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Modelling of headed stud in steel-precast composite beams

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Abstract. Use of composite steel construction with precast hollow core slabs is now popular in the UK, but the present knowledge in shear capacity of the headed shear studs for this type of composite construction is very limited. Currently, all the information is based on the results obtained from experimental push-off tests. A finite element model to simulate the behaviour of headed stud shear connection in composite beam with precast hollow core slabs is described. The model is based on finite element method and takes into account the linear and non-linear behaviour of all the materials. The model has been validated against the test results, for which the accuracy of the model used is demonstrated. Parametric studies showing the effect of the change in transverse gap size, transverse reinforcement diameter and in-situ concrete strength on the shear connection capacity are presented.

Key words: headed stud; composite construction; precast hollow core slabs; finite element modelling.

1. Introduction

Headed stud shear connectors are essential for composite action in steel/concrete composite beam to resist the longitudinal shear forces at the interface. The shear strength and stiffness of the connection is not only dependent on the strength of the connector itself, but also on the resistance of the concrete slab against longitudinal cracking caused by high concentration of shear force at each stud. The resistance of the concrete is a function of its splitting strength, which is directly related to the concrete around the stud.

Many researches have been carried out experimentally and numerically to investigate the behaviour of headed studs in steel-solid slab composite girders. Earlier research by Davies (1967) showed that the ultimate capacity of a stud connector in a push-off test is dependent to a large extent upon the pattern and spacing of the connectors.

A further study by Davies (1969) illustrated that the addition of transverse reinforcement improves the cracking resistance of the concrete slab in a composite girder. In 1971, experimental studies carried out by Johnson (1971), Menzies (1971) showed that the concrete strength influences the mode of failure of shear connection between steel and concrete, as well as the failure load. Jayas and Hosain (1987) carried out 18-full size push-out specimens and found that the spacing between studs affects the failure modes of the shear connection. Oehlers (1989) investigated the cracking modes around the shear connector and stated three distinct modes of cracking. In 1996, Li and Krister (1996) studied the behaviour of

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headed studs in high strength and normal strength concrete, it is found that the compressive strength of concrete significantly affected the load-slip behaviour and the shear connection capacity.

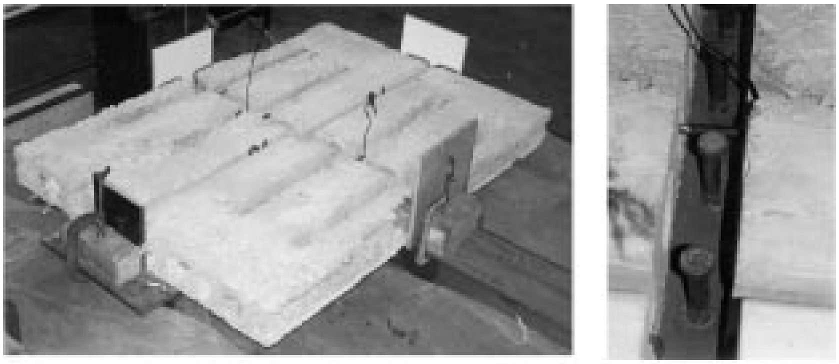
Although present knowledge on headed stud in solid slabs and metal decking construction are well established, the behaviour concerning the headed stud in precast hollow core slabs is very limited. The load-slip curve and the shear capacity of the headed studs are currently obtained from experimental push-off tests (Lam *et al*. 1998). Although the push-off tests provided a clear insight to the behaviour of these connectors, the tests are relatively expensive and time consuming. Finite element modelling of the push-off test will help in reducing the number of these tests require and give guidance for future experimental work.

Due to the complexity of the three-dimensional stress-strain state, there is limited success in the mathematical modelling of push-off tests with precast hollow core units. All current information is based on empirical formulae derived from the statistical solution from test results. Therefore, the main objective of the authors is to develop a 3-D finite element model using ABAQUS (2001) to simulate the load-slip behaviour of shear studs in composite steel-precast concrete beams, taking into account the linear and non-linear behaviour of all the materials. The results from the proposed model will be compared with the experimental data obtained from push-off tests.

2. Push-off tests

Fig. 1 showed the horizontal push-off test specimen use to determine the shear capacity and load slip behaviour of the headed studs in precast concrete hollow core slabs. The push-off test specimen consists of four 600 mm wide hollow core units. These units are connected to a grade S275, 254×254×73 kg/m universal column.

The steel beams were supplied with six pre-welded headed studs at 150 mm centres. All studs were 19 mm diameter ×100 long TRW-Nelson headed studs and were attached to the universal column using a semi-automatic fusion welding process as shown in Fig. 1. The 600 mm slab width was chosen instead of the more common 1200 mm wide unit as shown in Fig. 2, so that the effect of the edge joint was included in a test length of 1200 mm. Milled slots of 500 mm long were made open at alternative



(a) Push-off test specimen

(b) Details of the stud within the gap

Fig. 1 Push-off test specimen before insitu infill concrete is cast and details of the stud within the gap

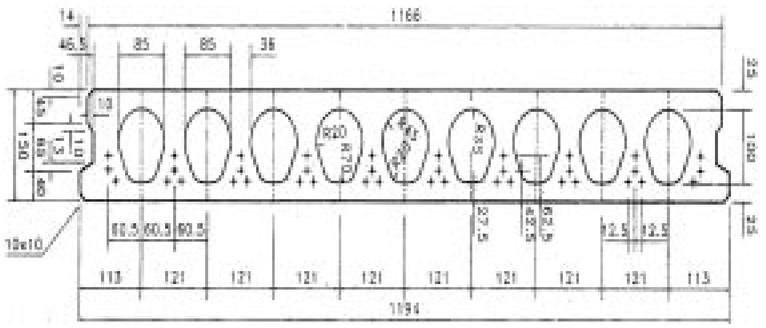


Fig. 2 Details of 150 mm deep hollow core unit

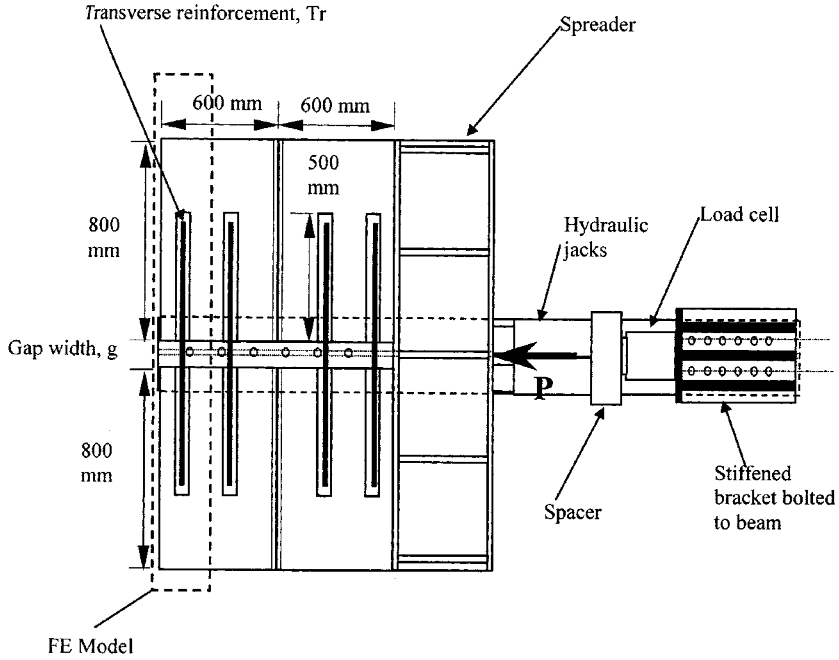


Fig. 3 General arrangement of horizontal push-off test

cores at the end of the units. Transverse reinforcement is placed inside the milled slot to limit the longitudinal splitting of the composite slab. The load is applied horizontally on the concrete slab via hydraulic jacks and the slip between the steel beam and the concrete slab is measured using linear voltage displacement transducers (LVDT's). Fig. 3 showed the general arrangement of the horizontal push-off test proposed by Lam (2000).

3. Finite element modelling

Assuming that the horizontal shear force is equally distributed among the shear studs, it is decided to simulate only a single strip of the push-off test specimen as highlighted in Fig. 3. The simulated push-off test specimen contained only one headed stud. A comparison will also be made between the obtained results from the one stud model and the three studs model to evaluate the degree of load distribution among the headed studs.

3.1. One stud model

The single stud FE-model consists of 800 mm long hollow core unit same as that in the experimental push-off test, see Fig. 3. The width of the specimen modelled is 240 mm wide, which is the distance between two hollow cores adjacent to the milled slot. The distance from the stud to the edge of the concrete slab is approximately equal to 120 mm. The thickness of the concrete slabs is 150 mm. The load is applied as a concentrated load to the steel beam so that local failure of concrete slabs due to concentrated load can be avoided. The oval shape of the cores in hollow core unit was modelled as a rectangle with the same area. One transverse reinforcing bar is placed in each slot. The reinforcing bar is modelled with the equivalent cross section area so that the reinforcement ratio is the same as in the test specimen.

3.1.1. Finite element mesh

For successful numerical modelling of the shear connection in composite beams with precast hollow core slabs, the following items must be properly represented: headed shear stud, transverse reinforcement, precast hollow core slab, insitu concrete infill and the steel section.

Combinations of three-dimensional solid elements, which are available in the ABAQUS software, are used to represent the push out specimen. These combinations are the three dimensional eight-node element (C3D8), the three dimensional fifteen-node element (C3D15), and the three dimensional twenty-node element (C3D20). In the modelling of the cast insitu concrete slab around and above the stud, C3D15 and C3D20 elements are used and C3D8 elements are used elsewhere. The shank of the stud consisted of C3D15 elements and the head of the stud consisted of both C3D15 and C3D20 elements. The width of the head is 1.5 times the stud diameter and its thickness is 0.5 times the diameter as specified in CP117 (1965).

Fig. 4 shows the finite element mesh of the steel beam and the precast concrete slab with the headed stud. Initially, different meshes were examined to find the most appropriate one that gives adequate results with less computing time in the solution process. Due to the symmetry, only half of the push-out test is modelled. Each precast concrete unit is divided into 10 elements along X-direction, 7 elements along Y-direction and 3 elements along Z-direction. The insitu concrete is modelled with 10 elements in X-direction, 2 elements in Y-direction, and 5 elements in Z-direction. The shank of the shear connector consisted of one C3D15 element in X-direction, 1 element in Y-direction and 2 elements along Z-direction. The head of the stud connector consisted of one C3D15 element and two C3D20 elements along X-direction and 1 element in Y-direction and 1 element in Z-direction. The mesh is fine in the areas where the stress concentration is high and satisfies the aspect ratio limits of the three dimensional solid elements. The flange the steel beam is divided into 3 elements along X-direction, 2 elements along Y-direction and 1 element in Z-direction. The web of the steel beam is divided into 4 elements along X-direction, 1 element in Y-direction and 1 element in Z-direction. The transverse reinforcing bar is divided into 1 element along X-direction, 7 elements along Y-direction and 1 element along Z-direction.

A basic observation by Jayas and Hosain (1987) showed that even at low load, there was separation

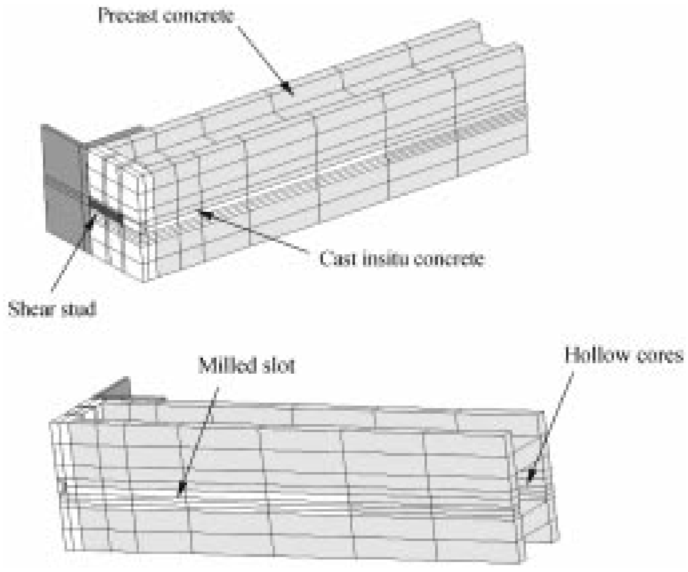


Fig. 4 Finite element mesh of the FE model

between the concrete behind the shear connector. According to this observation, only the nodes in front of the stud, in the direction of loading, are connected with the surrounding concrete nodes and other nodes of the stud are detached from the surrounding concrete elements. Also, only the nodes of the cast insitu concrete inside the milled slot are connected with the precast one while other nodes, along the insitu/precast interface were detached. This is because the bond between the insitu/precast joint could be destroyed at very low load level due to the presence of the hollow cores and the difference in the insitu and precast concrete strength.

3.1.2. Boundary condition

For the boundary conditions, all nodes of cast and precast concrete slab in the opposite direction of loading (surface 1) are restricted to move in X-direction to resist the compression load. All nodes along the middle of steel beam web (surface 2) are restricted to move in Y-direction due to symmetry. All concrete nodes, stud nodes, steel beam flange nodes, and steel beam web nodes which lie on the other symmetry surface (surface 3) are restricted to move in Z-direction because of symmetry as shown in Fig. 5.

3.1.3. Application of load

A static concentrated load is applied at the centre of the steel web as shown in Fig. 5. The load is applied using the modified RIKS method available in the ABAQUS. The basic algorithm of this method is Newton method in which, the solution is obtained as a series of increments with iterations to obtain equilibrium within each increment. The RIKS method is generally used to predict unstable and non-linear collapse of a structure. It used the load magnitude as an additional unknown and solves simultaneously for loads and displacements. Therefore, another quantity must be used to measure the progress of the solution. ABAQUS uses the arc length along the static equilibrium path in load-

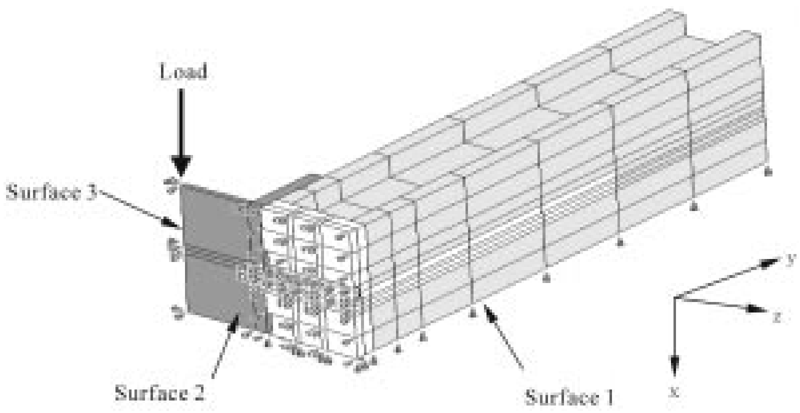


Fig. 5 Application of load and boundary conditions

displacement space. An initial increment of displacement is given on the data line and the initial load proportionality factor is equal to this initial increment using the automatic incremental scheme. This initial increment will be adjusted if the increment fails to converge. From then on, the value of load after each increment is computed automatically.

3.1.4. Material model of the push-off test specimen

Modelling of shear connection between steel and precast concrete requires successful representation of all the components associated with the connection. In a push-off test, the following components must be properly considered:

1. In-situ concrete infill.
2. Precast hollow core unit.
3. Headed stud.
4. Transverse reinforcing bar.
5. Steel section.

3.1.5. Material modelling of a cast in situ and precast concrete

To develop the model for the behaviour of the concrete, bilinear stress-strain curves were used for the cast insitu and the precast concrete. The FE model treated the concrete as an elasto-plastic material.

Fig. 6 shows the typical stress-strain curve of the concrete model. The model took into the account of inelastic behaviour of the concrete material. The option (*PLASTIC) is used to specify the plastic part of the material model that use the von mises yield surface. The softening part of the concrete stress-strain behaviour is neglected due to the limitation of the FE package (ABAQUS) used. It is assumed that the concrete behaves as a linear-elastic material up to the yield stress and perfect plasticity is obtained when yield stress is reached. For the elastic part of the stress-strain curve, it is required to identify both of Young's modulus and Poisson's ratio of the concrete. For the plastic part of the stress-

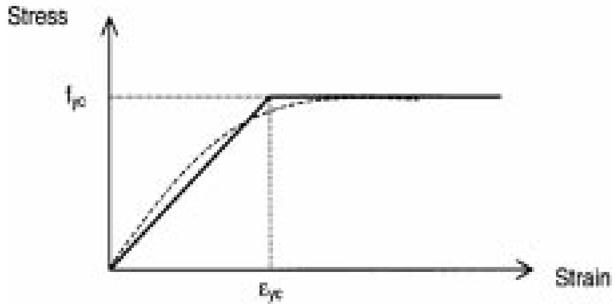


Fig. 6 Bilinear stress-strain curve for concrete (elasto-plastic model)

strain curve, it is required to identify the yield stress. In accordance to BS 8110 (1997), average values of yield strain, Young's modulus of concrete and the yield stress were calculated from the following equations:

$$\varepsilon_{yc} = 0.00024\sqrt{f_{cu}} \tag{1}$$

$$f_{yc} = 0.8 f_{cu} \tag{2}$$

$$E_c = \frac{f_{yc}}{\varepsilon_{yc}} \tag{3}$$

where

E_c: Young's modulus of concrete
f_{cu}: the cube strength of concrete
f_{yc}: the yield stress of concrete

Concrete strength of 50 N/mm^2 was used for the precast concrete while the cast insitu strength may vary according to the mix proportions and this effect will be taken into consideration in the parametric study.

3.1.6. Material modelling of headed stud and transverse reinforcing bar

The modelling of the headed shear stud is the most important since the region around the stud is subjected to severe and complex stresses. To determine the mechanical properties of the stud material, three coupons were machined from the headed studs. The ultimate strength of the headed stud was 510 N/mm^2 430 N/mm^2 and 480 N/mm^2 respectively. Therefore, an average strength of 470 N/mm^2 is taken as the maximum allowed yield stress, $f_{ys,}$ in simulating the stud material. The average stress-strain curve of headed stud is shown in Fig. 7 together with the simulated bilinear stress-strain model. The simulated model treated the steel material of stud as elasto-plastic material, i.e., it behaved as a linear elastic material with Young's modulus E_s up to the yield stress of steel f_{ys}. After this stage, it becomes fully plastic. In the present study the following values are considered for the stud material:

f_{ys}: 470 N/mm^2

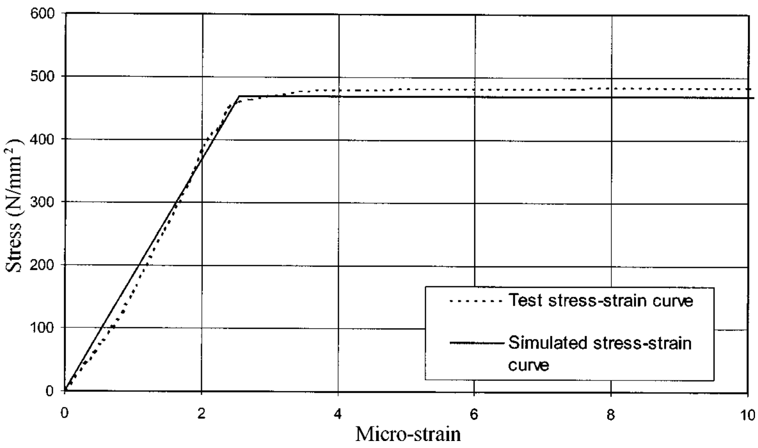


Fig. 7 Bilinear stress-strain curve for stud material (elastic-plastic model)

E_s: 200000 N/mm^2

The similar bilinear curve is used in modelling the reinforcing bar material using the following values of Young's modulus, E_s and yield stress, f_{ys}:

E_s: 200000 N/mm^2
f_{ys}: 460 N/mm^2

3.1.7. Material modelling of steel beam

The steel beam is modelled with yield stress of 275 N/mm^2 using a similar bilinear curve as shown in Fig. 7. It is believed that the effect of the steel beam is insignificant in a push-off test. Its function is to allow for the transmission of applied load to the connectors and hence the characteristic load-slip characteristic in the steel-concrete interface can be studied.

4. Experimental works

Over hundred push off tests with precast hollow core slabs were conducted by the author since 1998, from the parallel studies of the experimental push-off test (Nip and Lam 2001), transverse reinforcement was identified as a dominant factor affecting both the shear capacity and the stud ductility, therefore, tests with difference amount of transverse reinforcement were selected for the verification purposes. In addition, specimens with different slab thickness and insitu infill gap were also tested to evaluate the accuracy of the FE-model. Four pairs of specimens were tested to validate the finite element model. Test specimens were given with a reference in the following format. For example, T10-C25-150-65 represents:

T10: size of transverse reinforcing bar per slot.
C25: cast insitu infill concrete strength.
150: concrete slab thickness.
65: insitu infill gap width.

The mechanical behaviour of the materials used was determined from designated material tests. Each pairs of specimen were cast horizontally according to the requirements of the EC4 (1994). Twelve 100 mm cubes were made for each pair of specimens to evaluate the concrete cube strength. The steel beam used for the test was a 254×254×73 kg/m universal column. The shear connectors used were 19 mm diameter ×100 mm long headed shear studs for all the test specimens.

The procedure of testing was carried out in accordance to EC4. The load was applied in increments of 20 kN up to 40% of the expected failure load. After reaching this value, the load was removed and this loading was repeated 25 times. After this stage, the load was applied up to the failure and the load increment was decreased at higher load levels. At each load increment, readings of the slip between the steel beam and the concrete slab and the strain in the reinforcement bars were recorded on the data logger.

5. Results and discussion

Two modes of failure are generally observed during experimental push-off tests as well from the FE analyses. Specimen with high degree of transverse reinforcement failed by yielding of the headed stud, while specimen with low degree transverse reinforcement failed by yielding of transverse steel which led to conical concrete failure around the stud. By using the ABAQUS post processing, the stress distribution across the headed stud, the concrete slabs and the transverse reinforcement can be observed at each load increment and failure load determined. A very close correlation was noted between the test results and the FE analyses in slip characteristic and strain in transverse reinforcement at different load level. The comparison of the test results and the FE-solutions are as follow:

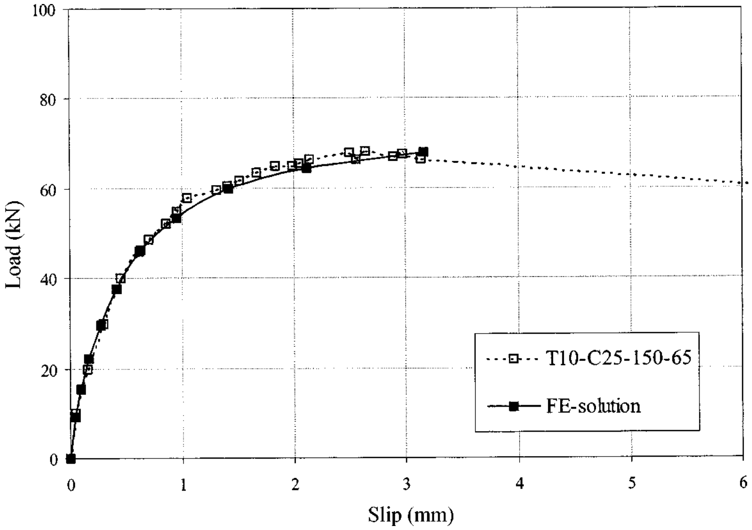


Fig. 8 Load vs. slip curves for the push-off test T10-C25-150-65 and FE-solution

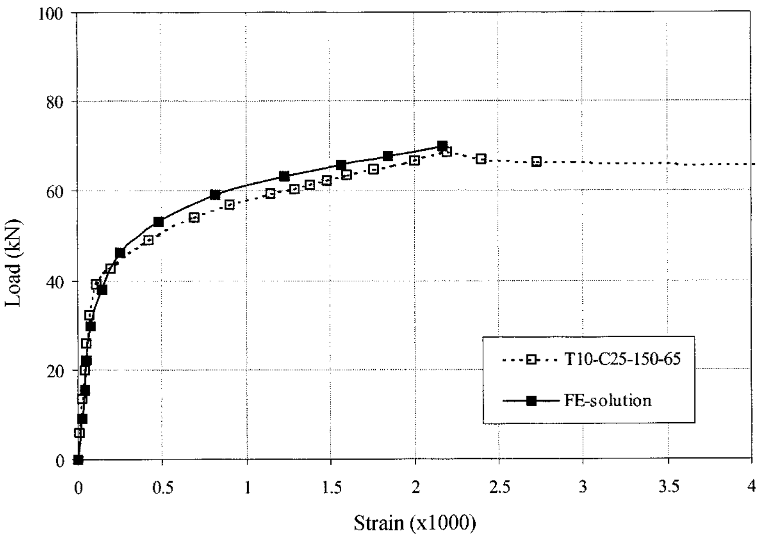


Fig. 9 Load vs. strain curves of transverse reinforcement for test T10-C25-150-65 and the FE-solution

5.1. Test T10-C25-150-65

Fig. 8 shows the comparison between the load-slip curves obtained from FE modelling and that obtained from experimental investigation, good agreement was observed between the results. The maximum experimental failure load was 68.4 kN at a slip of 2.63 mm compared with 67.9 kN at 3.16 mm.

For the specimen with low degree of transverse reinforcement, the failure mode of bar yielding is likely. The reinforcement bar yielded first leading to concrete failure around the stud, which has not reached its maximum compressive strength yet. Therefore, the concrete failed by tensile splitting. Fig. 9 shows the curves of load vs. strain of the transverse reinforcement obtained from the experimental test and FE-solution, the curves showed that the reinforcing bar has reached its yield strain at failure, good agreement from the experimental and analytical results were observed.

5.2. Test T16-C30-150-80

In this push-off test, a high degree of transverse reinforcement is used, T16 bars were used instead of the T10 bars used in the previous test. The curves of load vs. reinforcement strain comparison between the FE-solution and experimental result are showed in Fig. 10. It can be seen that unlike the previous test, the transverse reinforcement did not reach its yield strength in both FE-solution and experimental result. This stresses the fact that for higher degree of transverse reinforcement, the mode of failure is likely to be stud failure as observed from test. Fig. 11 shows good agreement between the load vs. slip obtained from FE-solution and that obtained experimentally. The maximum experimental load was 97.3 kN with a maximum slip of 5.53 mm compared with 95.5 kN with a slip of 6.9 mm obtained from FE-solution.

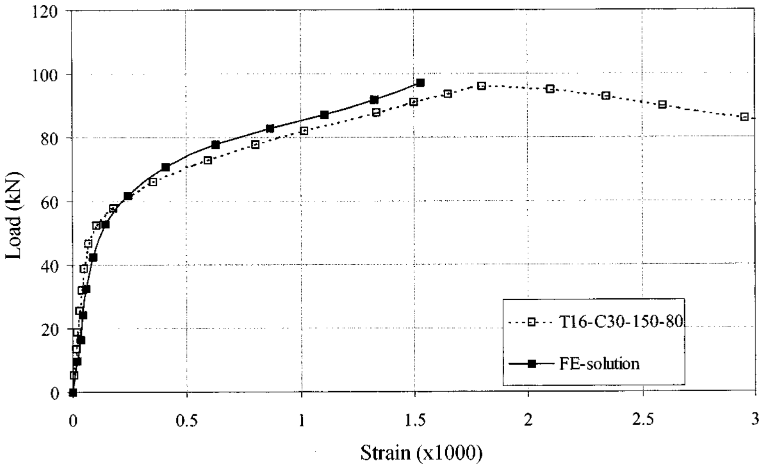


Fig. 10 Load vs. strain curves of transverse reinforcement for test T16-C30-150-80 and the FE-solution

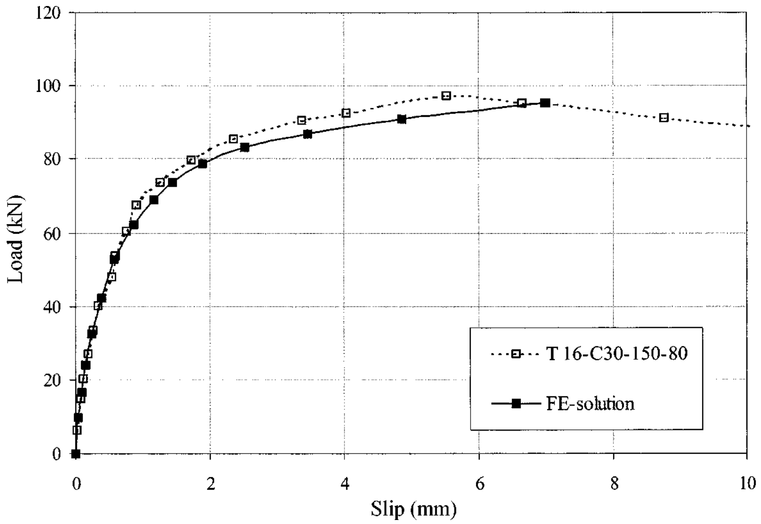


Fig. 11 Load vs. slip curves for the push-off test T16-C30-150-80 and the FE-solution

5.3. Test T16-C30-200-80

Fig. 12 shows the load-slip behaviour of the stud for push-off test T16-C30-200-80 compared with the FE-solution. In this test, 200mm deep hollow core slabs were used in the test. The experimental failure load of 99.53 kN was recorded with slip of 5.93 mm compared with 97.4 kN with slip of 5.5 mm obtained from FE-solution. Once again, good agreement was obtained from the FE-solution and hence demonstrated the accuracy of the FE-model.

5.4. Test T16-C30-200-60

Push-off test with reduced insitu gap was used to compare with the FE-model. A comparison between

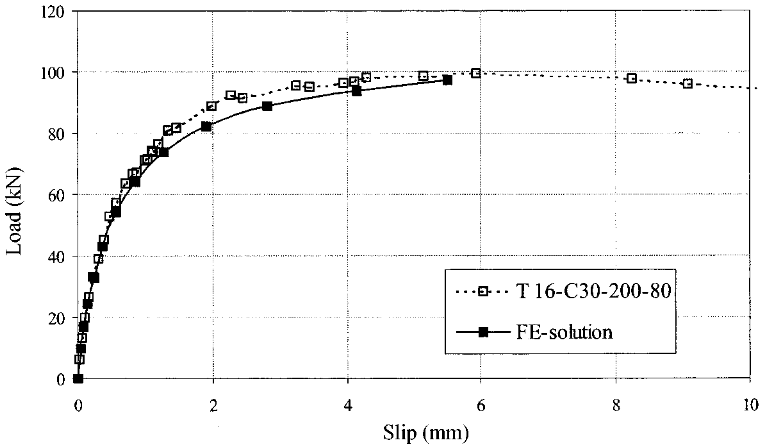


Fig. 12 Load vs. slip curves for push-off test T16-C30-200-80 and the FE-solution

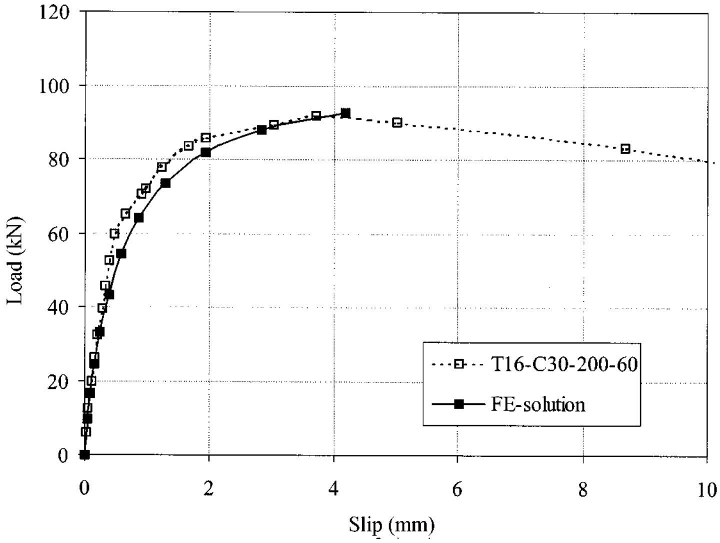


Fig. 13 Load vs. slip curves for push-off test T16-C30-200-60 and the FE-solution

the load-slip curves obtained from both FE-solution and experimental results are showed in Fig. 13. The experimental failure load recorded was 91.78 kN per studs with slip of 3.71 mm compared with 92.72 kN at a slip of 4.18 mm from FE analysis. A reduction in shear capacity was recorded due to the reduction of insitu gap width, which once again demonstrated by the FE-solution. The load-slip ductility was reduced due to the reduction of the insitu infill, which was observed in the test. Once again, the FE-model has been able to predict the mode of failure due to failure of the insitu concrete that led to reduction of the shear capacity of the headed shear stud.

6. Parametric studies

Parametric studies were carried out using the present finite element model. The effects of variations

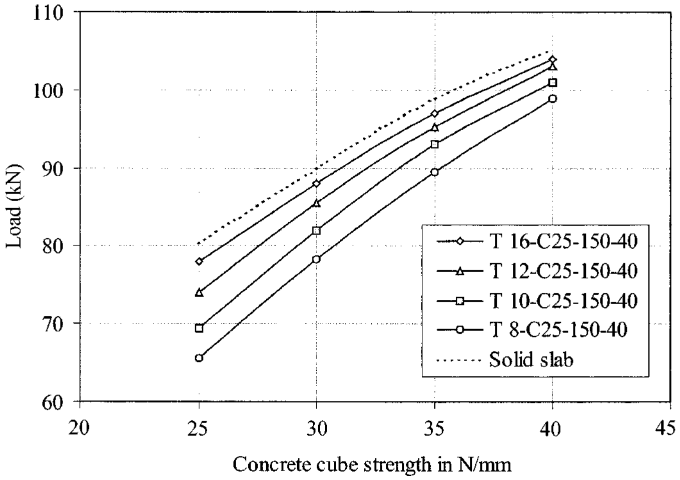


Fig. 14 Effect of T_r change on load per stud vs. in-situ concrete cube strength

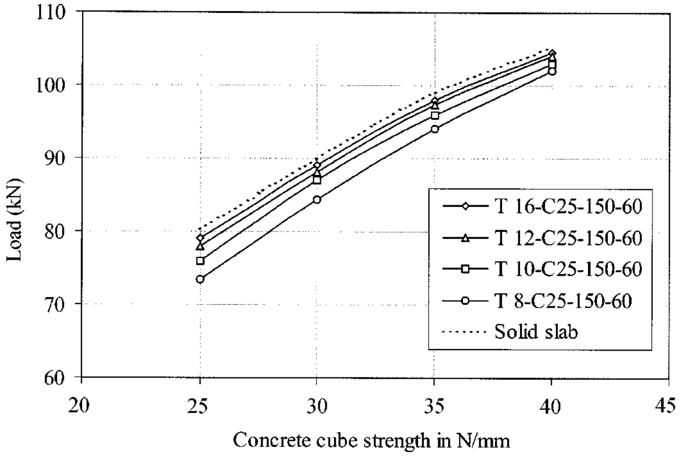


Fig. 15 Effect of T_r change on load per stud vs. in-situ concrete strength

in percentages of transverse reinforcement, in-situ concrete strength and gap size between hollow core slabs on the shear connection capacity were investigated. Figs. 14, 15 and 16 show the shear stud capacity versus in-situ concrete strength with specimens having different gap width of 40, 60, and 80 mm respectively. For each specimen, the shear stud capacity was obtained using different transverse reinforcement sizes 8, 10, 12, and 16 mm. Fig. 17 shows the load-slip curve of the stud for specimen having a gap size of 40 mm and different reinforcement bars with in-situ concrete strength of 25 N/mm^2.

Figures from 18 to 21 show the shear stud capacity versus in situ concrete strength with specimens having different transverse reinforcement diameters 8, 10, 12, and 16 mm respectively. For each specimen the shear stud capacity was obtained using different gap sizes between precast hollow-cored units 40, 60, and 80 mm.

Fig. 22 shows the load-slip curve of the stud for specimen having transverse reinforcement diameter

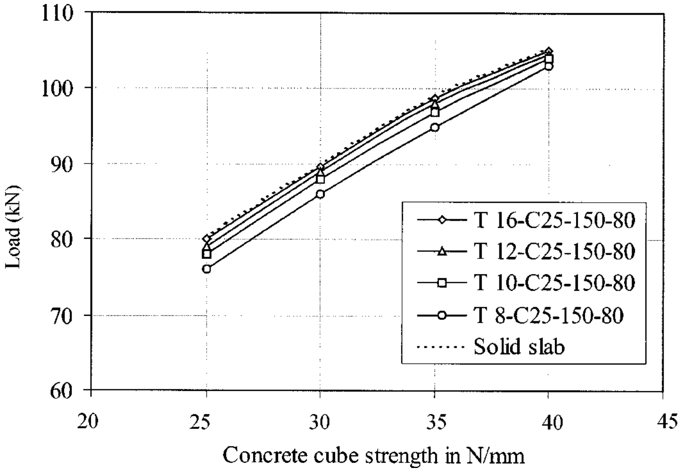


Fig. 16 Effect of T_r change on load per stud vs. in-situ concrete cube strength

of 8mm and different gap sizes using in situ concrete cube strength of 25 N/mm^2.

Figs. 23 and 24 show the load-slip curves of the stud at different in situ concrete cube strengths by using certain gap 40 mm and different reinforcement diameters 8 mm, 10 mm, 12 mm and 16 mm respectively.

6.1. Effect of transverse reinforcement

Fig. 14 shows the relationship between the failure load per stud and the in situ concrete cube strength. The curves are obtained for a gap width, g of 40 mm and using different transverse reinforcement, T_r. It can be seen that the shear stud capacity is increased with the increase in transverse reinforcement. This is because the transverse reinforcing bars enhance the in-plane shear resistance of the composite slab by crossing the precast and the in situ concrete interface. By increasing the bar cross-section area, the assistance of the precast concrete to the in situ concrete increases in resisting transverse forces from shear connectors. When the reinforcing bar reaches yield stress, the concrete around the stud fails leading to earlier failure of connection. This is because the presence of the transverse bar controls the longitudinal splitting of the slabs by carrying tensile splitting forces. The use of 16mm diameter in this test specimen provides shear capacity for the connection close to that one of adequately reinforced solid slab of the same strength as the in situ concrete and has the same depth. In another meaning if a small gap is used in the precast slabs specimen, the bar diameter should be increased to obtain shear stud capacity close to that one of solid RC slab. Also, it can be seen that effect of the reinforcement size decreases with the increase of in-situ concrete strength.

The same curves between the load per stud and the concrete cube strength are obtained in Figs. 15 and 16 for '*g*' equals 60 and 80 mm respectively. It can be seen from figure 15 that the increase in the gap size, the decrease in the effect of the reinforcement bar on the shear stud capacity. Also, it can be noticed that the curves obtained for the bar diameters 12 and 16 mm are close. This means that, for a gap of 60 mm, the required reinforcement diameter that provides approximately the same stud capacity in solid slab specimen may be reduced to 12 mm. Also, Fig. 16 shows that for a gap 80 mm, the effect of change in transverse reinforcement size on the shear stud capacity is reduced. The authors

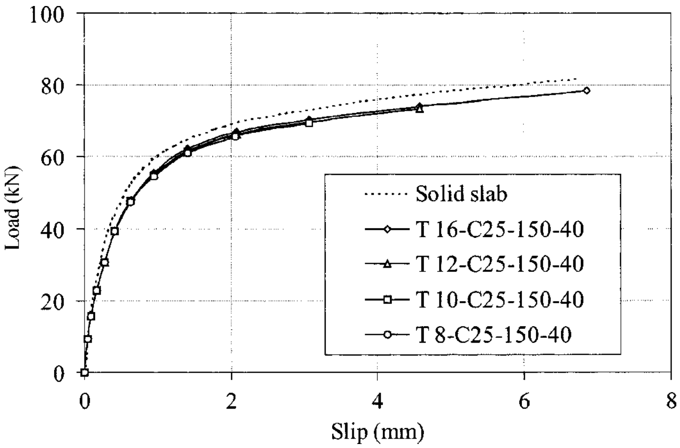


Fig. 17 Effect of T_r change on the load-slip curve

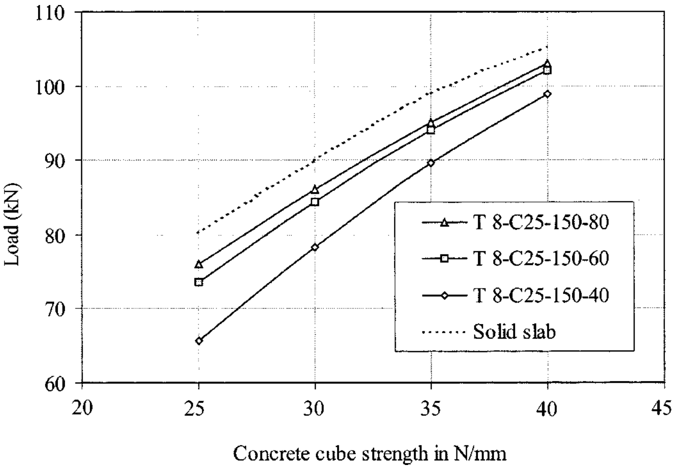


Fig. 18 Effect of '*g*' change on load per stud vs. in-situ concrete cube strength

recommend that a gap of 80 mm will provide a good interaction between the precast and cast concrete with a small reinforcement ratio. The shear stud capacity will be closed to that obtained from the solid concrete slabs with the same insitu concrete strength.

Fig. 17 shows the load-slip curve of the stud for a gap width of 40 mm. The curves are obtained using different bar diameters with in-situ concrete strength of 25 N/mm^2. It can be seen that the change in the transverse reinforcement has no significant effect on the shear capacity of the connection, but it affects the load-slip behaviour of the stud and hence the ductility.

6.2. Effect of gap width

Fig. 18 shows the failure load per stud versus in situ concrete cube strength for a precast composite specimen using T_r equals to 8 mm and different gap width. It can be seen that the shear stud capacity is increased with the increase in gap size for the same reinforcement bar diameter. This is attributed to the increase of stresses in the in situ concrete for smaller gap sizes. This leads to crushing of concrete

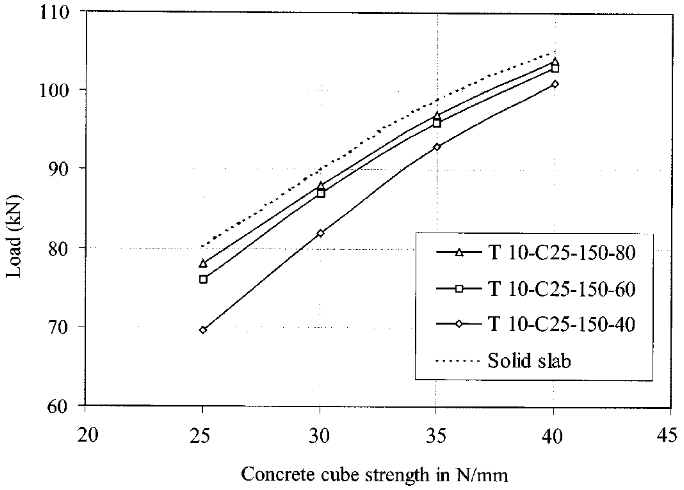


Fig. 19 Effect of '*g*' change on load per stud vs. in-situ concrete cube strength

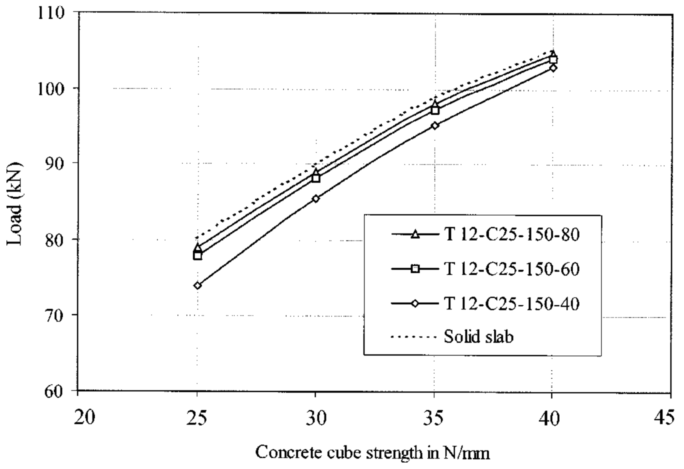


Fig. 20 Effect of '*g*' change on load per stud vs. in-situ concrete cube strength

around the stud. Also it can be seen that for gaps 60 and 80 mm, the shear stud capacities are close using the same 8 mm bar. This means that the increase in the gap size leads to reducing the effect of reinforcement size and this effect is clear in smaller gap sizes.

The same curves between the failure load per stud and concrete cube strength are obtained in Figs. 19, 20 and 21 using T_r of 10, 12, and 16 mm respectively. It can be seen from Figs. 19 and 20 that the increase in transverse reinforcement reduced the effect of gap size change on the shear stud capacity. Also it can be noticed that the difference between the obtained curves at 60 and 80 mm is decreased by the increase in reinforcing bar diameter. Fig. 21 shows that for specimen with 16 mm bar diameter, the effect of change in gap width on the shear stud capacity is not at all significant.

Fig. 22 shows the load-slip curve of the headed stud with 8 mm transverse reinforcement. The curves are obtained using different gap width and in-situ concrete strength of 25 N/mm^2. It can be seen that the

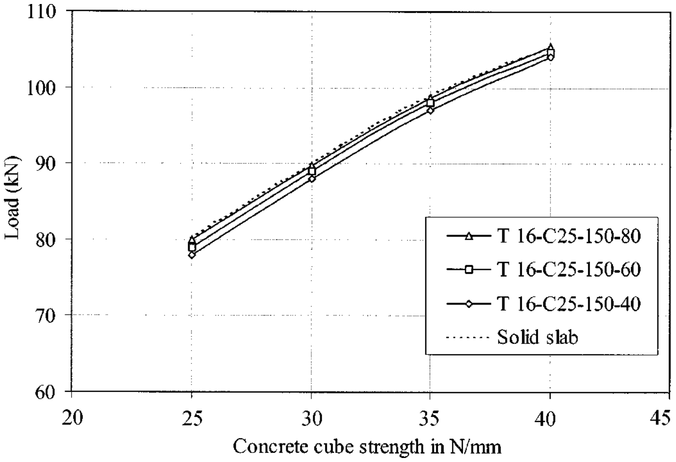


Fig. 21 Effect of '*g*' change on load per stud vs. in-situ concrete cube strength

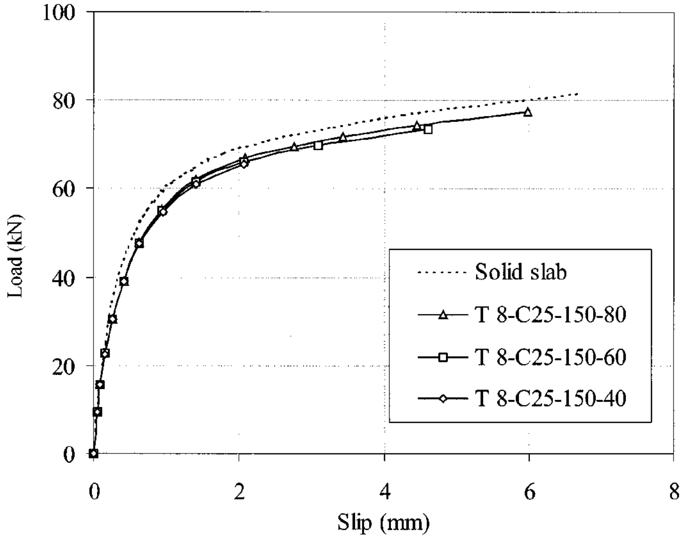


Fig. 22 Effect of '*g*' change on the load-slip curve

change in the transverse gap width has no significant effect on the shear capacity of the connection. It affects only the load-slip behaviour.

6.3. Effect of strength of in-situ in-fill

Figs. from 23 to 26 show the load-slip curves of the stud using different in-situ concrete strengths for gap width equal to 40 mm and reinforcing bars of 8, 10, 12 and 16mm respectively. It can be seen that both the load-slip behaviour and the shear stud capacity are affected remarkably by the change in the in situ concrete strength. The shear stud capacity and the stiffness of the stud are increased with the increase of in-situ concrete strength.

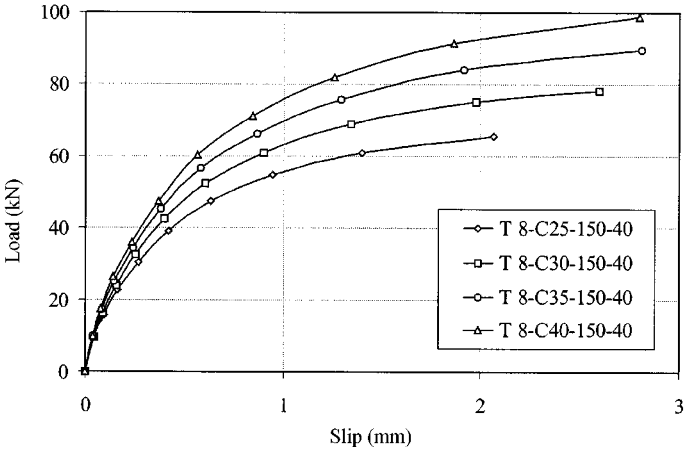


Fig. 23 Effect of in-situ concrete strength change on the load-slip curve

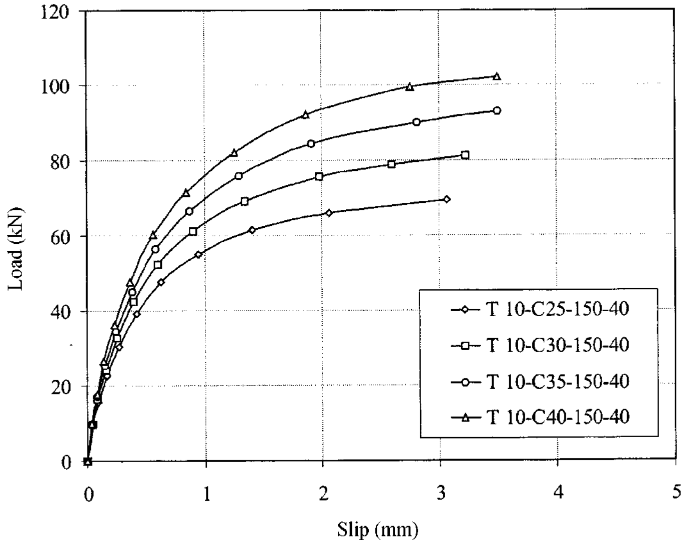


Fig. 24 Effect of in-situ concrete strength change on the load-slip curve

Table 1 summarises parametric studies of the 19 mm diameter ×100 mm height headed stud in push-off tests with 150 mm precast hollow core slabs

7. Three studs model

To investigate the load distribution of studs during push-off test, a three studs model is created to compare with the one stud model described earlier. Figs. 27(a) and (b) show the finite element mesh used to represent the three studs steel-precast concrete push-off test specimen. This specimen consisted of two 600 mm width ×150 mm deep hollow core units. These units are attached to the flange of the

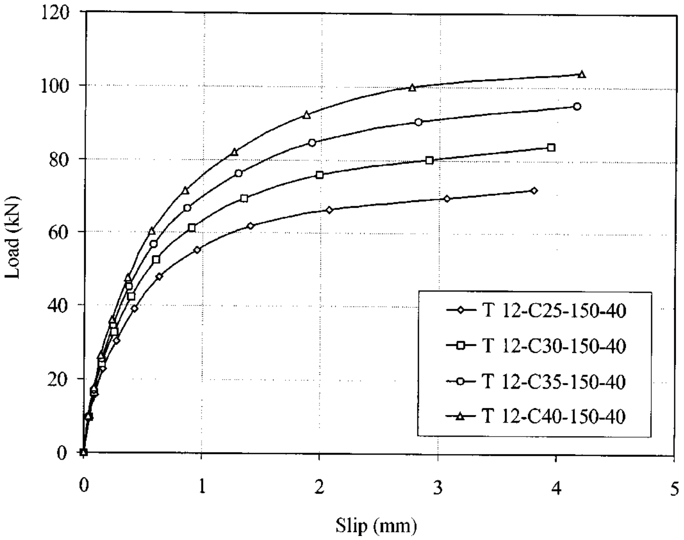


Fig. 25 Effect of in-situ concrete strength change on the load-slip curve

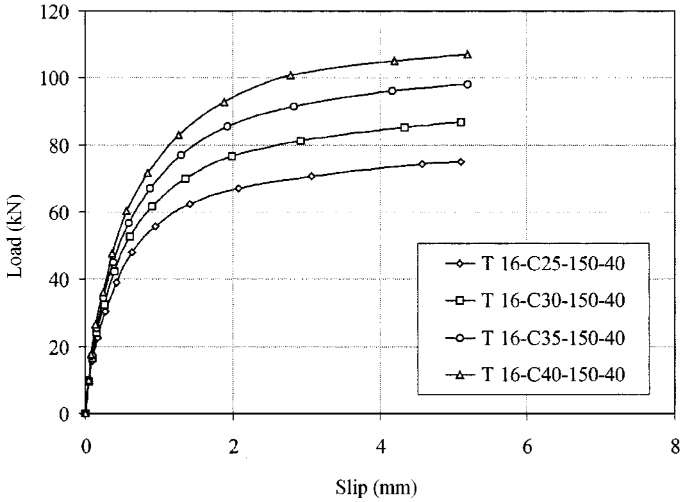


Fig. 26 Effect of in-situ concrete strength change on the load-slip curve

steel beam that has three 19mm diameter ×100 mm headed studs and 150mm between each other. One transverse reinforcement bar is placed in each 500 mm slot and filled with cast in-situ concrete to make up the composite slab. The same element type and procedures used in modelling the one stud model are used in modelling three studs model.

The material properties of the precast hollow-cored concrete, cast in-situ concrete, studs, steel beam, and reinforcement are represented as the one stud model mentioned earlier. The boundary conditions and load used were exactly the same as the one used for the one stud model. Fig. 28 shows the boundary condition of the three studs model.

Table 1 Ultimate shear capacity (kN) of headed studs in push-off tests with precast hollow core slabs

Gap width g (mm)	Bar size T_r (mm)	In-situ concrete cube strength (N/mm^2)			
		C25	C30	C35	C40
40	8	66	78	90	99
	10	70	82	93	101
	12	74	85	95	103
	16	78	88	97	104
60	8	74	84	94	102
	10	76	87	96	103
	12	78	88	97	104
	16	79	90	98	105
80	8	76	86	95	103
	10	78	88	97	104
	12	79	89	98	105
	16	80	90	99	105

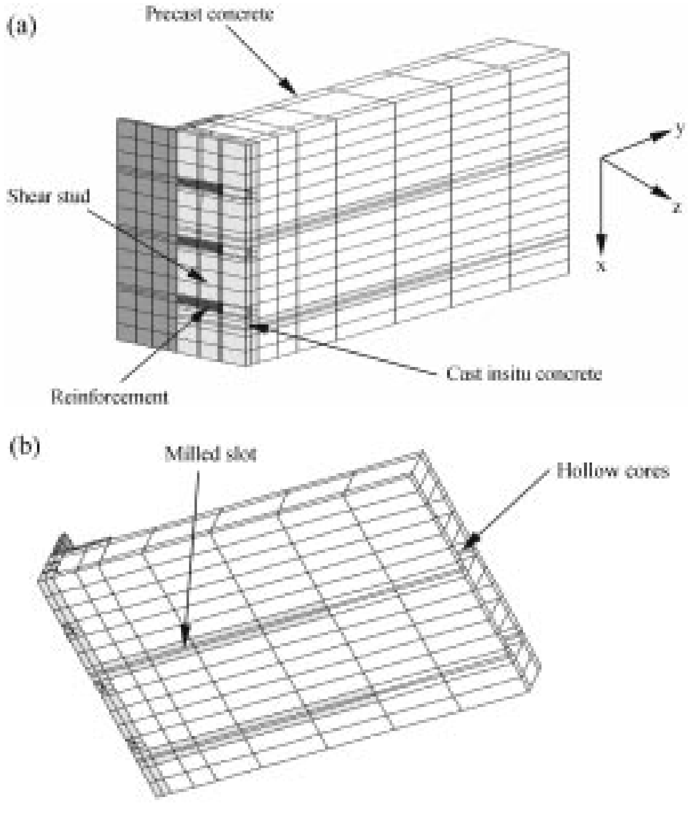


Fig. 27 (a) Finite element mesh of the model. (b) Finite element mesh of the model

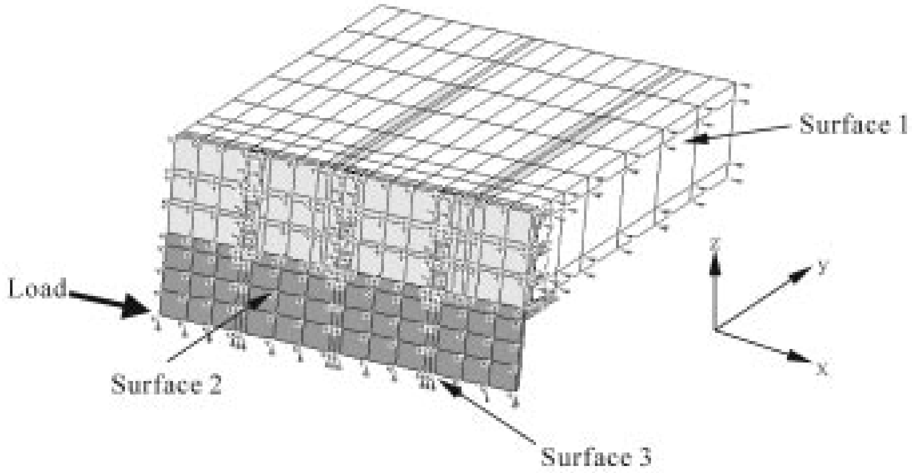


Fig. 28 Application of load and boundary conditions

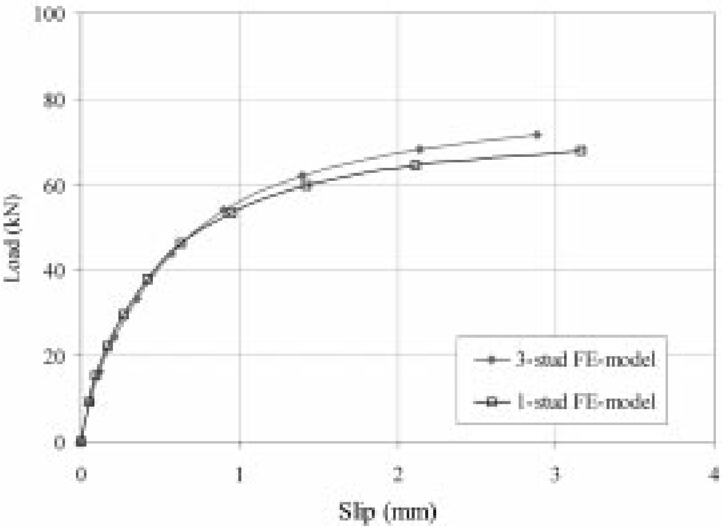
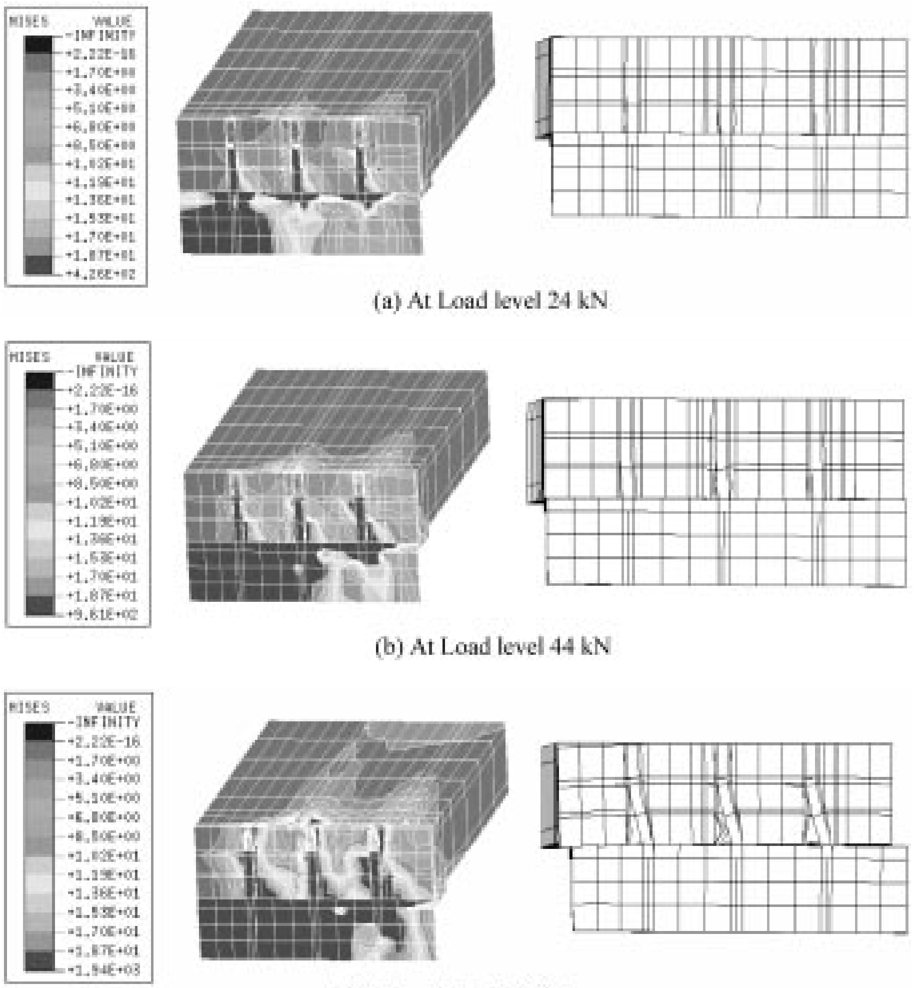


Fig. 29 Load-slip curves of push-off test T10-C25-150-65

8. Comparison between one stud and three studs models

Fig. 29 shows a comparison between the load-slip curves of the headed stud between the one stud and the three studs models. The shear capacity of the headed stud in the one stud model is 68 kN compared with 71 kN per stud of that in the three studs model. The difference in shear capacity between the two models is only 4% with the higher shear stud capacity recorded from the three studs model. This is expected since the redistribution of stress among the studs after yielding allowed the studs to carry a slightly higher load and hence the increases in shear capacity. The same load-slip characteristic is obtained up to about 80% of the stud capacity, after which a slightly larger slip is observed in the one stud model.



(a) At Load level 24 kN

(b) At Load level 44 kN

(c) At Load level 72 kN

Fig. 30 Contour stresses and displaced shape for T10-C25-150-65

Fig. 30 shows the Von Mises stresses contour and displaced shape of the three studs model at different load levels. These indicated that the assumption of equal distribution of horizontal shear force is correct as both the contour and deformed shape indicated that the load is evenly distributed.

9. Conclusions

This paper described the three-dimensional finite element model of headed shear stud in composite beams with hollow core slabs. A general finite element program ABAQUS was used for the analysis. The FE-model took into account of the linear and non-linear behaviour of all the material properties and the FE-solutions obtained were compared with results from experimental push-off tests.

Three studs model was constructed to compare with the one stud model to evaluate the effect of load distribution among the studs. Result from the Von Mises stresses contour and displaced shape showed that horizontal shear force was equally distributed to all studs at failure; therefore one stud model was adopted.

Experimental push-off tests with various parameters such as reinforcement ratio, slab thickness and insitu infill gap were used to evaluate the FE-model. The FE-model demonstrates excellent correlation with the push-off test results and is effective in predicting the various modes of failure that observed in the experimental tests. Therefore, it is concluded that the FE-model could be confidently used for further parametric study.

Parametric studies showing the effect of the change in transverse gap size, transverse reinforcement diameter and in-situ concrete strength on the connection capacity were presented. It is found that:

1. The shear stud capacity increased with the increases in gap width between hollow core slabs with transverse reinforcement less than 16 mm. This increase is obtained for gap width up to 80 mm. For gap width greater or equal to 80 mm, there is no effect on the shear capacity and it may be taken as solid slab that has the same thickness and strength of the in-situ infill.
2. The shear capacity is increased with the increases in transverse reinforcement with gap width less than 80 mm. This increase is obtained for reinforcement up to 16 mm. For bar sizes higher or equal to 16mm, there is no effect on the shear capacity and it may be taken as the similar solid slab one that has the same thickness and strength of the in-situ infill.
3. Both of the increases in bar sizes and gap width has no significant effect on the shear stud capacity but it does affect the load-slip behaviour and is very important if the beam is designed for partial shear connection.
4. The in-situ concrete strength has a remarkable effect on the shear stud capacity and load-slip behaviour for any precast hollow-cored push-off specimen.

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