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Monotonic behavior of C and L shaped angle shear connectors within steel-concrete composite beams: an experimental investigation

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Abstract. Shear connectors are essential elements in the design of steel-concrete composite systems. These connectors are utilized to prevent the occurrence of potential slips at the interface of steel and concrete. The two types of shear connectors which have been recently employed in construction projects are C- and L-shaped connectors. In the current study, the behavior of C and L-shaped angle shear connectors is investigated experimentally. For this purpose, eight push-out tests were composed and subjected to monotonic loading. The load-slip curves and failure modes have been determined. Also, the shear strength of the connectors has been compared with previously developed relationships. Two failure modes of shear connectors were observed: 1) concrete crushing–splitting and 2) shear connector fracture. It was found that the L-shaped connectors have less shear strength compared to C-shaped connectors, and decreasing the angle leg size increases the shear strength of the C-shaped connectors, but decreases the relative ductility and strength of L-shaped connectors.

Keywords: composite beams; shear connector; C-shaped angle; L-shaped angle; push-out test; monotonic loading

1. Introduction

A steel-concrete composite beam comprises of a steel beam, a concrete slab, and shear connectors (SHC). Steel is utilized for its excellent tensile strength, while concrete is used for its high compressive strength. Many kinds of research have been conducted in this area with this clarification using experimental and finite element analysis (Shariati *et al.* 2017, Davoodnabi *et al.* 2019) or novel methods of analysis using neural network solutions (Toghroli *et al*. 2014, Sadeghipour Chahnasir *et al*. 2018, Sedghi *et al.* 2018, Mansouri *et al*. 2019, Shariati *et al.* 2019a, Shariati *et al.* 2019b). Composite systems are economical and efficient systems in which each material is used at its optimum property. Composite beams have some merits over ordinary beams, such as reduced steel section, reduced beam deflection, and reduced floor vibration (Shariati *et al.* 2011c, Shariati *et al.* 2012d, Shariati *et al.* 2013, Khorramian *et al.* 2016, Shariati *et al.* 2016, Hosseinpour *et al.* 2018, Wei *et al*. 2018).

To withstand horizontal shear forces and prevent separation, SHCs are used to attaching the concrete slab and steel beam. (Shariati *et al.* 2010, Shariati *et al.* 2011b). Many forms of SHCs have been proposed and used to be adapted for composite beams (Shariati *et al.* 2012a, Shariati *et al.* 2012c, Shariati 2013, Shariati 2014, Shariati *et al*. 2014a, Khorramian *et al*. 2015, Shariati *et al.* 2015, Tahmasbi *et al*. 2016, Nasrollahi *et al*. 2018, Shariati *et al*. 2020). However, economic motivations and new construction techniques still drive the industry toward innovations. In industrial countries, stud SHCs stay prevalent due to their availability and rapid installation using a stud welder. Connectors such as channels and angles are widely used in developing countries because of their availability and inexpensive welding labor (Shariati *et al.* 2011a, Shariati *et al.* 2012b, Shariati *et al.* 2014b, Khorramian *et al.* 2017). Since composite beams have advantages such as considerable span length, small floor depth, and high stiffness, they are widely used in a variety of structures and buildings. The development of different composite beams is highly valued to mitigate some shortcomings of specific composite structures. There are different types of SHCs, such as Channel, Angle, Stud, and Perfobond sections. Limited studies have been conducted on push-out tests with different loading patterns to evaluate slip and failure load in the channel SHCs. Channel SHCs exhibited a ductile performance when a series of load patterns are applied on a variety of specimens equipped with C-shaped connectors; however, this behaviour was amplified in more extended channels (Shariati *et al.* 2011a). The composite beams demonstrated the brittle behaviour when channels were embedded in unconfined plain concrete; nevertheless, when the channels were embedded in high strength concrete, the behaviour of the composite beam was ductile (Shariati *et al.*

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2012a). Also, more extended channel SHCs showed better flexibility in lower channels (Shariati *et al.* 2012c). Bearing capacity increases linearly with length in a way that a C-shaped channel with 150 mm length has almost 60% higher load carrying capacity in comparison to a 100 mm channel. Moreover, when a C-shaped channel is embedded in high strength concrete, failure modes are determined by concrete (Pashan 2006). Although slip between I-beam and slab is inevitable, it could be considered small with an appropriate SHC design. Thick channel connectors affect the lower slip and higher load capacity (Viest 1951). Using Engineering Cementitious Concrete (ECC) produced by synthetic fibres incorporates well with channel connectors and increases both ductility and loading capacity, especially in reversed low-cycle loading (Maleki *et al.* 2008b).

Stud SHCs have been researched extensively, but studies regarding angle SHCs are still limited. Specifically, installed angle SHCs placed in different positions on the beam have not been investigated. Angle SHCs are typically used in two various forms of installation. In the first type, a steel beam flange becomes welded perpendicularly to one angle leg, and the other leg and concrete slab (C-shaped) are embedded together. Whereas in the second type, a leg of the angle is welded parallel to the beam flange, and the other leg is embedded vertically in the concrete slab (L-shaped). Few studies have been performed on the behaviour of SHCs at elevated temperatures. By combining the profiled slabs, shear studs perform appropriately as a shield around the concrete against fire damages due to the steel profile coverage. Since lightweight concrete has better strength against fire, shear studs embedded in lightweight concrete show a higher ductility in comparison to studs embedded into normal concrete (Mirza *et al.* 2009, Mclister *et al.* 2014). Angle SHCs indicate suitable ductility, but they have noticeable stiffness loss. Using angle as an SHC at elevated temperatures could protect the strength loss by up to 50 % of the initial strength (Davoodnabi *et al.* 2019). Three main types of failure have been observed during the tests; (BSI) SHC fracture, (2) concrete crushing, and (3) concrete shear plain failure. According to experimental studies, connectors' strength loss and deterioration while facing the fire may vary in different situations (Zhao *et al.* 1995, Lu *et al.* 2012, Shahabi *et al.* 2016).

Limited researches have been disclosed in both C-shaped and L-shaped angle SHCs with its behavior. Push-out experiments regarding specimens comprised of different SHCs, of which included channel and L-shaped SHC was first conducted by (Rao 1970). The study consists of a comparison of the SHCs and channel. However, the results imply that channel connectors administer substantial ductility and show a higher load-carrying capacity compared to angle SHCs. Five forms of SHCs that comprised of L-shaped angles were exposed to monotonic as well as cyclic loading over a minimal sum of push-out tests, was conducted by (Ciutina *et al.* 2008), which ruled that cyclic loading does, in fact, account for 10% to 40% reductions for all connectors through shear resistance. This included L shaped angle SHCs, measured against corresponding monotonic strength.

Subsequently, the behavior of C-shaped angle SHCs has been examined in a few studies. (Yokota *et al.* 1987) was the first publisher for shear angle connectors back in 1987. Numerous types of SHCs, namely C-shaped angles, T-shaped SHCs, and channels, were studied. The failure mode appertaining to the specimens was influenced by shapes and directions of SHCs as well as the strength of concrete. In the mentioned study, after undergoing 58 push-out experiment samples, the ultimate strength of the connectors was attained. In order to obtain the shear strength of C-shaped angle connectors, an observational function is employed as follows

$$Q = 88rw\sqrt{t}\sqrt{f_c} \tag{1}$$

Where:

Q = SHC NS (kgf)
t = SHC WT (cm)
f_c = Compressive strength (kgf/cm^2)
w = Length (cm)
r = 1 for angles

By integrating FE analyses and fatigue tests, the strength before the fatigue of the welded joint between C-shaped angle SHCs and bottom plate in steel-concrete composite slabs was studied (Choi *et al.* 2008). Results showed that the stress was considerably lower than the fatigue limit at the welded joint.

To understand the effects and performances of C-shaped angle SHCs under live and moving loads which occur mostly in continuous composite steel beam as main support in bridges, an investigation was designed by (Fukazawa *et al.* 2002). The outcome indicates a satisfactory level of fatigue durability and stiffness of the composite slabs.

To identify the relation between displacement on T-shaped and C-shaped angle SHCs shear force in the steel-concrete composite slab, a study was conducted by (Saidi *et al.* 2008) whereby a numerical methodology was also constructed. At the corner of the SHC in the model was a rotation, and its horizontal movement was assumed as the T-shaped SHCs and the boundary condition of the angle. (Ros *et al.* 2009) offered a brand-new approach of testing on C-shaped angle connectors to explore the relationship of shear load-slip. Direction based on the shear force of the SHC has been justified to influence the shear capacity of the SHC, according to the results of the investigation.

The ABAQUS software was utilized to progress a FE model, which was then validated by (Khalilian 2015) through push-out laboratory tests. This resulted in a current expression to predict the shear strength of angle SHCs, that was proposed as below

$$Q = 4300\, L^{0.64}\, t^{0.27} f_c^{0.11} \leq 0.6F_u.t.L \tag{2}$$

Where:

Q = angle connector SS (N)
t = WT (mm)
L = length (mm)
F_u = steel US (MPa)
f'_c= Compressive strength

In this paper, a comprehensive investigation of the effects and performances of C-shaped and L-shaped angle SHCs is

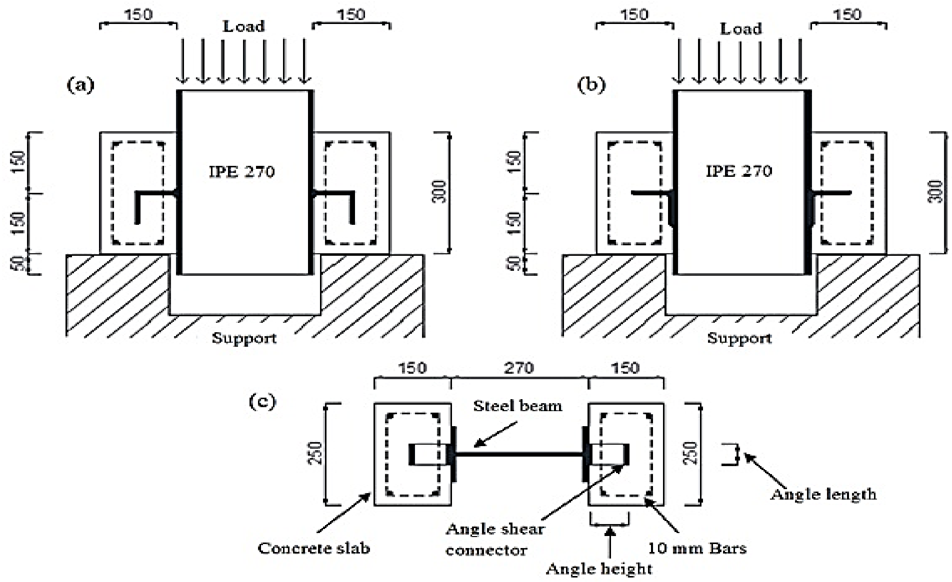


Fig. 1 Specimen elements: (a) Side view for C-shaped angle connectors (MV specimens), (b) Side view for L-shaped angle connectors (MH specimens) and (c) Upper view

Table 1 Mix Proportion of Concrete

Material	Cement	Water	Sand	Gravel
Weight Ratio	1	0.42	2.75	1.75

Table 2 Specimen properties

Specimen	**Angle height (mm)**	**Angle length (mm)**	**Angle thickness (mm)**	**Concrete strength (MPa)**
MV60	60	50	6	29.45
MV80	80	50	8	22.43
MV100	100	50	10	25.42
MV*80	80	100	8	31.07
MH60	60	50	6	29.25
MH80	80	50	8	29.5
MH100	100	50	10	24.97
MH*80	80	100	8	27.92

performed. Eight fabricated push-out test specimens are placed under a monotonic load to examine the behavior of different variables on the ultimate bearing capacity of the angle SHCs. The provided and relevant equations are used to numerically foresee the shear capacity of the connectors, which are then compared to the results acquired from experimental results of the ultimate shear capacity. Lastly,results collected from the two types of study are evaluated, and the variations in the geometric parameters are discussed.

2. Test procedure

Eight push-out test specimens were created of composite slabs and angle SHCs. Two angle SHCs were welded to each flange of hot-rolled steel I-section, European IPE270. Two concrete blocks with embedded tie reinforcement were then poured parallel to the flanges of the I-section so that the two angle SHCs were engaged with the concrete slabs. Grade ST37 steel with nominal minimum yield strength of 240 MPa was used in all structural steels. Fig. 1 demonstrates the configuration of angle SHCs welding to the steel I-beam flange in L-shaped and C-shaped arrangements.

The concrete mix proportion is indicated in Table 1. Three standard 150×300 mm cylinders were made from each concrete batch to work out the compression strength of the concrete used in the specimens. Following casting, the specimens were cured in a humidity chamber for

(a) (b)

Fig. 2 Setup of push-out test: (a) Universal testing machine and (b) applying load with the cap plate to the specimen

Table 3 Failure modes together with ultimate load capacity as regards to the test specimens

Specimen	Failure mode	Failure load (kN)
MV60	Connector fracture	153.35
MV80	Concrete crushing-splitting	138.84
MV100	Concrete crushing-splitting	150.57
MV*80	Concrete crushing-splitting	163.65
MH60	Connector fracture	119.44
MH80	Concrete crushing-splitting	136.9
MH100	Concrete crushing-splitting	132.28
MH*80	Concrete crushing-splitting	205.15

approximately 28 days and removed for testing at 28 days.

One of the majorly used angle types in composite beams was the equal leg angles. To investigate the variables that affect the shear strength of angle SHCs, related specimens were carefully selected. Manipulative variables that could affect the strength capacity of each SHCs are angle position, thickness, height, and length of the angles. It is important to ensure that the geometries of the concrete blocks are exactly alike in the experimented specimens (Maleki *et al.* 2008a). A height of 300 mm, a width of 250 mm, and a depth of 150 mm deduced the dimensions of all concrete slabs. 10 mm was chosen as the diameter of steel transverse and longitudinal reinforcements embedded in the concrete slabs. Using 7 mm fillet welds, the angle SHCs were welded to the flange of a steel I-beam.

Two letters and a number make the specimens' designation. M is the first letter that abides with one-directional monotonic loading. V or M is usually the second letter, which corresponds with the C or L-shaped configurations. The angle size follows the letters in mm.

Table 2 signals that four specimens of various lengths and angles were tested in each configuration. The load has been tested on every specimen by a universal testing machine (UTM) with 1000 kN capacity (Fig. 2(a)). The load was adopted via the cap plate to the beam, as shown in Fig. 2(b). The concrete blocks were placed on the bench supports without any horizontal tie between them. This allows separation between the steel beam and concrete block to be observed as the block slides horizontally on the bench. The test was conducted at a rate of 0.1 mm/s for all specimens with displacement control. Specimens were put under a monotonic load repeatedly until they began to fracture and continued loading until failure. The lower portion of the SHCs was wholly welded to the flange steel beam. Also, the remaining parts of the connector were entirely embedded in concrete; furthermore, the concrete block and steel beam were completely attached by this mechanism. Concerning the state of coherence and the position of beam and concrete blocks, it has no difference to gather the results of split either at the interface of steel and concrete or form the machine itself. Thus, the load-displacement outcome from each specimen was plotted automatically through the hardware adhered to the UTM. Moreover, the measured displacement is the relative displacement between the top of the steel beam, which includes the base of the concrete block across every time iteration

3. Experimental results

3.1 Behavior of Load-Slip

The results of the push-out tests are shown in Fig. 3.

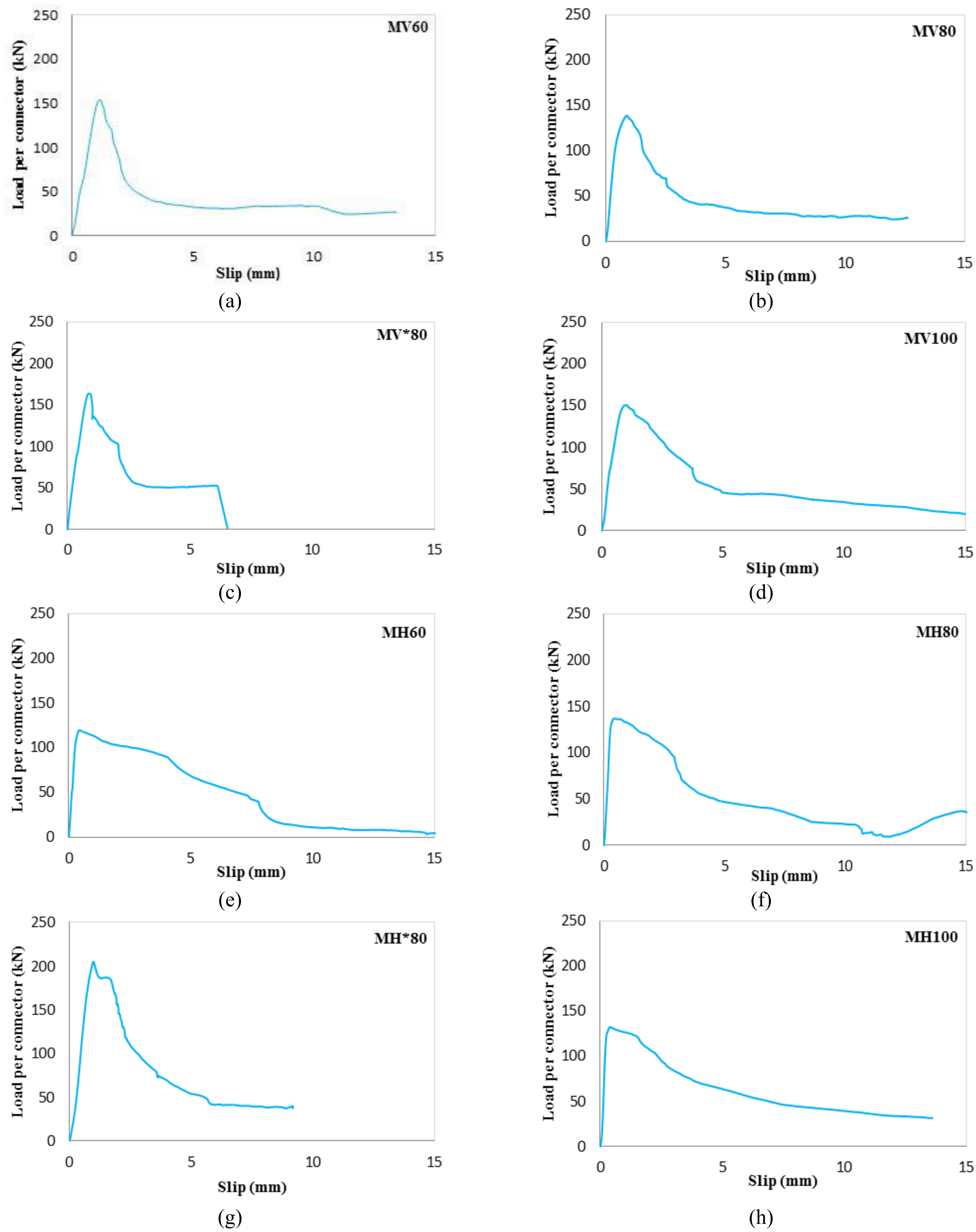


Fig. 3 Load-slip diagrams belonging to the specimen: (a) MV 60, (b) MV 80, (c) MV*80, (d) MV100, (e) MH60, (f) MH80, (g) MH*80, (h) MH100

In all the plots, the horizontal axis is the slip among concrete blocks along with the steel beam in mm, and the vertical axis shows half of the applied load in kN, which was quantified by the load cell. In other words, the load is, in fact, the resistance of one SHC.

3.2 Modes of failure

In all the specimens, the test ended when the concrete crushing and splitting was excessive or when the connector sheared off. The mode of failure and the ultimate load have been represented in Table 3.

Fig. 4 Typical angle fracture mode of failure (MH60)

Fig. 5 Ordinary failure of concrete. Splitted and crushed mode of failure (MH100)

For specimens in push-out tests subjected through monotonic loading, dominant failure modes are: 1) The angle SHC's fracture. 2) Compressive failure of concrete in one plane and tensile failure in another plane, which is called crushing-splitting failure. Figs. 4 and 5 show typical views of these two failure modes inspected in virtue of the push-out specimens.

Generally, when the load is symmetrically applied, it is expected that the two concrete blocks show similar deformation and failure patterns. However, if sudden excessive failure happens in one block, the specimen tilts toward one side, and then the load is no longer symmetrically applied. In these asymmetrical failure cases, the results are not exact, and at best, they are conservative. This happened in specimen MV*80. As shown in Fig. 5, the left block failed excessively while the right block is uncracked. This specimen was expected to carry much more load.

It should be noted that the L-shaped connectors (MH series) tend to separate from the concrete block. This is because there is no flange embedded in concrete to resist tensile forces normal to the beam. This appears in the tests as sliding of the block on the test bench, as shown in Fig. 5. This is why reference (SSEDTA 2001) recommends passing rebar through a hole in the connector when embedded in concrete.

3.3 Comparison of the push-out test results with available equations

It is possible to tie a correlation among the test results of C-shaped specimens with Eq. (2). Table 4 compares these results for 50 mm length angles. It can be seen that the obtained results from Eq. (2) are on the conservative side in all cases.

A companion to the European code EC4 (BSI 1992) is SSEDTA in which Eq. (3) is given for L-shaped angle connector strength embedded in concrete.

$$P_{Rd} = \frac{10\, l\, h^{\frac{3}{4}}\ f_{ck}^{\frac{2}{3}}}{\gamma_v} \tag{3}$$

Where:

P_{Rd} = Shear capacity of the connector (N)

l = Length of the angle (mm)

h = Height of the upstanding leg of the angle (mm)

f_{ck} = Characteristic strength of concrete (N/mm^2)

γ_v = Partial safety factor (taken here as 1.0)

Push-out test results have been checked against Eq. (3) in Table 5. It can be seen that other than MH*80 specimen, the other results are close and acceptable. Note that Eq. (3)

Table 4 Eq. (2) with Test result comparison

Specimen	Load per connector (kN)		Test/Eq. (2)
	Test	Eq. (2)	
MV60	153.35	124	1.24
MV80	138.84	130	1.07
MV100	150.57	140	1.07

Table 5 Eq. (3) with Test result comparison

Specimen	Load per connector (kN)		Test/Eq. (3)
	Test	Eq. (3)	
MH60	119.44	102.33	1.17
MH80	136.90	127.69	1.07
MH100	132.28	135.08	0.98
MH*80	205.15	246.18	0.83

Table 6 Comparison between no tilt and tilted angle results

Specimen	F(kN)	h(mm)	L(mm)	fc(MPa)
A7550-M	109.6	75	50	28.5
MA112.5	115.4	80	50	19.44
MA1135	134.11	80	50	19.97
A10050-M	141	100	50	28.5
MA112.5	120.09	100	50	26.12
MA1135	201.13	100	50	31.11

defines a linear relationship between the length of the angle and the shear strength. Therefore, it predicts a strength for MH*80 (with 100 mm length) that is twice of MH80 (with 50 mm length). The tests show that this might not be the case, as MH*80 has only 1.5 times the strength of MH80.

For better comparison, Table 6 represents the outcome of two push-out tests alongside the no tilt angle contrasted with the conclusion through tilted ones. When compared with other cases, the highest capacity was the angle of 135, as determined on the table. The tilted angle of 112.5 degrees has a lower shear capacity than the angle with no tilt when L100 is given due consideration. Higher capacity is accustomed in the tilting of 112.5 degrees on the grounds that it is of a higher height when comparing L80 with L75. It is anticipated that for L80, the SHC comprised of no tilt withstands extra shear stresses than the tilted angle of 112.5 degrees. Therefore, it can be concluded that the tilted angle of 135 has the highest shear capacity, while the angle SHC with no tilt has a higher shear capacity than the tilted 112.5 degrees.

4. Discussion of the results

4.1 Angle SHCs (C-Shaped)

The results of C-shaped angle connectors push-out tests are compared against the tests by (Hiroshi Yokota and Kiyomia 1987). However, direct comparison is not possible since concrete strength and angle sizes vary in the tests. A method of normalizing the results for concrete strength is to assume the square root of concrete compressive strength is actually reciprocal to the shear strength of angle shear. Also, as indicated in Eq. (1), the square root of the angle thickness can be assumed to be related to the strength. Therefore, the concrete compressive strength in all push-out specimens is normalized to 30 MPa by using Eq. (4).

$$(P_u)_{New} = (P_u)_{Experimental} \times \sqrt{\frac{30}{f_c^{'}}} \tag{4}$$

Where:

P_u = Nominal strength of an angle SHC (kN)

f'_c = Compressive cylinder strength of concrete (N/mm^2)

Fig. 6 shows the load-slip curve of the three C-shaped push-out test results for angle connectors with 50 mm length and concrete compressive strength of 30 MPa. It can be seen in this figure that by increasing the size of the SHC, more shear strength is obtained. It is worth mentioning that with the larger angle size, the thickness and the height of the angles are also increased.

Also, from Eq. (1) it is possible to normalize the results according to the thickness of C-shaped angle SHCs as follows

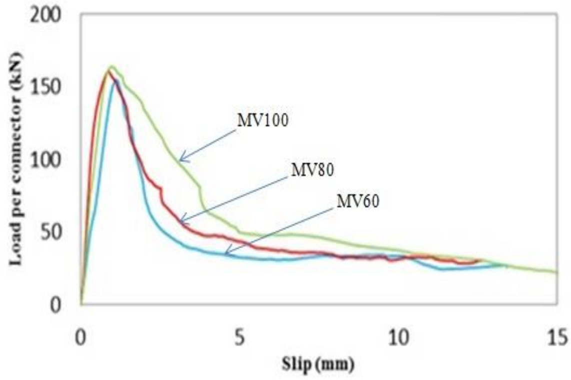


Fig. 6 Load-slip curve based on push-out C-shaped angle connectors with 50 mm length along with a concrete compressive strength of 30 MPa

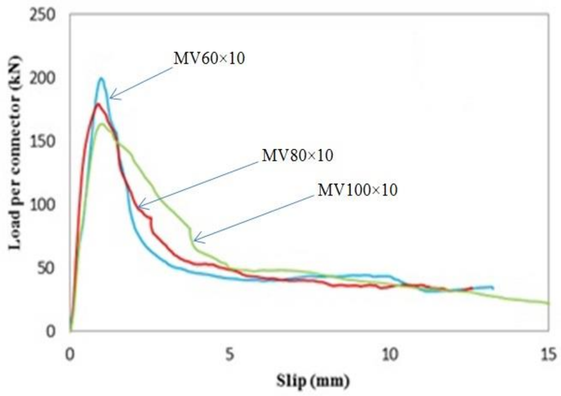


Fig. 7 Load-slip curve of push-out C-shaped angle connectors with f'_c = 30 MPa, l_c = 50 mm, and t_f = 10 mm

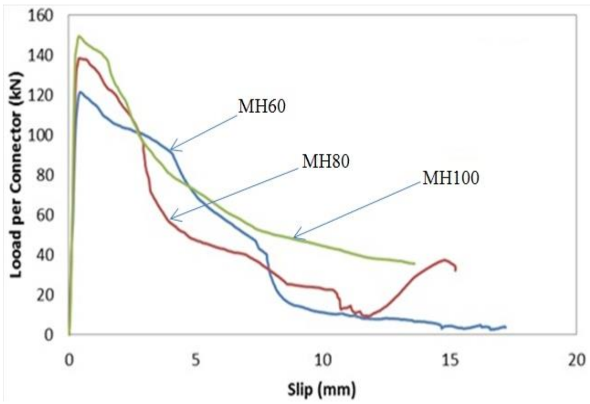


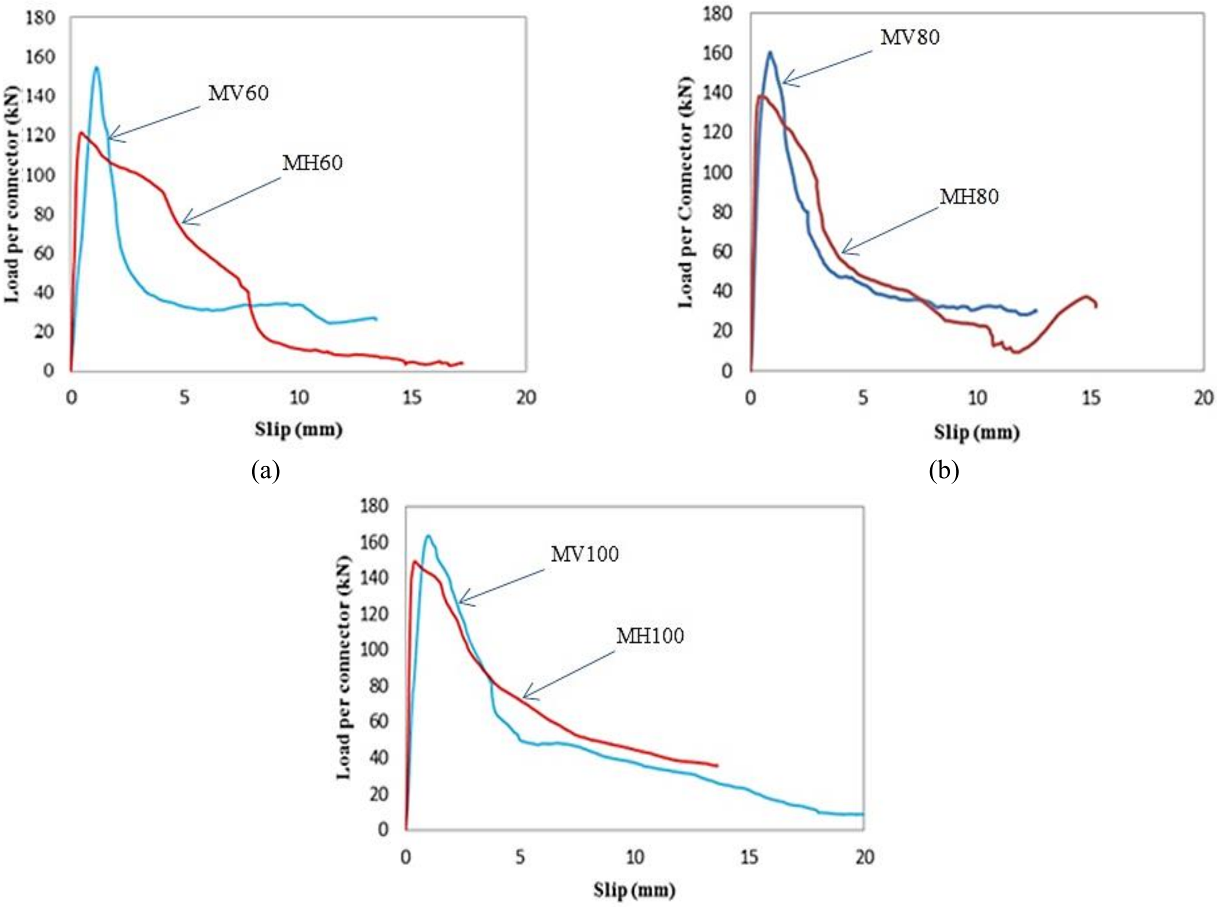
Fig. 8 The load-slip curves of push-out L-shaped angle connectors with $f_c^{'} = 30MPa$ and $l_c = 50mm$

$$(P_u)_{New} = (P_u)_{Experimental} \times \sqrt{\frac{10}{t_f}} \qquad (5)$$

Where:

t_f = Flange thickness of angle SHC (mm)

Fig. 7 demonstrates the load-slip curve of 50 mm length push-out C-shaped angle connectors entirely normalized to the concrete compressive strength of 30 MPa and 10 mm



(a) (b) (c)

Fig. 9 Comparison of L-shaped angle connectors with C-shaped angle connectors in specimens with (l_c = 50 mm, f'_c = 30 MPa): (a) 60 mm height, (b) 80 mm height and (c) 100 mm height.

thickness. It is seen that the shear strength decreases as angle size increases. The angle SHC with a 60 mm height has more shear strength than 80 and 100 mm height. This shows the influence of the height of the angle on the shear strength of C-shaped angle connectors. With an increase in the height of the angle, more bending is introduced at the base of the angle. This, in turn, causes more slip and tensile cracks in concrete. The other remarkable result of Fig. 7 is that with an increase in size (or the height) of SHCs, the ductility of C-shaped angle connectors increases.

4.2 Angle SHCs (L-Shaped)

Eq. (3) was provided by the BSI code, to determine the shear strength out from L-shaped angle connectors. Eq. (3) demonstrates that the shear strength of angle SHCs is related directly to the concrete compressive strength to the two-thirds power. Based on this, the results of the push-out tests for MH specimens are normalized to 30 MPa. Fig. 8 shows the load-slip diagram of L-shaped angle connectors with 50 mm length and concrete compressive strength of 30 MPa.

From Fig. 8, it can be seen that with an increase in size, which also increases the thickness of the angle, the shear strength of the connector increases.

4.3 Comparison of L-shaped angle connectors with C-shaped angle connectors

Fig. 9 compares the test results of L-shaped and C-shaped angle connectors when normalized to the concrete compressive strength of 30 MPa.

According to Fig. 9, it was evident that all C-shaped angle connectors with 50 mm length have more shear strength than L-shaped connectors of the same length. The other notable point is that L-shaped connectors have slightly more ductility.

5. Conclusions

This paper is intended to investigate the angle SHCs in two different installation positions empirically. Push-out tests were performed on four C-shaped connectors as well as four L-shaped angle connectors of 50 along with 100 mm lengths. The test results were presented as load-slip curves for each specimen. The results were also compared against suggested equations and test results of previous studies. Generally speaking, the analysis results indicated how the shear strength of C-shaped SHCs is, in fact, more than that of the L-shaped connectors. Also, the following findings were established through the results of this experimental study:

1. Concrete crushing-splitting or fracture of the connector is the failure mode of SHCs, which was witnessed in the push-out tests.
2. For specimens considered in this study, the dominant mode of failure was the concrete crushing-splitting mode of failure. Only two specimens with small size angles (MV60 and MH60) failed in connector fracture mode. Generally, with increasing size, including the span of angle SHCs, the fracture appertaining to the connector is not expected.
3. The L-shaped connectors tend to separation from the concrete block. This is due to not having a flange embedded in concrete. Using rebar passing through a hole in the upstanding leg of the angle will eliminate this tendency.
4. Increasing the angle height in C-shaped angle connectors of identical thickness decreases the shear capacity of the connector. This is because the angle leg bends like a cantilever, and with the height increase, the more bending moment is absorbed in the leg.
5. The shear capacity of L-shaped angle connectors of the same thickness is increased, at the time that its angle height is increased.
6. The shear strength of the two connectors is increased just as its length is increased.

In general, C-shaped angle connectors are preferred over L-shaped connectors for design practice.

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