Paper ID: 1073

Finite Element Modelling Approach to the Behavior of Angle Shear Connector in Steel Concrete Composite Members

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Abstract

A shear connector is a structural element embedded at the connection between a steel beam and a concrete slab in composite construction. This study aims to conduct investigations by Finite Element Modelling for the purpose of determining the shear strength of angle shear connector subjected to monotonic loading. Using ABAQUS / Explicit package a large number of 3D push-out tests were simulated through modeling. After that a series of comprehensive validations were conducted. In this investigation, the effects of concrete compressive strength, the cutting length, size of the embedded connector and its orientation on the shear capacity have been examined. The model incorporates the interaction between structural components and material non-linearities. The analysis is carried out using a dynamic explicit procedure. Specimens using welds at the connector tip in push-out tests demonstrated increased ultimate capacity but lower ductility compared to those using welds at the connector base. An enhancement of concrete strength from 30 MPa to 40 MPa for specimens using welds at the connector tip led to a rise in ultimate load. Connector size and cutting length are positively correlated with ultimate capacity.

Keywords: *Shear connector; Steel Concrete Composite Members; Angle Shear Connector; Finite Element Modelling; Push out test.*

1 Introduction

Angle shear connectors are usually produced by welding L-shaped steel angles onto the steel flange. The angles shear connectors provide a larger contact area and can resist higher shear loads. Readily available sections and simple welding procedures make the angle shear connector easy to use. Design of successful shear connector is very much dependent on load slip behavior of the connector under experimental investigations. Such investigations can be done by experimental tests which are time consuming and costly option. The study by Lee et al. (2024) studies structural behavior of angle shear connectors using a mix of experimental push-out tests, method of nonlinear finite element analysis (FEA), and theoretical modelling. Then they have come up with another theoretical model to calculate the shear strength of angle shear connectors formulated on failure mode and is cross-validated by the regression analysis (Lee et al., 2024). Sung-Min Choi works up the fatigue properties of the weld splice joints between angle-shape shear connectors and the bottom plate in the steel–concrete composite slab. The research arrives at the conclusion that the welded joints will not break under fatigue when sufficiently loaded in a realistic way (Sung-Min Choi, 2008.). The study conducted by Balasubramanian and Rajaram (2016), an experiment was carried out to investigate the behavior of angle shear connectors in steel concrete composite buildings under static load. The study points out that shear connectors are essential to prevent relative slip between the interface of the steel and concrete and composite action (Balasubramanian & Rajaram, 2016).

The ability to predict the nonlinear load-slip correlation and the ultimate shear capacity of the shear connectors in composite beams using numerical solutions is certainly a good alternative. The method of finite element (FE) has developed into a formidable means of numerically analyzing very broad sectors of engineering problems. A proper finite element model helps to significantly reduce the number of tests that are required in prediction of structural behavior. Few studies are present on the finite element modeling of the push-out test of angle shear connectors. This paper is devoted to designing a finite element model of the angle connectors which would reproduce the results obtained with the help experiments that are accurate. The developed FE model incorporates material nonlinearities. The behavior of the angle shear connector is investigated by considering the connector length, thickness, cutting length, and concrete strength as variable parameters.

2 Geometry of push-out test

The specimen was made up of two same slabs of size 350 mm width by 250 mm length and 130 mm thickness, which were connected to the beam flanges. Angle connectors measuring 75 mm × 75 mm and 50 mm × 50 mm were used to connect the steel beam and slabs at their interface. The thickness of these connectors was 6 mm and 5 mm. The specimens are divided into two sets, and they have two different welding orientations and cutting length. There are some specimens welded at the connector tip and specimens welded at the connector base. The dimensions of the specimens are given in the Table 1 and Figure1.

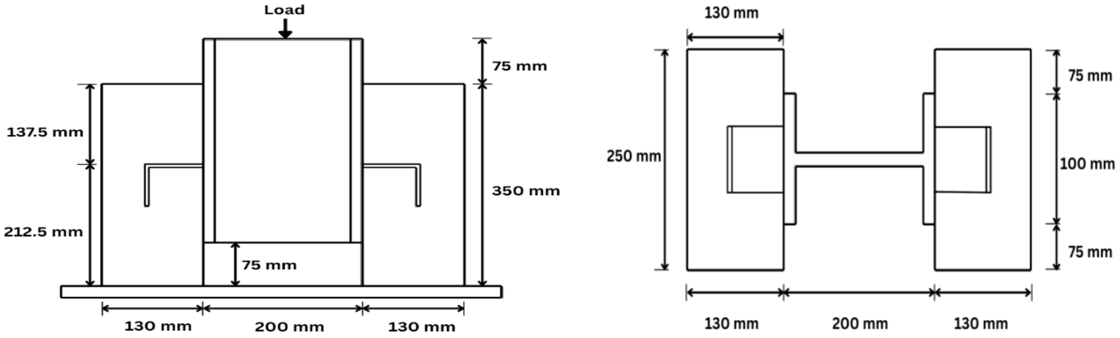


Figure 1 Push-out test specimen with angle shear connector

Table 1 Properties of the push-out test specimens

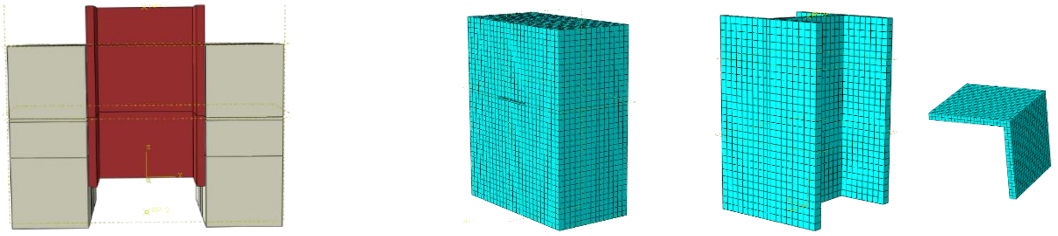
Set	Specimen	Welding Orientation	f'_c(MPa)	Angle Size (mm)	a (mm)	l (mm)	t (mm)
C	C1	at the connector tip	40	75x75x6	75	75	6
	C2	at the connector base		75x75x6	75	75	6
	C3	at the connector tip		75x75x6	50	75	6
	C4	at the connector base		75x75x6	50	75	6
	C5	at the connector tip		50x50x5	75	50	5
	C6	at the connector base		50x50x5	75	50	5
	C7	at the connector tip		50x50x5	50	50	5
	C8	at the connector base		50x50x5	50	50	5
D	D1	at the connector tip	30	75x75x6	75	75	6
	D2	at the connector base		75x75x6	75	75	6
	D3	at the connector tip		75x75x6	50	75	6
	D4	at the connector base		75x75x6	50	75	6
	D5	at the connector tip		50x50x5	75	50	5
	D6	at the connector base		50x50x5	75	50	5
	D7	at the connector tip		50x50x5	50	50	5
	D8	at the connector base		50x50x5	50	50	5

3 Finite element model

In the present work, the push-out test was simulated with the aid of finite element program ABAQUS. The model has included steel section detailed geometries, concrete slab coupled with shear connectors, with suitable material properties, contact definition and both contact and free surfaces.

3.1 Finite element type and mesh

The FE model consists of three components. They are the concrete slab, steel beam, and angle shear connectors. The element (C3D8R) has been used for the analysis. The C3D8R element represents an 8-node linear hexahedral solid element. It is also an element type that avoids mesh locking in the case of incompressible material response and extremely applicable in the instance whenever there is a nonlinearity concern. In Figure 2, the real total picture of the push-out test specimen with finite element mesh is presented.



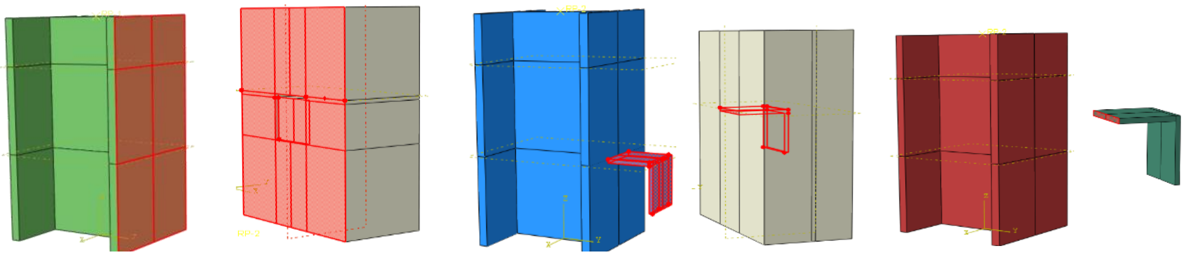
Model of push-out test

Concrete slab, steel beam and angle element type (C3D8R)

Figure 2 Push-out test model with finite element type and mesh

3.2 Contact interaction and constraint conditions

All the parts of the model were assembled properly, and appropriate interactions as well as constraints were used for proper simulation. The nodes of the concrete slab around the angle shear connector were tied using the tie constrain as shown in Figure 3. For getting relative displacement the friction penalty method can be used. The concrete surface was taken as slave surface and the steel beam surface was taken as master surface. Interaction between surfaces of the steel beam and concrete slab was characterized by tangential behavior as well as normal behavior. The normal behavior was specified using the “Hard” contact option. Hard Contact imposes non penetration among surfaces in contact. The frictional penalty method was used to model tangential behavior and the friction coefficient used was 0.2 as suggested by EC4. The surface-to-surface contact between concrete slab and steel beam is shown in the Figure 3.



(a)Steel beam surface and concrete surface (b)Nodes surrounding the connector (c)Shear connector welded to beam

Figure 3 Contact interaction and constraint conditions.

3.3 Loading and boundary conditions

The simulation of experiment greatly depends on boundary conditions. Boundary conditions need to be selected in a way that portrays the physical setup realistically. Nods on upper side of steel section were constrained to a point of reference by coupling. The most appropriate loading rate has been found 0.01 mm/sec and this has been used at the reference point. The bottom surface of the concrete slab was also constrained to a reference point. Both translational and rotational movements of the bottom surface of the concrete slab were restricted by applying constrain through the reference point. The rate at which the load is applied is so small that deformation of the structure is gradual to the extent that the procedure seems to be quasi-static.

3.4 Analysis method

The dynamic explicit analysis approach has been used in this research work. ABAQUS dynamic explicit method is a time integration method. This approach is applied in the solving of problems that include complex contact, large deformations, and nonlinear materials. It has applied in numerous issues including crack and break of concrete material. It is a dynamic method, but explicit analysis is regularly applied in ABAQUS to quasi-static simulations.

3.5 Material modelling for concrete

This study uses the Concrete Damage Plasticity (CDP) in order to model the concrete behavior. The approach has been chosen due to the ability of the method to capture the inelastic response of concrete (under tension and compression). In ABAQUS, the plasticity parameters are necessary to determine the behavior of a material after yielding. The most salient plasticity parameters are the dilation angle (ψ), eccentricity of flow potential(ε), the brittle to ductile ratio (K_c), the viscosity parameter(μ) and biaxial to uniaxial compressive strength ratio (f_{b0}/f_{c0}). Table 2 provides the parameters of Concrete Damage Plasticity model.

Table 2 Parameters for concrete damage plasticity model

ψ	ε	f_{b0}/f_{c0}	K	μ
36°	0.1	1.16	0.667	0

For compressive behavior this paper used the stress-strain behavior of concrete under uniaxial compression as identified in the EN1992-1-1. Concrete material behaves in a linear manner till the initial yield stress. Then the material behaves in a nonlinear way until the final compressive stress. The stiffness of the concrete decreases as the load becomes greater at any point of the strain softening of stress strain graph, this state is characterized with compressive damage variables. The compressive damage variables for concrete are determined as per ABAQUS documentation (2014). Such values are to be well-defined to be non-negative and can only increase with increasing stress levels. The tensile behavior of concrete may be defined in ABAQUS in different ways. It can be defined either by specifying a stress -to strain curve in tension, or by following the brittle fracture energy cracking method. The fracture energy cracking technique is more appropriate in unreinforced or less reinforced concrete, like that of push-out test, where the brittle failure predominates in the reaction. Fracture energy is stated to be the amount of energy required to construct one unit area of crack (Hillerborg et al. 1976). The most appropriate method of describing the trend of the softening in concrete was identified to be the exponential function. The concept of softening response of concrete can be defined in many ways. The most appropriate method of describing the trend of the softening in concrete was identified to be the exponential function of (Cornelissen et al. 1986) which is used in this study.

3.6 Material modelling for steel

The Steel material stress-strain relation is taken to be bi-linear and it is simply an elastic plastic concept. Young modulus of elasticity of the steel beam was considered as 210GPa. The value of Youngs modulus of elasticity of the angle shear connector was considered 200GPa. The yield strength of the angle shear connector was taken 350 MPa and the ultimate strength was taken 500MPa. The density of all the steel component was taken as 7800 kg/m^3. The Poisson's ratio was taken as 0.3 for all the steel material.

3.7 Validation of FE model

The study by Khorramian investigates the behavior of tilted angle shear connectors under monotonic loading. Two general failure mechanisms, concrete crushing-splitting and connector fracture, were revealed in the results. Specimen MA 112.5 L80 using the proposed FE model were analyzed in this study (Khorramian et al., 2015). In Figure 4, the test result is compared with the load-slip curves that are acquired through finite element analyses. The failure mode of the push out test experiment is compared with the FEM analysis results. It became certain that the FEM analysis fell at an acceptable level with experiment.

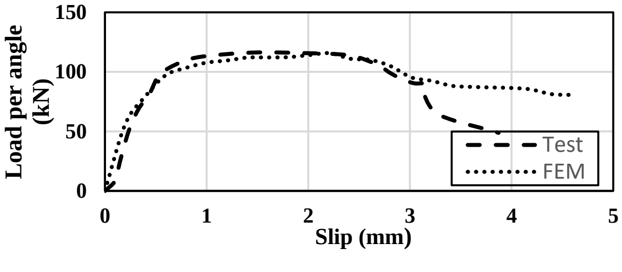


Figure 4 Validation of FE push-out model with test result.

4 Results and discussions

The primary failure mechanisms observed in FEM simulations typically include concrete crushing, concrete cracking, local yielding of the steel angle. These failure modes provide a deeper understanding of load transfer mechanisms in composite structures. In most cases, failure in the push-out test specimens began with concrete cracking. Shear fracture or buckling of the angle connectors subsequently progress after concrete crushing. Specimens using welds at the connector tip display different failure pattern than the specimen using welds at the connector base as shown in Figure 5. For tip welding stress concentration is on the intersection of shear connector and steel beam and the value of stress decreases by moving inside from the tip. For base welding high stress concentration is observed near the welded region as shown in Figure 6.

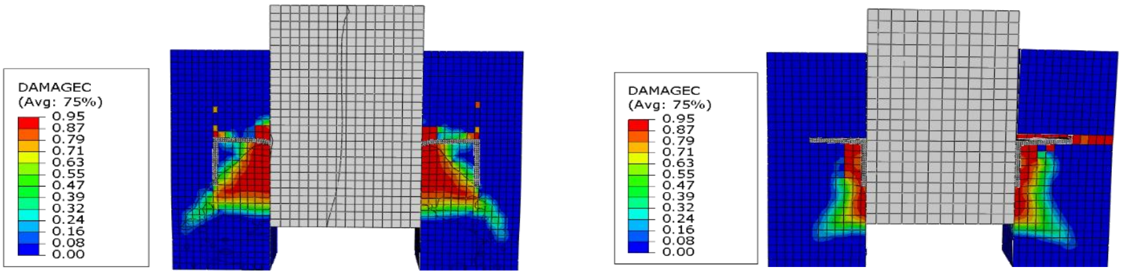


Figure 5 Compression damage for tip and base welded connector

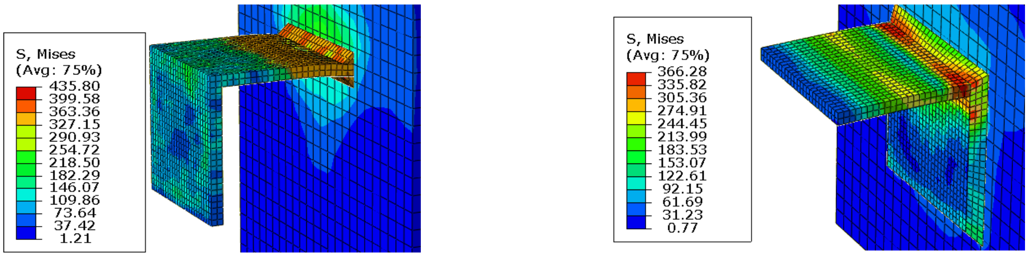


Figure 6 Stress distribution for tip and base welded connector

Table 3 Ultimate load and corresponding slip for the specimens of set C

Specimen	Size (mm)	Welding Orientation	a (mm)	f_c'- (MPa)	FEM-Q_u-(kN)	S_u(mm)
C1	75x75x6	at the connector tip	75	40	220.00	3.60
C2	75x75x6	at the connector base	75		189.78	2.86
C3	75x75x6	at the connector tip	50		158.05	2.88
C4	75x75x6	at the connector base	50		150.07	2.40
C5	50x50x5	at the connector tip	75		198.48	3.21
C6	50x50x5	at the connector base	75		137.80	2.80
C7	50x50x5	at the connector tip	50		147.95	5.30
C8	50x50x5	at the connector base	50		121.44	4.00

Table 4 Ultimate load and corresponding slip for the specimens of set D

Specimen	Size (mm)	Welding Orientation	a (mm)	f_c' - (MPa)	FEM-Q_u-(kN)	S_u(mm)
D1	75x75x6	at the connector tip	75	30	199.57	4.33
D2	75x75x6	at the connector base	75		171.37	3.37
D3	75x75x6	at the connector tip	50		141.60	3.78
D4	75x75x6	at the connector base	50		137.22	2.71
D5	50x50x5	at the connector tip	75		163.26	3.27
D6	50x50x5	at the connector base	75		133.43	3.44
D7	50x50x5	at the connector tip	50		128.55	4.04
D8	50x50x5	at the connector base	50		107.17	4.63

The impact of different parameters on the load-slip behavior and ultimate strength of the specimens is presented in the Table 3 and Table 4. The most important criteria of this push out test is concrete strength. FEM specimens of two sets C and D have eight identical specimens with the difference of concrete strength of 40 MPa and 30MPa.

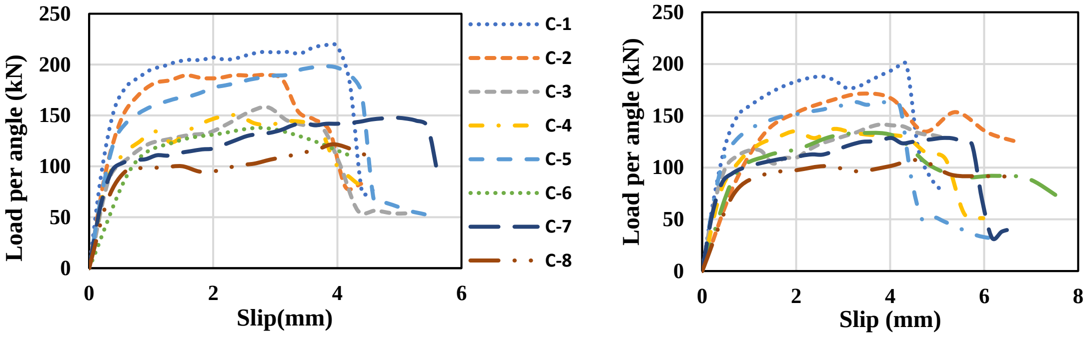


Figure 7 Load-slip curves for the specimens

Overall nature of load slip curve in specimen sets C and D is very similar. The ultimate capacity decreases about 15.09 % for decreasing the compressive strength from 40MPa to 30MPa. It was observed that, as presented in Figure 7, the load carrying capacity increases with the increase of angle cutting length. In the tip welding connection, it was found that the ultimate load capacity was 39.21 % higher by increasing the cutting length to 75 mm as compared to 50 mm with 40 MPa strength of concrete. It was realized that the increment was 40.94% at 30 MPa concrete strength. It is clear that in all the cases for the connector welded at the connector tip shows more shear capacity compared to the connector welded at the connector base. The specimens have the same load-slip behavior but different load-carrying capacity for the impact of the two forms of angle connectors. In the case of 40 MPa concrete strength the increase of ultimate capacity was to be found up to 37.72% when the angle size increased from 50×50×5 mm to 75×75×6 mm with welding at the base.

5 Conclusions

The ultimate capacity decreases for decreasing the compressive strength of concrete. There is a near linear progression of the ultimate load capacity of shear connector as the length of angle cutting progressively increases. The ultimate capacity of shear connector rises with increment of the angle size. The specimens with tip connected shear connector exhibit greater shear capacity as compared to base connected shear connector. In case of all the FEM specimen the failure occurred because of cracking of concrete and subsequently local yielding of steel. The stress concentration is observed near the welded region of the connectors.

References

Balasubramanian, R., & Rajaram, B. (2016). Study on behaviour of angle shear connector in steel-concrete composite structures. International Journal of Steel Structures, 16(3), 807–811.

BS EN 1992-1-1 (2004). Eurocode 2-Design of Concrete Structures: Part 1-1: General Rules and Rules for Buildings, British Standards Institution, London, UK.

Choi, S.-M., Tateishi, K., Uchida, D., Asano, K., & Kobayashi, K. (2008). Fatigue strength of angle shape shear connector used in steel-concrete composite slab. Steel Structures, 8(3), 199–204.

Cornelissen, H., Hordijk, D. and Reinhardt, H. (1986). “Experimental determination of crack softening characteristics of normal weight and lightweight concrete”, Heron, Vol. 31, No. 2, pp. 45–56.

Eurocode 4 (2005). “Design of composite steel and concrete structures-Part 1.1: General rules and rules for buildings”. EN 1994-1-1, Comité Européen de Normalisation (CEN), Brussels, Belgium.

Hillerborg, A., Modeer, M. and Petersson, P.E. (1976). “Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements”, Cement and Concrete Research, Vol. 6, No. 6.

Khorramian, K., Maleki, S., Shariati, M., & Ramli Sulong, N. H. (2015). Behavior of tilted angle shear connectors. PLOS ONE, 10(12), e0144288.

Lee, J.-S., Haroon, M., Shin, K.-J., Woo, J.-H., & Lee, H.-D. (2024). Angle shear connectors: Pushout tests, numerical simulations and shear strength model. Results in Engineering, 21, 101737.

Qureshi, J., & Lam, D. (2012). Behaviour of headed shear stud in composite beams with profiled metal decking. Advances in Structural Engineering, 15(9), 1547–1558.

Rob, F. (2019). shear strength of angle shear connectors in steel-concrete composite members.