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DIRECT SHEAR RESISTANCE OF INCLINED HEADED SHEAR STUDS

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Abstract

During welding process of shear studs connectors, some were unintendedly welded with a certain degree of inclined angle. The inclined shear studs may not sufficient to transfer sufficient forces to the surrounding concrete in order to have complete composite actions. Therefore the main aim of this study is to investigate the shear transfer mechanism of the inclined headed shear connector using a push-out test. A three-dimensional finite element model was developed using dynamic explicit solver in ABAQUS commercial software by considering nonlinear material properties of the concrete, steel beam, reinforcements and headed shear studs. The result in terms of load-slip curve behaviour was satisfactory to predict the behaviour which obtained in experimental. Thus this model was used to perform a parametric study of 10 push-out specimens with the different shear studs inclination angle. Results have shown that the shear resistance of inclined shear studs was depending on the direction of the inclined angle towards loading direction. Ultimate shear capacity is increased about 20% when the shear stud inclined in opposite direction of applied load. Whereas, a decrease in ultimate shear resistance was found when shear studs were inclined in the parallel direction of applied force. Hence, inclined shear stud should be treated carefully since it can reduce the degree of shear interaction in steel-concrete composite beam design.

Keywords: Headed shear stud, Inclined angle, Load-slip, Push-out, Steel-concrete composite beam, Ultimate shear capacity.

1. Introduction

A composite structure, such as a composite beam or column, consists of a steel section and a reinforced concrete slab interconnected by shear connectors. The mechanical shear connector between the steel section and concrete material allows for the transfer of forces between the steel and concrete and resist vertical uplift forces at the interface [1]. Flexible connectors, such as channels, joists, and headed studs, are commonly used because they allow the shear load to be redistributed between groups of connectors. As a result, a high degree of composite action can develop prior to failure, which is the aim of the research in this field.

Design of the static strength of headed shear studs is available in various design codes, such as BS5950 [2] and Eurocode 4 (EC4) [3]. Shear studs are attached to the steel section using a powerful stud welding system. During this process, some of the shear connectors are unintendedly welded with a certain inclined angle. Inclined shear studs may not transfer sufficient forces to the surrounding concrete to have complete composite actions, thus potentially invalidating the assumption of composite action. However, inclined shear studs also may probably offer increased in ultimate load capacity, depending on the direction of the inclined angle in relation to the loading direction. According to the current knowledge of the applicant, inclined headed stud connectors have not been published to date.

The more relevant research was conducted by Leekitwattana et al. [4], who used the concept of inclined connectors in a sandwich panel by utilising the geometry of the profiled steel sheeting as shear connectors. Apart from headed studs, channel-type connectors are also being used [5] due to their ductile behaviour, as the minimum deformation can reach 6 mm according to the ductile criterion specified by EC4 [3].

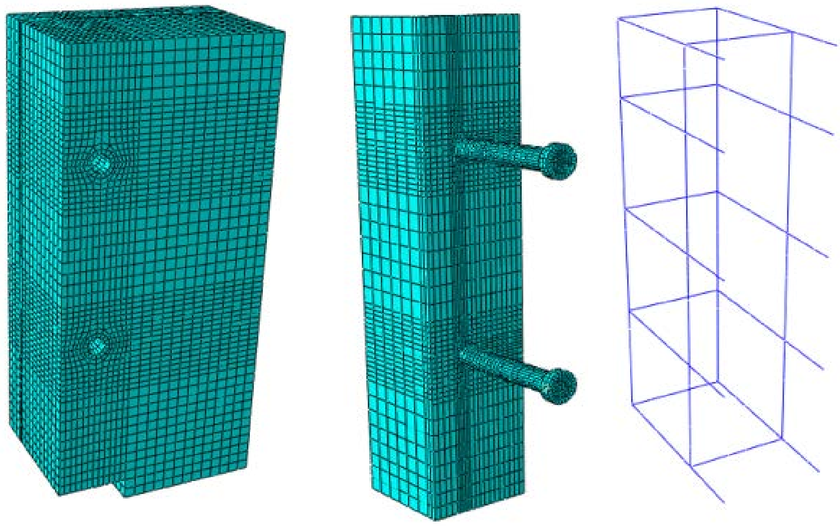
Most of the recent research studies have focused on the fastest and most economical method for installing studs to floor decking in composite construction using innovative shear connectors. Costa-Neves et al. [6] proposed perforated shear connectors, where the concrete becomes virtual dowels. The authors modified profobond and T-profobond geometry by creating holes to allow for more interaction between the concrete steel plates. Hosseinpour et al. [7] recently proposed hollow steel tube shear connector to overcome the ductility problem in web opening shear connector in slim floor composite beam. Pavlovic et al. [8] used bolted shear connectors instead of headed studs to incorporate the elements of sustainability. The authors found that this type of connector achieved 95% of the shear resistance compared to headed stud shear connectors.

Tahir et al. [9] proposed a new stud system fastened with high-strength pins. This type of connector is considered the fastest and most economical for installing floor decking. However, the authors found that the capacity of the studs is reduced due to pin fracturing that occurs before yielding of the shear stud. Therefore, any understanding of the shear transfer mechanism of the effect of the inclined headed shear connector in a composite beam shall lay fundamental behaviour of the inclined shear connectors and can be used in the design. The aim can be achieved by investigating the stiffness, strength and materials failure mode through the push-out test, numerically via ABAQUS software. The modelling set-up will be based on the test specimen according to EC4 [3].

2. Finite Element Analysis

2.1. Modelling, boundary condition and materials constitutive model

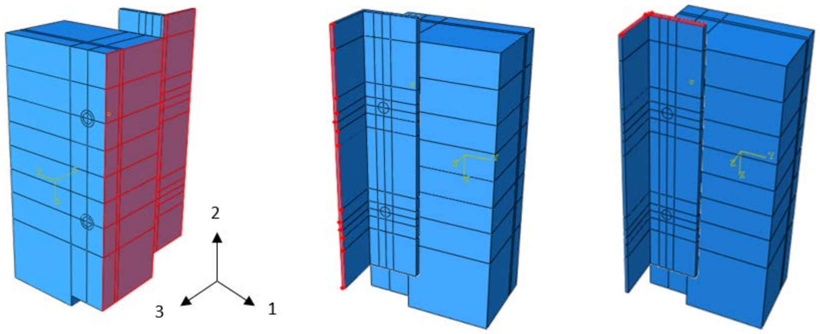
Three-dimensional finite element models were developed for analysing the push-out test by ABAQUS software with the explicit solver. The model was validated using experimental results published by Gattesco et al. [10]. Due to the complex contact interactions and boundary conditions, the static implicit method was encountered convergence difficulties and dynamic explicit method was used. Half models were developed considering its symmetries of geometries, boundary conditions and locations of loadings, which was existed in the FEM as shown in Fig. 1. Continuum, 3D, 8-node reduced integration elements (C3D8R) were applied to the concrete slab and solid shear stud models. Continuum, 3D, 8-node incompatible modes (C3D8I) were used for the steel beam due to the high concentrated axial load on a steel beam. For reinforcing bars, 3D, 2 node elements (T3D2) were used in the modelling. In order to get appropriate results, the size of meshes was chosen from a convergence study. This could also eliminate the problem of the Hourglass effect caused by the used of reduced integration elements.



(a) Concrete Slab **(b) Steel beam and stud** **(c) Rebar**

Fig. 1. Finite element type and mesh.

Symmetric boundary condition (BC) was applied to the surfaces at the symmetric planes as shown in Fig. 2. The symmetric boundary condition was applied to surface 1 and surface 2, Figs. 2(a) and (b) where the displacement U_1 and rotational R_2 and R_3, and displacement U_3 and the rotational R_1 and R_2 of all nodes on the specified surface, respectively were restrained. In the analysis, displacement control has been used where the load was applied downward or upward to the top surface of the steel beam as shown in Fig. 2(c). In displacement control, the load was applied as a displacement boundary condition on the top surface of the steel beam web and flange. Plastic damage models for concrete, which available in ABAQUS was used in concrete material modelling.



(a) Surface 1-symmetric BC **(b) Surface 3-symmetric BC** **(c) Loading surface**

Fig. 2. Boundary condition and loading surfaces.

A stress-strain curve is illustrated in Fig. 3. The value of the proportional limit stress, Young's modulus and Poisson ratio is taken according to EC2 [11] and EC4 [3]. The stress-strain relationship of structural and reinforcement steel was modelled as shown in Fig. 4(a) by the bilinear curve. The curve illustrates a simple elastic-plastic model. The headed shear connector's material was modelled by a tri-linear stress-strain curve as shown in Fig. 4(b). The material behaviour is initially elastically followed by strain-softening law and then yielding.

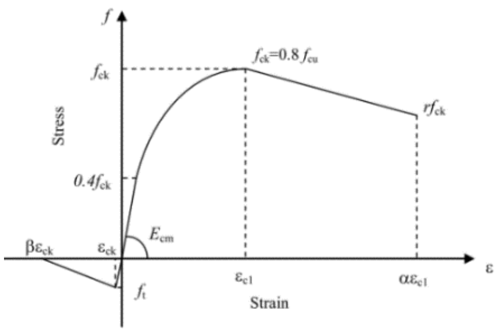
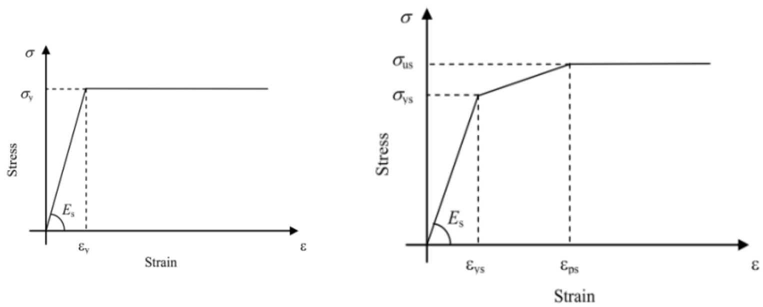


Fig. 3. Stress-strain curve for the concrete material.



(a) Structural steel and reinforcement **(b) Headed shear stud**

Fig. 4. Stress-strain relationship.

2.2. Parametric studies

The study was conducted to examine the effect of the shear stud inclination angles to direct shear resistance. The details of specimens configuration and its definition is shown in Fig. 5 and Table 1. Total of 11 push-out test specimens was used in the parametric study. The specimens had different inclination angle (θ) as 0, (±) 10 and (±) 30 degree and combinations of these three angles. The models were grouped according to the shear stud's inclination angle. Pulling and pushing forces were applied to obtain various possible cases of inclination angle towards force application. Similar material properties for the materials which used in validation [10] were used in parametric studies as shown in Table 2.

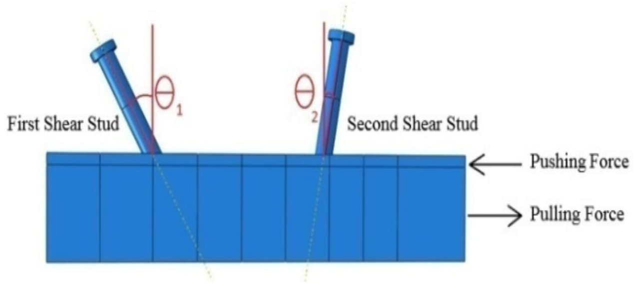


Fig. 5. Specimen's definition.

Table 1. Specimen's configuration.

Models	Group	First stud angle (θ_1)	Second stud angle (θ_2)	Force direction
FEVR- θ_1(0)- θ_2(0)	0	0°	0°	Push
FEPH- θ_1(0)- θ_2(10)	1	0°	10°	
FEPH- θ_1(0)- θ_2(30)	2	0°	30°	
FEPH- θ_1(10)- θ_2(10)	3	10°	10°	
FEPH- θ_1(30)- θ_2(30)	4	30°	30°	
FEPH- θ_1(30)- θ_2(-10)	5	30°	-10°	
FEPL- θ_1(0)- θ_2(10)	1	0°	10°	Pull
FEPL- θ_1(0)- θ_2(30)	2	0°	30°	
FEPL- θ_1(10)- θ_2(10)	3	10°	10°	
FEPL- θ_1(30)- θ_2(30)	4	30°	30°	
FEPL- θ_1(30)- θ_2(-10)	5	30°	-10°	

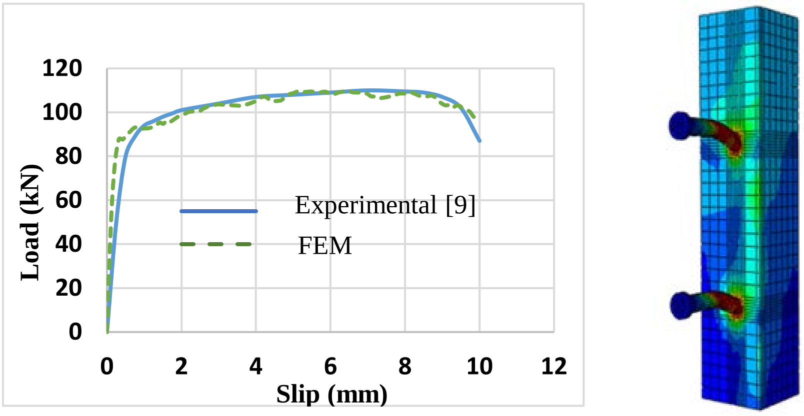
Table 2. Material properties.

Material	E (GPa)	σ_y (MPa)	σ_u (MPa)	f_{ck} (MPa)	f_{ct} (MPa)
Concrete	30.47	-	-	24	2.6
Headed shear stud	208	350	450	-	-
Structural steel	210	430	-	-	-
Reinforcement bar	208	460	-	-	-

3. Results and Discussions

3.1. FE validation

The load–slip curves obtained from the finite element analyses are compared with the test result [10] in Fig. 6(a). For comparison purpose, the results of shear load are shown in term of load per shear stud. It can be seen that the good agreement has been achieved between FE and experimental results. The mean value *of* P_{test} /P_{FEA} ratio is 0.99. Similar maximum slip at failure was obtained. The maximum slip at failure (S_{ult}), measured at the load dropped to 11.5% below the peak load. The failure mode obtained in FEA is yielding (red colour) at shanks area of studs as shown in Fig. 6(b) The developed finite element models successfully predict the ultimate shear capacity and as well as load–slip behaviour of the headed shear stud.



(a) Load-slip curve **(b) Failure in FEA**

Fig. 6. Validation of finite element model.

3.2. Parametric studies

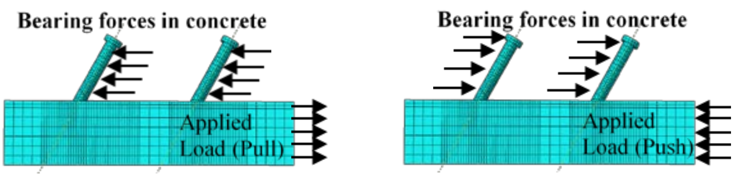
Ten (10) FE models have been used to investigate the effect of the inclination angle of the headed shear stud. The results in terms of ultimate shear strength (P_u) are compared to ultimate shear strength FE models *(FEVR-*θ_1*(0)-*θ_2*(0))* with zero inclination angle *(*P_{ver}*)* as shown in Table 3. This table also shows the maximum end slip (S_{max}) recorded for all FE models. It can be seen that ultimate shear load is obtained by model *FEPL-*θ_1*(30)-*θ_2*(30)* where it reached ultimate load P_u = 134.17 kN at slip 9.49 mm where the pulling force was applied. The ultimate load is 22% more than the FE model with zero inclination angle.

According to EC4 [3], the studs are classified as ductile. Whereas the lowest value of the ultimate load is P_u = 93.49 kN which obtained by model FEPH-θ_1(30)-θ_2(30). This model has a similar inclination angle with model FEPL- θ_1(30)-θ_2(30) except different applied force direction. The ultimate load is reduced about 15% compared to FE models without inclination angle and less ductile with max slip, S_{max} = 8.66 mm. All FE models which inclined towards the opposite direction of applied pulling force in the push-out test tends to have higher value and more ductile than a model with zero inclination angle. Whereas lower shear values were obtained in all FE models where studs were inclined in the parallel direction of applied force in the steel beam. This increase in shear capacity is attributed to the increase of bearing capacity of concrete at front area of shear studs.

The bearing capacity increment is caused by larger amount of concrete confinement to sustain applied shear forces as illustrated in Fig. 7. Whereas, the reduction in ultimate load is due to limited bearing stresses located at front of stud shank surface area caused by its inclination angle. This mechanism also was described by Pavlovic et al. [8].

Table 3. Comparison of shear connection capacity.

Model	Group	P_u (kN)	P_u/P_{ver}	S_{max} (mm)
FEVR- θ_1(0)- θ_2(0)	0	109.68	1	9.93
FEPH- θ_1(0)- θ_2(10)	1	106.46	0.97	10.01
FEPL- θ_1(0)- θ_2(10)		142.38	1.29	10.20
FEPH- θ_1(0)- θ_2(30)	2	98.84	0.90	9.60
FEPL- θ_1(0)- θ_2(30)		130.84	1.19	10.05
FEPH- θ_1(10)- θ_2(10)	3	97.12	0.88	9.96
FEPL- θ_1(10)- θ_2(10)		116.58	1.06	9.65
FEPH- θ_1(30)- θ_2(30)	4	93.49	0.85	8.66
FEPL- θ_1(30)- θ_2(30)		134.17	1.22	9.49
FEPH- θ_1(30)- θ_2(-10)	5	130.84	1.19	10.71
FEPL- θ_1(30)- θ_2(-10)		132.78	1.21	10.09



(a) Opposite direction **(b) Parallel direction**

Fig. 7. Bearing forces in concrete in the direction of the applied force.

4. Conclusions

The effect of the inclination angle of the welded headed studs to ultimate shear strength and ductility in steel-concrete composite beam behaviour was examined numerically using the push-out test. The inclined of headed shear studs lead to an increase or decrease in ultimate shear capacity depending on applied shear force direction. The maximum reduction in ultimate shear capacity is obtained in the model with a higher inclination angle where both studs were bends in the direction of applied forces in the steel beam. Hence, bend shear studs should be treated carefully since they can caused the steel-concrete composite beam to be under design. However, the results also show a benefit of installing headed shear studs with inclination angle as long as the direction of applied shear forces are known in the design.

Acknowledgements

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Nomenclatures

E_c	modulus of elasticity of concrete
E_{cm}	Modulus of elasticity of concrete
E_s	Elastic modulus of steel
f_{ck}	Compressive cylinder strength of concrete
f_{cu}	Compressive cube strength of concrete
r	Concrete crushing softening factor

Greek Symbols

β	Concrete cracking softening factor
$\acute{\varepsilon}_c$	Compressive strain of concrete
$\acute{\varepsilon}_{c1}$	Strain at the peak point of concrete compression
$\acute{\varepsilon}_{ck}$	Strain at concrete cracking
$\acute{\varepsilon}_{ps}$	Strain at peak point of steel
$\acute{\varepsilon}_t$	Tensile strain of concrete
$\acute{\varepsilon}_{ys}$	Strain at the beginning of hardening stage
σ_y	Yield stress
σ_{ys}	Yield stress of steel
σ_{su}	Ultimate stress of steel

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