

Experimental Study on the Behavior of Shear Connectors in Steel Concrete Composite Beam

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Abstract

This research presents an experimental investigation of the structural behaviour of angle (L) type and channel (C) type shear connectors used in steel-concrete composite beams, utilising the standard push-out test method. It focuses on evaluating and comparing the shear capacity, load–slip characteristics, and failure modes associated with each type of connector. Three series with six push-out specimens made up the test program. L-type or C-type connectors are welded to steel sections and embedded in concrete slabs. Axial loading was applied monotonically until failure. The concrete's compressive strength, the L-type and C-type shear connectors' length, and their web thickness were among the test parameters. Crushing of the concrete adjacent to the channel or angle web was the observed mode of failure in specimens. L-type connectors showed more slip than C-type connections were observed and also found that channel connectors greatly exceed angle connectors regarding shear capacity and stiffness, and there was no welding failure in any of the specimens. This research enables engineers to select the appropriate connector type for safer and more efficient structural designs.

Keywords: Steel–concrete composite beam, shear connector, L-type connector, C-type connector, push-out test.

1. Introduction

A steel-concrete composite beam is widely used in modern construction because of its high strength, stiffness, and economic efficiency (Johnson, 2004). Shear connectors facilitate the interaction between steel and concrete components. There are numerous types of shear connectors, but channel and angle connectors have attracted attention for their ability to improve load transfer and enhance structural performance. Channel and angle connectors have been explored as alternatives to conventional headed studs, motivated by fabrication considerations and potential improvements in ductility or strength. Both the usual (normal) and inverted orientations of channel connector installation have distinct effects on the failure mechanism and load-slip behaviour. The shear behaviours of the connectors are crucial to guarantee the composite action of the steel and concrete in a composite structure (Johnson, 2018). The welded-headed shear stud is the most used type of shear connector (Lam & El-Lobody, 2005). In real-world use, it has been observed that there are various issues with employing welded stud shear connectors in steel-concrete composite beams. Firstly, the welding effort becomes excessive in large-span composite beams, making quality control for the welding difficult. Secondly, welded studs exhibit inadequate fatigue characteristics and are susceptible to cracking at the weld joints (Gu, 2019; Xu, 2018). With more focus on the structural performance under extreme environments, the resistance to elevated temperatures and fatigue performance of shape steel shear connectors were also studied, which shows good resistance and fatigue performance (Shariati, 2012). Other types of shear connectors, such as I-shaped, angle-shaped, and channel-shaped connectors, have been developed as a result of the stud-type shear connector's limited load-carrying capacity and poor performance under cyclic and fatigue loading (Xue, Nie, & Fan, 2008; Vianna, da Silva, & Andrade, 2013). These connectors are used for heavily loaded composite floor beams. Due to the limited load-bearing capability of studs and fatigue issues brought on by live loads on composite bridges, a new form of angle connection with an anti-uplift bar has been widely used in France (Trouillet, 1990). To determine the load-slip characteristics, ultimate strength, and failure mechanisms of these connectors, a push-out test was conducted (Eurocode 4, 2004). There are several factors that affect the performance of channel and angle connectors, such as their geometry, material properties, concrete strength, and level of embedment (Esdauletova et al., 2024). Push-out test is a reliable method for evaluating the shear capacity, stiffness, and ductility of connectors. That's why the Push-out test is used in this research paper to examine the behaviour of channel and angle shear connectors. This study mainly investigates the load-slip behaviour and load-bearing capacity of angle and channel (both normal and inverted) shear connectors and investigates the failure Modes of those shear connectors in a composite beam with a solid concrete slab under static axial compression.

2. Methodology

The study included six push-out test specimens divided into three groups based on connector type and orientation: Normal Channel (NC), Inverted Channel (IC), and Angle (L) connectors. Each group had two specimens to ensure consistency and repeatability. These specimens were constructed using two identical concrete slabs attached to the flanges of a steel I-beam with shear connectors welded at the interface. The connectors were 5 mm thick and welded using E6013 electrodes with 6 mm fillet welds, ensuring structural integrity during testing.

2.1 Model parameters and concrete properties used

All specimens had the same concrete compressive strength of 30 MPa, and while geometric dimensions were mostly uniform, differences in connectors, such as type and orientation, were carefully selected to study their impact on shear performance. The steel I-beams were cut from a 12 ft member into six equal pieces, each 350 mm long. Welding was carried out by a certified welder following AWS guidelines, and a 75 mm recess was left between the bottom of the slab and the beam to allow measurable slip during the test. The connectors were all placed at a fixed height of 212.50 mm from the slab bottom for consistency shown in Figure 1 and Table 1.

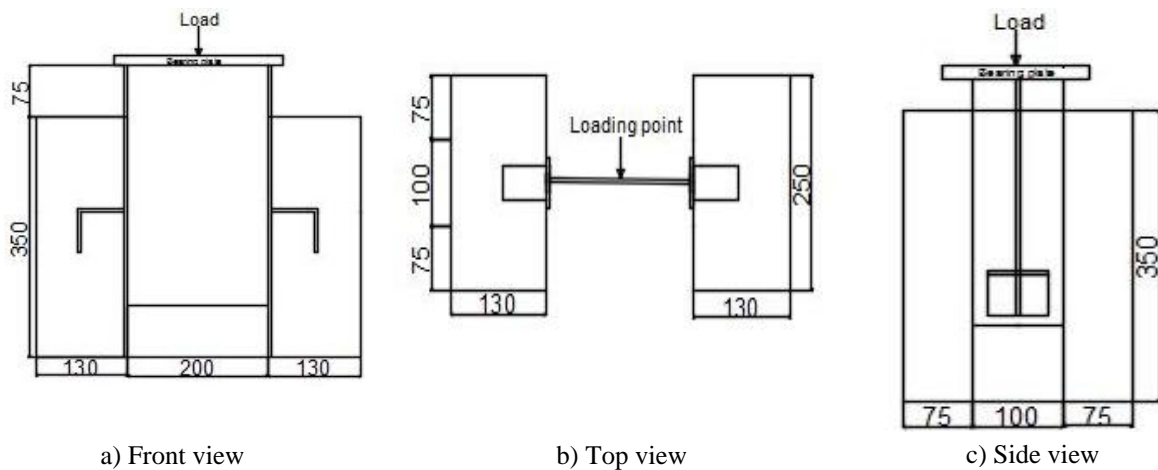


Figure 1. Push-Out Test Specimen with Angle Connector (all dimensions are mm).

In terms of materials, Ordinary Portland Cement (OPC) complying with ASTM C150 was used. The fine aggregate was sylhet sand, and the coarse aggregate was 20 mm nominal size crushed black stone from Pakur, both meeting ASTM C33 standards. S355 structural steel was used for the steel beam and connectors, while ASTM A572 Grade 50 steel plates were used for shear connectors, providing a minimum yield strength of 345 MPa and ultimate strength of 450 MPa. The concrete mix was prepared to achieve a 30 MPa strength, using an ACI-based design with a water-cement ratio of 0.4. The slump value was maintained between 70 to 100 mm. After mixing and casting, the concrete was cured in water for 28 days, and the specimens were coated with lime wash to make crack detection easier during loading shown in Figure 2.



Figure 2. (a) I-steel beam, (b) Channel & angle connectors, (c) Specimen casting and (d) Specimen

Table 1. Properties of the Push-out Test Specimens.

Series	Specimen	f_c' (MPa)	Connector size(mm)	Orientation	Web length h (mm)	Flange length l (mm)	Cutting length a (mm)	thickness t (mm)
IC	S1	30	38×63×6	Inverted welding	75	38	63	6
	S2		38×63×6	Inverted welding	75	38	63	6
NC	S3		38×63×6	Normal welding	75	38	63	6
	S4		38×63×6	Normal welding	75	38	63	6
L	S5		75×63×6	Heel welding	75	75	63	6
	S6		75×63×6	Heel welding	75	75	63	6

During casting, three concrete cylinders were also prepared and tested after 28 days. The average compressive strength of the cylinders was found to be approximately 35.28 MPa, about 17% higher than the target strength shown in Table 2. Testing was performed using a Universal Testing Machine (UTM), with the steel section loaded vertically while the concrete slabs were restrained to simulate realistic conditions. LVDTs were installed on both sides to monitor relative slip between steel and concrete shown in Figure 3. The load was applied incrementally and at each stage, load and slip data were recorded. Visual inspections were carried out throughout the loading process to observe crack formation and deformation. The test was continued until the specimen failed through one or more mechanisms: connector fracture or pull-out, concrete cracking or crushing, or significant slip indicating the loss of composite action.

Table 2. Concrete Cylinder Properties.

Cylinder	Desire strength (MPa)	Strength at test day (MPa)	Average strength (MPa)	Strength increase (%)
1		36.38		
2	30	35.52	35.28	17.62
3		33.96		



Figure 3. Test Setup & Instrumentation.

To investigate the behaviour of channel and angle shear connectors under axial loading, push-out tests were conducted shown in Figure 3, and load versus slip curves were generated to study the slip at the interface between the concrete slab and the steel I-beam. The load from a single connector was used to plot these curves. To minimise errors during testing, the relative slip was calculated as the average of two LVDT readings.

3 Result and Discussion

In this study, six specimens were evaluated to investigate the performance of angle and channel connectors on composite steel I-beams subjected to axial loads. In general, failure in the push-out test specimens began with cracking in the concrete, followed by either shear fracture or buckling of the connector.

3.1. Load-slip behaviour

The load-slip curves for the push-out tests are shown in Figure 4 for the channel and angle shear connector specimens, respectively. These curves for the connectors reveal three distinct stages: elastic, plastic, and failure. During the elastic stage, the interface slip between the I-beam and the concrete slab, constructed with a concrete strength of 30 MPa, is minimal, with no visible cracks in the concrete. The specimen exhibits high shear stiffness, and the load is supported by the inverted channel, normal channel, and angle connectors, along with the end-bearing concrete and concrete dowels. As the test progresses into the plastic stage, the slip increases more rapidly, and the load-slip curves become nonlinear until the load reaches the shear capacity. With continued loading, the curve drops sharply, indicating the onset of the failure stage. During this stage, the concrete dowels in the holes are crushed, the concrete at the base spalls, and significant deformations occur in the inverted channel, normal channel, and angle connectors, leading to a rapid decline in the specimen's bearing capacity.

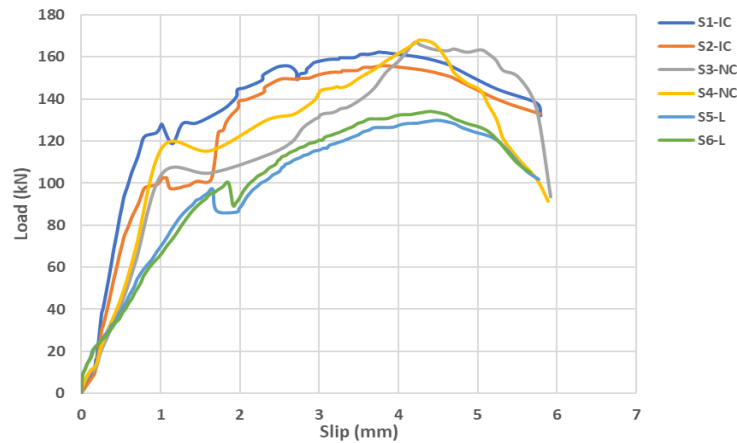


Figure 4. Load (kN) vs Slip(mm) Curves of All Test Specimens.

The maximum load and corresponding vertical slip for the channel and angle shear connector specimens are presented in Table 3. Comparing the load-slip curves of the three connector types—inverted channel, normal channel, and angle connectors—reveals that the curves for the inverted and normal channel connectors exhibit similar trends, both displaying the characteristic three-stage behaviour. In contrast, the angle connector curves show a more abrupt transition to failure, as the structure cannot sustain the load after the angle connectors fail.

Table 3. Ultimate Load and Corresponding Slip of the Specimens.

Series	Specimen	f'_c (MPa)	Q_u (KN)	S_u (mm)	Average Q_u (KN)	Average S_u (mm)
IC	S1	30	156.61	3.79	159.53	3.77
	S2		162.45	3.75		
	S3		166.76	4.20		
NC	S4		168.23	4.27	167.49	4.23
	S5		134.00	4.41		
L	S6		129.98	4.48	131.99	4.44

Channel connectors, whether inverted or normal, typically show greater strength, sustaining an ultimate load of approximately 163 kN before failure. This renders them appropriate for uses that need higher load-bearing strength, like substantial bridges or composite flooring. At this stage, they show less slip, around 4.00 mm, aiding in structural stability by restricting movement before failure. In comparison, heel-connected angle connectors exhibit a reduced average ultimate load of 131.99 KN, rendering them less effective at managing high forces. Moreover, they usually show more slipping, measuring about 4.44 mm, which signifies increased deformation before failure. (Hernández Rodríguez et al., 2023; Lee et al., 2024) They also found the same characteristics for the angle connector. Although this enhanced slip could lead to a somewhat more adaptable connection, it may raise issues related to overall stability when subjected to heavy loads.

3.2. Failure mode

For specimens where the channel connector was used (normal NC & inverted IC), in both cases, horizontal cracks started to form in the concrete at the level of the connector shown in Figure 5. On the other hand, for specimens with an angle (L) connector (angle leg attached to the flange), vertical splitting cracks developed along the direction of the applied load as shown in Figure 5. After the concrete slab split, failure in the angle connectors was also observed. Notably, there was no welding failure in any of the specimens. Additionally, in specimens with channel connectors (normal & inverted), buckling was seen in the connectors after failure; also, buckling did occur in the angle connectors. Overall, channel connectors demonstrated higher shear capacity and more ductile behaviour than angle connectors because their placement offered a larger area to resist shear forces. Finally, in the channel connector specimens, a rectangular gap was observed parallel to the sheared surface, suggesting deformation of the flange plate at the interface before failure.



Figure 5. Failure mode of the specimen (Inverted & Normal Channel Connector Angle Connector).

3.3. Parametric Study based on connector orientation and connector type

Normal Channel connectors achieved 5% higher load capacity than Inverted Channel connectors, but at the cost of 12.2% more slip, suggesting a trade-off between strength and stiffness shown in Table 4. When comparing connector types, switching from channel to angle connectors resulted in a significant 19.28% decrease in load capacity and 11% increase in slip, primarily due to geometric differences and reduced contact area in angle connectors shown in Table 5.

The study compares the performance of channel connectors (inverted and normal) with angle connectors in terms of load-slip behaviour. Channel connectors outperform angle connectors, showing 19.28% higher ultimate load capacity (163.51 KN vs. 131.99 KN) due to their robust geometry and greater contact area for shear transfer. They also demonstrate less slip at peak load (4.00 mm vs. 4.44 mm) shown in Table 5. indicating higher stiffness. Post-peak, both types show gradual load decline, suggesting ductile behaviour; however, channel connectors have a steeper drop, while angle connectors decline more gradually. Initial stiffness is notably higher for channel connectors, making them more effective in resisting early deformation and enhancing structural stability.

Table 4. Difference in Ultimate Load and Corresponding Slip (Percentage).

Parameter	Inverted Channel (IC)	Normal Channel (NC)	Difference (%)
Average Ultimate Load (Q_u , kN)	159.53	167.49	+5.00%
Average Slip at Ultimate Load (S_u , mm)	3.77	4.23	+12.20%

Table 5. Variation of Load and Slip for Channel and Angle connector.

Parameter	Channel Connectors	Angle Connectors	Difference (%)
Average Ultimate Load (Q_u , kN)	163.51	131.99	-19.28%
Average Slip at Ultimate Load (S_u , mm)	4.00	4.44	+11.00%

4 Conclusion

This study discusses the experimental and parametric investigation through push-out tests of specimens with channel and angle shear connectors incorporated in a solid concrete slab. The experimental outcomes were analysed. Concentrating on failure types, shear strength, displacement at failure, and load-displacement response of the test samples and feedback was given.

1. Load-slip curve analysis confirmed a three-stage mechanical response (elastic, plastic, failure) across all connector types, with channel connectors maintaining a ductile post-peak behaviour and higher stiffness throughout. The findings clearly show that channel connectors (IC and NC) greatly exceed angle connectors regarding shear capacity and stiffness.
2. Channel connectors (IC and NC) mainly failed by concrete crushing with horizontal cracks at the connector level and connector buckling, whereas angle connectors developed vertical cracks along the load direction, with one case showing connector fracture; no welding failures occurred.
3. Connector orientation significantly affects performance.

In summary, channel connectors perform better due to their robust geometry and superior mechanical performance, and are better suited for applications requiring high shear resistance, stiffness, and structural integrity, such as bridges and composite floor systems. On the other hand, angle connectors, while offering more flexibility, are less effective under high loads.

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