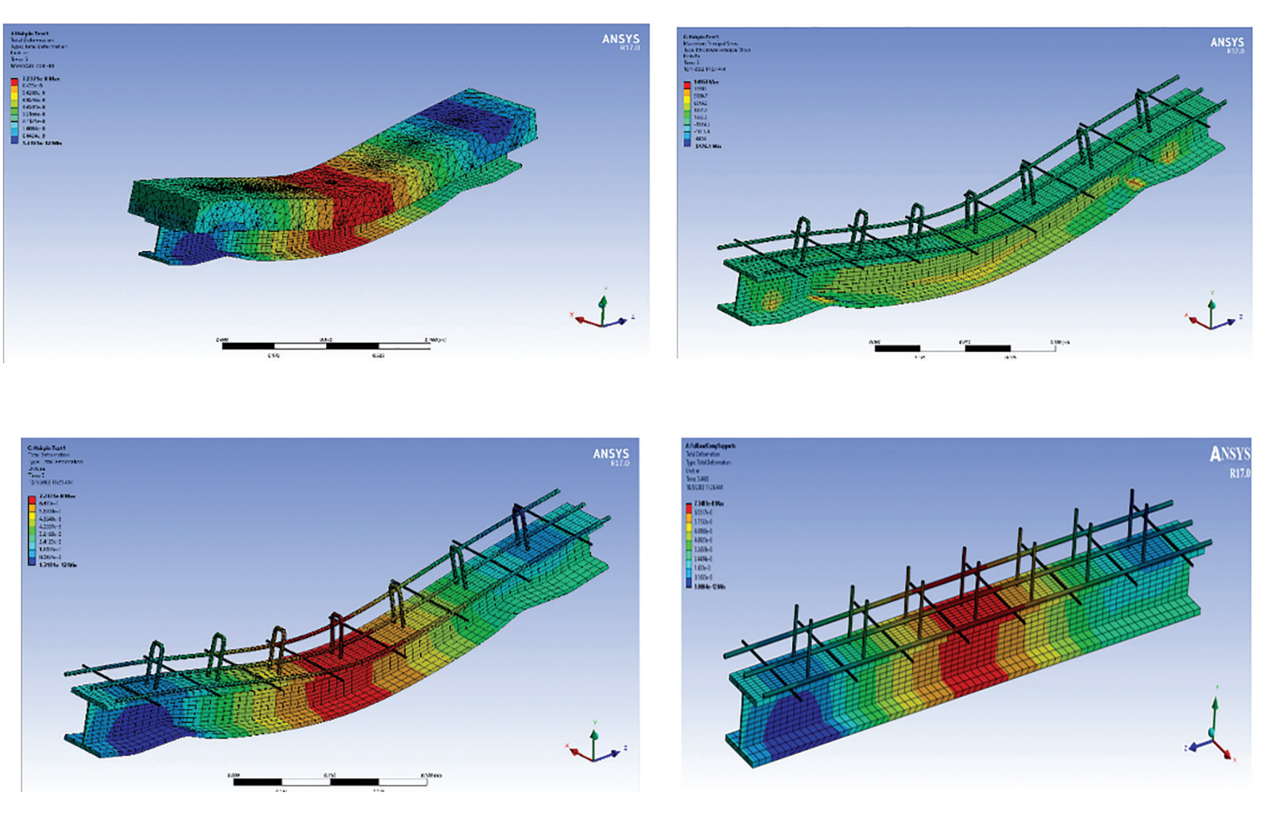

Figure 7. Typical beam results.

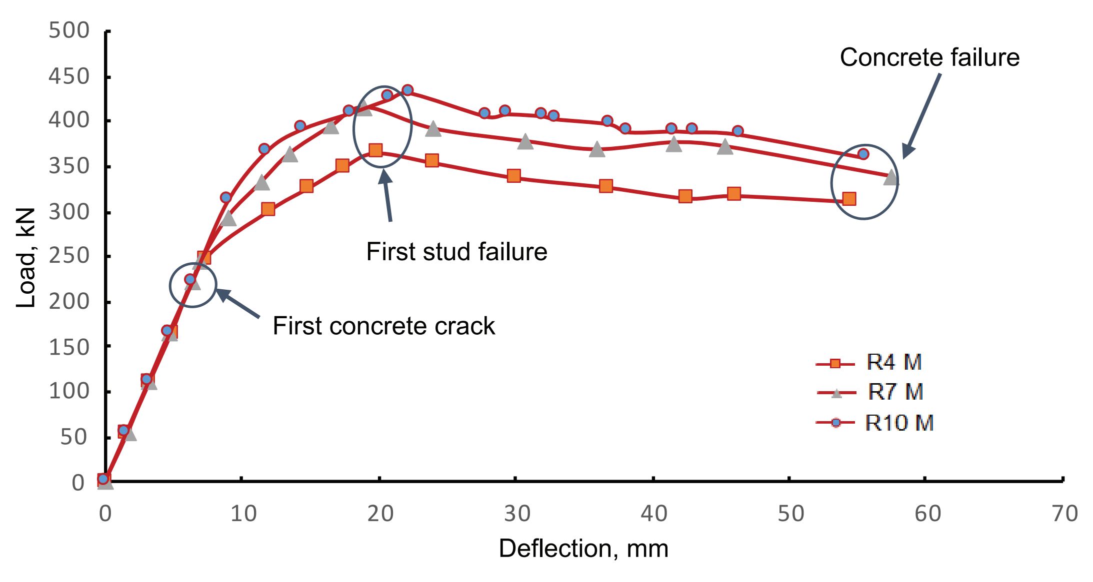

Figure 8. Load deflection curves for mild (low-stiffness) inverted-U-shaped connectors. Note: R4 M = specimen with four mild connector rows; R7 M = specimen with seven mild connector rows; R10 M = specimen with ten mild connector rows. 1 mm = 0.039 in.; 1 kN = 0.225 kip.

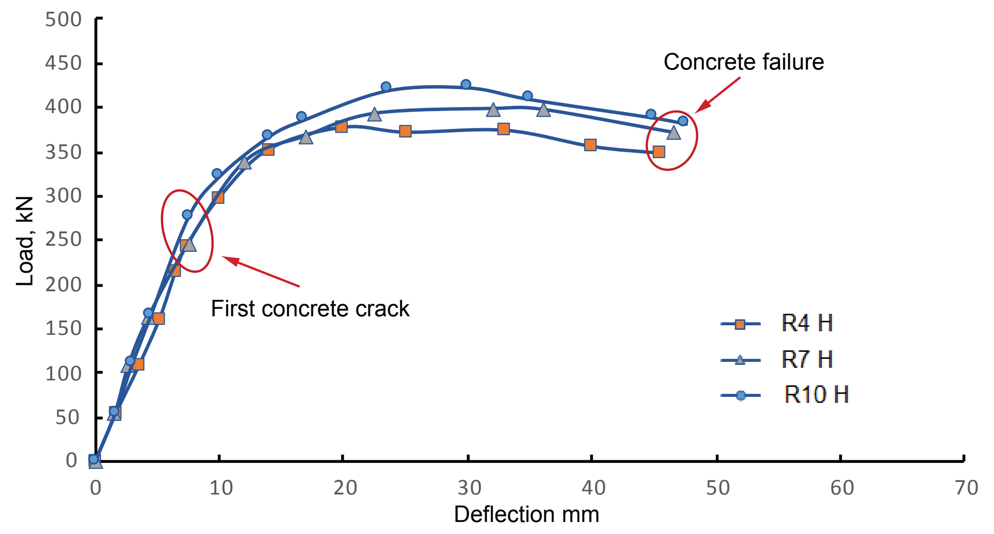

Figure 9. Load deflection curves for rigid (high-stiffness) inverted-U-shaped connectors. Note: R4 H = specimen with four rigid connector rows; R7 H = specimen with seven rigid connector rows; R10 H = specimen with ten rigid connector rows. 1 mm = 0.039 in.; 1 kN = 0.225 kip.

The models established in this work represented the global behavior of two different types of composite beams. The variable parameters used in this research were connector geometry, connector stiffness, and number of connectors. In contrast to prior efforts, the models in this study produced findings that were similar to those achieved by Daou et al.,[21] despite using a different version of finite element software. In the elastic zone, the models in this study produced nearly equal results to Daou et al. but diverged in the final load step, when the concrete reached high levels of compressive stress. This change in behavior at high compressive stress that exceeded the maximum design compressive stress was expected.

The comparison of the numerical results from the models with inverted-U-shaped connectors (mild and rigid) with those from the previously modeled composite beams with shear studs (mild and rigid connectors) shows enhanced performance for the models with inverted-U-shaped connectors. Typical comparisons of the numerical results obtained from the models with mild and rigid shear stud connectors

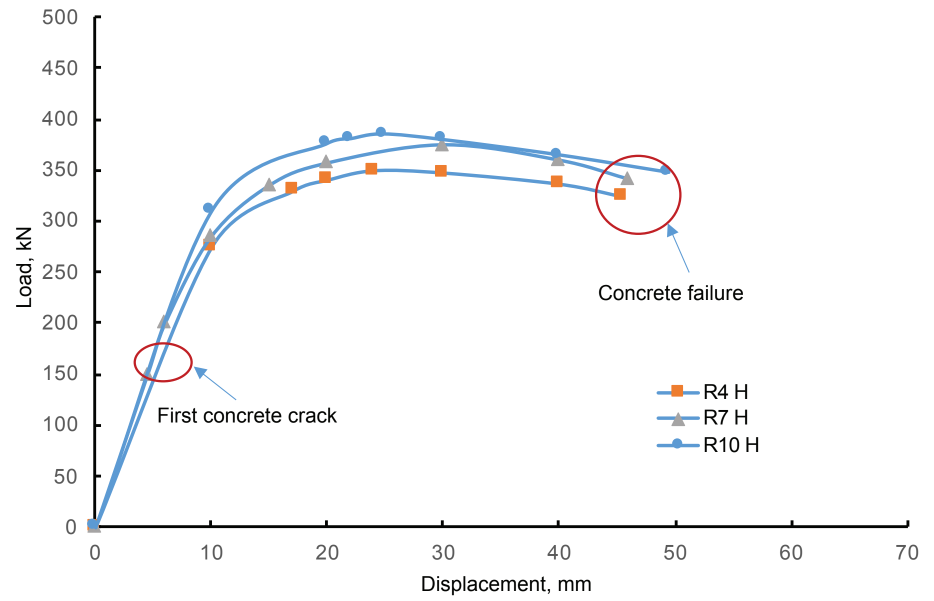

Figure 10. Comparison between load deflection curves for specimens with four rigid (high-stiffness) connector rows (R4 H). Note: 1 mm = 0.039 in.; 1 kN = 0.225 kip.

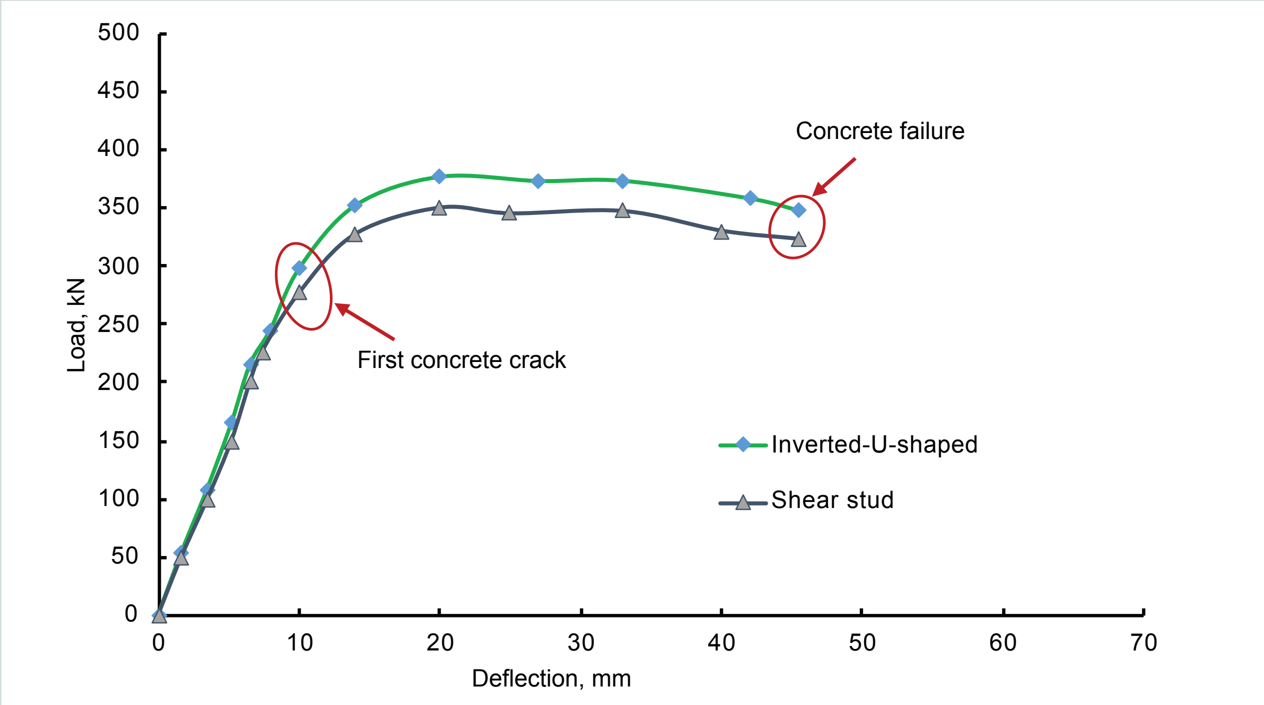

Figure 11. Comparison between load deflection curves for specimens with 10 mild (low-stiffness) connector rows (R10 M). Note: 1 mm = 0.039 in.; 1 kN = 0.225 kip.

and inverted-U-shaped connectors are depicted in **Tables 2** through **4**.

Conclusion

Research on shear connections between steel and concrete materials is crucial because composite buildings have always piqued the engineering profession's curiosity. In this research, an inverted-U-shaped connector for composite steel–concrete beams was presented. A numerical analysis of a two-point applied load test was performed to produce numerical research on the inverted-U-shaped connectors. Six specimens with inverted-U-shaped connectors with varying positions and stiffness were examined. The obtained results were compared with other composite beams with stud shear connectors. In addition, the stress distribution on the specimens was investigated to characterize the internal behavior of the connection. In composite construction, inverted-U-shaped connectors

Table 2. Composite beam numerical load results

Connector type	Number of connector rows	Stud maximum load, kN	Stud failure load, kN	Inverted-U-shaped maximum load, kN	Inverted-U-shaped failure load, kN	Maximum load increase, %	Failure load increase, %
Mild	4	327.57	274.73	366.03	281.30	11.74	2.40
	7	364.32	282.47	415.10	337.36	13.94	19.43
	10	375.80	309.32	432.36	365.34	15.05	18.11
	Average	355.89	288.84	404.49	328.00	13.57	13.31
Rigid	4	350.28	324.73	390.25	360.15	7.64	2.82
	7	374.91	341.96	408.80	380.80	9.04	11.36
	10	385.61	348.01	430.87	389.25	10.53	11.85
	Average	370.26	338.23	409.98	376.73	9.07	8.67

Note: 1 kN = 0.225 kip.

Table 3. Composite beam concrete stress results

Connector type	Number of connector rows	Numerical stress			Experimental stress	
		Studs	Inverted-U-shaped	Percentage increase	Studs	Inverted U-shaped
Mild	4	436.34	475.36	8.2	552.62	To be determined
	7	256.81	280.90	8.7	315.78	
	10	185.73	208.56	10.95	221.05	
	Average	292.96	321.61	9.28	363.15	
Rigid	4	693.41	745.20	6.95	847.13	
	7	387.83	428.45	9.48	484.07	
	10	276.76	306.66	9.75	338.85	
	Average	452.66	493.44	8.73	556.68	

Note: All values are in megapascals. 1 MPa = 0.145 ksi.

Table 4. Percentage difference in numerical concrete stress results between rigid and mild connectors

Number of connector rows	Type	Numerical maximum compressive stress, MPa	
		Studs	Inverted U-shaped
4	Mild	436.34	475.36
	Rigid	693.41	745.20
	Percentage difference	37.07	36.21
7	Mild	256.81	280.90
	Rigid	387.83	428.45
	Percentage difference	33.78	34.43
10	Mild	185.73	208.56
	Rigid	276.76	306.66
	Percentage difference	32.89	31.98

Note: 1 MPa = 0.145 ksi.

might be used instead of headed studs. In terms of manufacturing process, installation, and strength capacity, the inverted-U-shaped connector offers various benefits. The following conclusions are offered based on the prior evaluation and discussion of numerical results:

- The use of inverted-U-shaped (mild and rigid) connectors improves the deformation behavior and degree of shear connectivity for steel–concrete composite beams when compared with using shear stud connectors (mild and rigid).

- The final failure of composite beams with mild connectors (inverted-U-shaped and shear stud) was due to a combination of concrete and shear stud connector failure, whereas the final failure of rigid connectors (inverted-U-shaped and shear stud) was due only to concrete failure.

- The inverted-U-shaped connectors showed an average improvement of 13.57% in maximum load for beams with mild connectors and 9.07% for beams with rigid connectors when compared with shear stud connectors.

- The inverted-U-shaped connectors showed an average improvement of 13.31% in failure load for beams with mild connectors and 8.67% for beams with rigid connectors when compared with shear stud connectors.

- Increasing the number of inverted-U-shaped connectors improved the connection strength, which reduced the relative movement of the composite section.

- The stress distribution on concrete slabs with inverted-U-shaped connectors exhibited numerical failure modes that were better than composite sections with shear stud connectors.

- The number and the type of shear connectors (stud and inverted-U-shaped) affect both the deflection and the capacity of the composite beams.

- The type of connector affects the maximum compressive stress of the composite beams. The increase of stresses in rigid connectors compared with mild connectors in the beam capacity was 37.07%, 33.78%, and 32.89% (for shear stud connectors) and 36.21%, 34.43%, and 31.98% (for inverted-U connectors) for 4, 7, and 10 rows, respectively.

- The arrangement of the inverted-U-shaped connectors, which increases concrete confinement, is credited with the enhanced composite beam behavior.

- All beams with rigid shear connectors exhibited strong composite behavior, whereas those with mild shear connectors exhibited partial composite action.

- The full composite action (due to concrete failure) of all beams with rigid connectors can be achieved by increasing the spacing between the connectors until the connectors reach their yield strength limit. However, because the beams with mild connectors did not achieve complete composite action (due to a combination of concrete and shear connector failure), the spacing between the connectors can be reduced to determine the maximum spacing needed for full composite action.

Recommendations for further work

The results in this paper were based on constant cross-section dimensions, and the number of connector rows (shear stud and inverted-U-shaped) was limited to 10. The following recommendations are made for further study:

- Confirm the validity of the numerical models with inverted-U-shaped connectors by comparing the results with experimental tests.

- Verify all the obtained results by considering full-scale composite beam members.

- Evaluate additional connector arrangements to accurately predict the minimum number of inverted-U-shaped connectors required to provide full composite action.

- Perform additional analysis to accurately predict the strength, ultimate slip capacity, and ductility of inverted-U-shaped connectors embedded in a composite slab.

- Perform testing on a new series of composite beams with both rigid and mild inverted-U-shaped connectors in the same specimens, where the rigid connectors are placed at the beam ends due to the high shear stress at these positions. Determine the optimal distribution of the inverted-U-shaped connectors along the beam.

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Notation

E_c = modulus of elasticity of concrete

E_s = modulus of elasticity of steel

f_c' = concrete compressive strength

f_t = concrete tensile stress

f_y = yield strength of steel

ε_s = strain

ν_c = Poisson's ratio for concrete

ν_s = Poisson's ratio for steel

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Abstract

Steel and concrete are the most essential and frequently encountered building materials. These materials are used in combined structural systems, such as concrete cores surrounded by steel pipes, as well as composite structures with steel and concrete components. In numerous countries, the combination of concrete cores, steel frames, and composite slab construction has become the typical construction approach for multistory commercial buildings. The shear stud connector is one of the elements used in the construction of composite sections. The use of inverted-U-shaped reinforcement experimentally and numerically significantly improves punching shear resistance for post-tensioned slabs compared with slabs that use stud connectors. Other experimental and numerical studies using inverted-U-shaped reinforcement in post-tensioned beams indicate an enhancement in their shear strength. Recently, an experimental investigation was performed on composite beams to inspect the effect of mild and rigid shear stud connectors. The experimental and numerical results for the composite beams showed good correlation. The goal of this study was to numerically model the capacity and deformation of composite beams with inverted-U-shaped connectors of varying configuration and mechanical properties and compare the beam performance with composite beams using shear stud connectors.

Keywords

Composite beam, FEA, finite element analysis, inverted-U-shaped connector, shear connector.

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