11. FE MODELLING OF SHEAR CONNECTION

11.1 INTRODUCTION TO FEM

Many researchers have carried out experimental and numerical studies to investigate the behavior of headed stud in composite beam. Oehlers [95] investigated the cracking mode around the shear connector and stated three distinct mode of cracking. Experimental studies carried out by Johnson [90] indicated that the concrete strength influences the mode of failure of shear connection between steel and concrete as well as failure load. Li and Krister [104] studied the behavior of headed studs in high strength and normal strength concrete. They found that the compressive strength of concrete significantly affects the load-slip behavior and shear connector capacity. Lam and Elliott [105] mentioned that the load–slip curve and shear capacity of headed stud are currently obtained from experimental push-off test. Although the push-off test provides a clear insight in to the behavior of these connectors, the tests are relatively time consuming and expensive. Hence analytical models are required for the analysis.

Over the years, the finite element technique has been so well established that today it is considered as one of the best methods for solving a wide variety of practical problems efficiently. There are many finite element based computer programs, which are widely used in practically all branches of engineering for the analysis of structures, solids and fluids. As such, techniques related to modelling and simulation in a rapid and effective way play an increasingly important role in building advanced engineering systems.

Following are the basic steps of finite element analysis [106]:

1. Discretize the body
2. Approximate the behaviour of each element
3. Calculate element properties
4. Assemble element properties

5. Apply boundary conditions
6. Solve for unknown nodal displacements
7. Calculate strains and stresses
8. Interpret the results

Figure 11.1 shows the sequence of processing the information in finite element analysis.

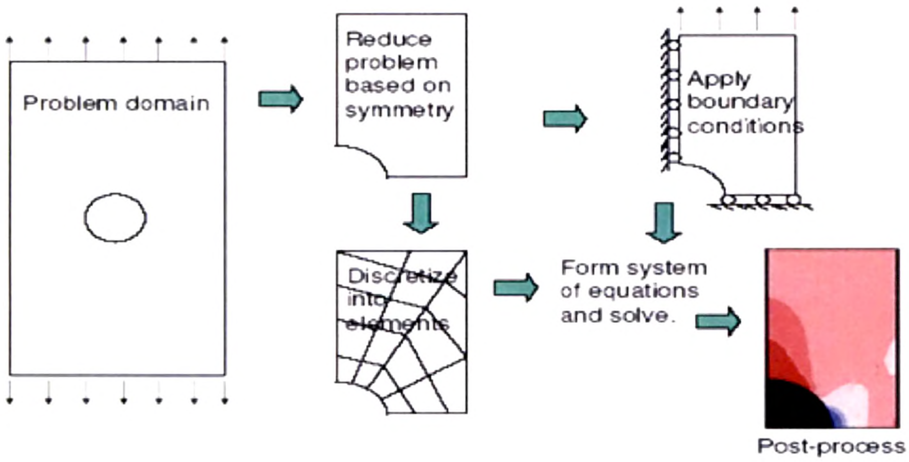
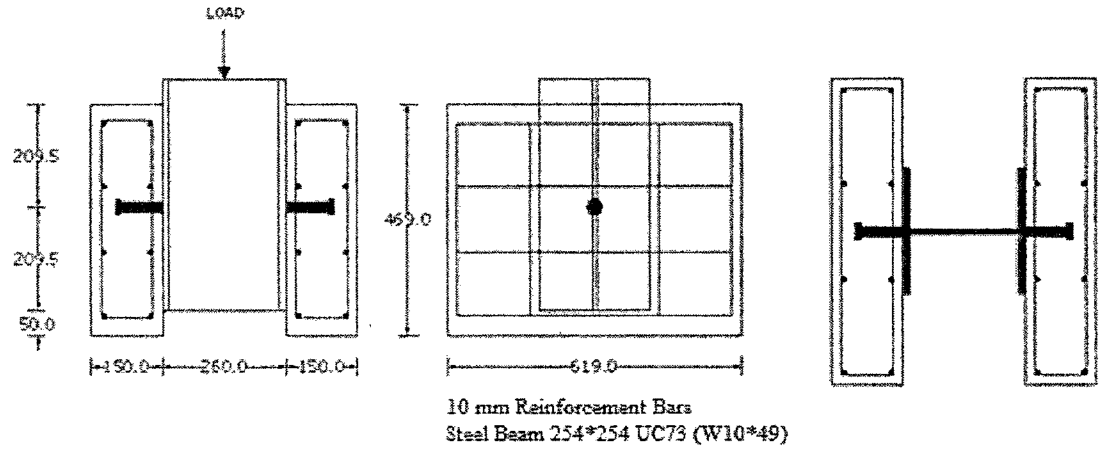


Fig. 11.1 Illustrative Example of FEA

11.2 DESCRIPTION OF PUSH-OUT TEST

The property of a shear connector most relevant to design is the relationship between the shear force transmitted and the slip at the interface. This load-slip curve should ideally be found from test on composite beams, but in practice a simpler specimen is necessary. The most common way used to evaluate shear stud strength and behaviour is push-out test. In this test the flanges of a short length of I-beam are connected to two small concrete slabs. The details of standard push out test are shown in **Fig. 11.2.**

The slab is bedded onto the lower platen of a compression testing machine and load is applied to the upper end of the steel section. Slip between steel member and two slabs is measured at several points, and the average slip is plotted against the load per connector. In practice, the designers normally specify shear connector for which the strength have already been established, for it is an expensive matter to carry out sufficient test to determine designer strength for a new type of connector. The test has to be carried out for a range of concrete strength, because the strength of concrete influences the mode of failure as well as the failure load. The fact that either concrete crushing or steel yield may occur means that for design the connector must be checked for both failure modes.



(a) Front Elevation (b) Side Elevation (c) Plan

Fig. 11.2 Details of Push out Test Setup [7]

Specimen for push out test is prepared as follows:

- Each concrete slab should be cast in the horizontal position, as it is done for composite beam in practice.
- Bond at the interface between flanges of the steel beam and the concrete should be prevented by greasing the flange or by other suitable means.
- The specimens should be air-cured.
- For each mix a minimum of four concrete specimens for the determination of the cylinder strength should be prepared at the time of casting the push-out specimens. The concrete strength should be taken as the mean value.

Figure 11.3 shows trend of some of the results of "**push-out**" tests on different shear connectors. The brittle connectors reach their peak resistance with relatively small slip and then fail suddenly, but the ductile connectors maintain their shear carrying capacity over large displacements. Based on the load slip curve two important parameters can be obtained - the plastic plateau and the connector stiffness k. While ultimate strength analysis is based on plastic behaviour of shear connectors, the 'k' value is required for serviceability analysis and to find slip strain and stresses at partial interaction. In the ultimate analysis it is assumed that concrete slab, steel beam and the dowel are fully stressed, which is known as "rigid plastic" condition. In this condition the flexural strength of the section is determined from equilibrium equation [90].

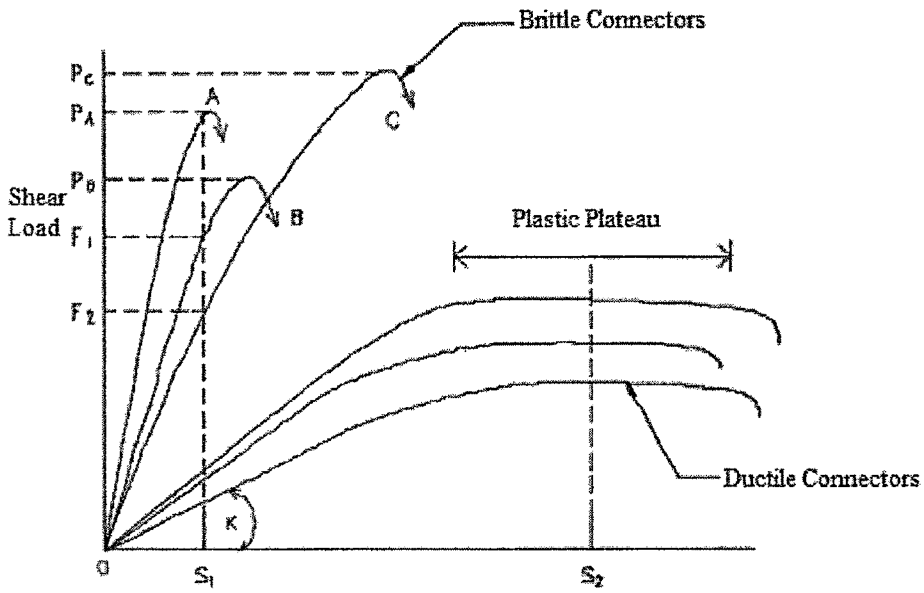


Fig. 11.3 Load-Slip Characteristics of Shear Connector

The load-slip relationship is influenced by many variables, including:

- Number of connectors in the test specimen,
- Mean longitudinal stress in the concrete slab surrounding the connectors,
- Size, arrangement and strength of slab reinforcement in the vicinity of the connectors,
- Thickness of concrete surrounding the connectors,
- Freedom of the base of each slab to move laterally, and so to impose uplift forces on the connectors,
- Bond at the steel-concrete interface,
- Strength of the concrete slab, and
- Degree of compaction of the concrete surrounding the base of each connector.

11.3 DESIGN STRENGTH OF SHEAR CONNECTORS

The design strength of some commonly used shear connectors as per IS: 11384-1985 [1] for Fe 540-HT connector material is given in **Table 11.1.**

Generally shear connectors are uniformly spaced. The spacing of connectors should not be greater than four times the slab thickness or greater than 600 mm. The distance between the edge of the connector and the edge of the plate or flange to which it is connected shall not be less than 25 mm.

Table 11.1 Design Strength of Shear Connectors for Different Concrete Strengths

Type of Connectors		Design Strength of Connectors (Load per stud (P_c) in, kN)		
Headed stud		**Concrete Grade**		
Diameter in mm	Height in mm	M-20	M-30	M-40
25	100	86	101	113
22	100	70	85	94
20	100	57	68	75
20	75	49	58	64
16	75	47	49	54
12	62	23	28	31

P_{Rd_1} and P_{Rd_2} represent respectively the shear failure of the stud and the local concrete crushing around the shear connector.

$$P_{Rd_1} = \frac{0.8 f_u (\frac{\pi d^2}{4})}{\gamma_v} \quad \text{... (11.1)}$$

$$P_{Rd_2} = \frac{0.29 d^2 ((f_{ck})_{cy} E_{cm})^{1/2}}{\gamma_v} \quad \text{... (11.2)}$$

where, f_u = ultimate tensile strength of steel *($\leq$ 500 N/mm^2)*, $(f_{ck})_{cy}$ = cylinder strength of concrete, E_{cm} = mean secant (elastic) modulus of concrete, γ_v = partial safety factor for stud connector = *1.25,* and d = diameter of shear connector.

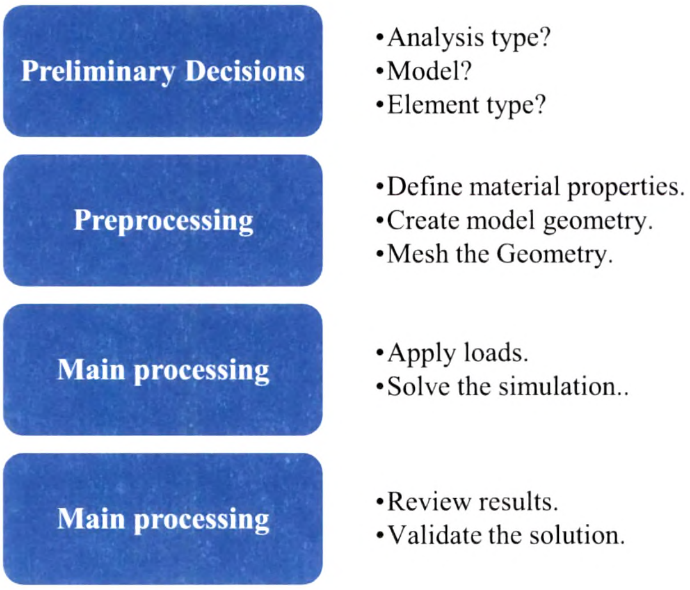
Equation (11.1) is based on shear failure of the stud whereas Eq. (11.2) is based on local concrete crushing around the shear connector. The lower of the above two values governs the design [7].

11.4 ANSYS As An Analysis Package

ANSYS is a general-purpose Finite Element Analysis (FEA) software package. The software implements equations that govern the behaviour of the elements and solves them all; creating a comprehensive explanation of how the system acts as a whole. These results then can be presented in tabulated or graphical forms. This type of analysis is typically used for the design and optimization of a system far too complex to analyze by hand. ANSYS software enables engineers to perform the following tasks:

- Building computer models or transfer CAD models of structures.
- Apply operating loads or other design performance conditions.
- Study physical responses, such as stress levels, temperature distributions etc.

The ANSYS has many finite element analysis capabilities, ranging from a simple, linear, static analysis to a complex, nonlinear, transient dynamic analysis, which is used by engineers worldwide in virtually all the fields of engineering [98]. Analysis procedure in ANSYS is as follows:



11.5 FE Modelling of Push-Out test With Solid Slab

11.5.1 Geometry Modelling

Successful use of finite element method in many studies involving complex structures or interactions among the structural members has been one of the motivations for applying this method in the present study. It has ability to accurately model the different materials and interaction of each part of the system. In preliminary development of FE model several materials properties, particularly the concrete cracking parameters and non-linearity of steel were tried to determine a suitable combination that produce acceptable results. Proper representation of the various components of the push out test is necessary for the successful behavior of the model. Lam and El-Lobody [76] used three dimensional eight-node element (C3D8), three dimensional fifteen-noded element (C3D15) and three dimensional twenty-noded element (C3D20) for modelling a push-out test as shown in **Fig. 11.4.**

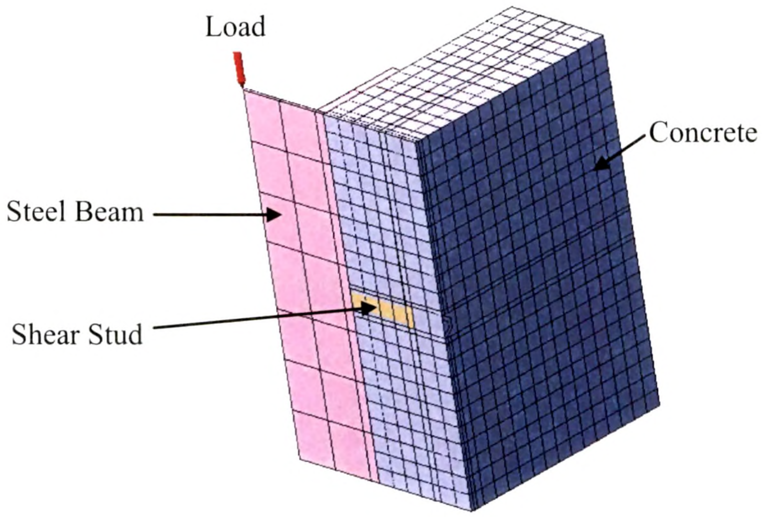


Fig. 11.4 Three Dimensional Model of Push-Out Test

As three dimensional modelling and analysis are very rigorous and time consuming, the push out test is idealized here as a two dimensional model considering nonlinearity and assuming it to be a plane strain analysis problem. ANSYS software is used to investigate the behavior of shear connection in composite beams with solid slabs.

Here Plane 183 element [107] is used for shear stud, steel beam and the concrete slab. The plane 183 is the higher order two dimensional element. Plane 183 has quadratic displacement variation behavior and well suited for modelling irregular meshes. This element is defined by 8 or 6 nodes having two degrees of freedom at each node i.e. translation in the nodal X- and Y- directions as shown in **Fig. 11.5**. The element may be used to discretize a plane stress or plane strain problem.

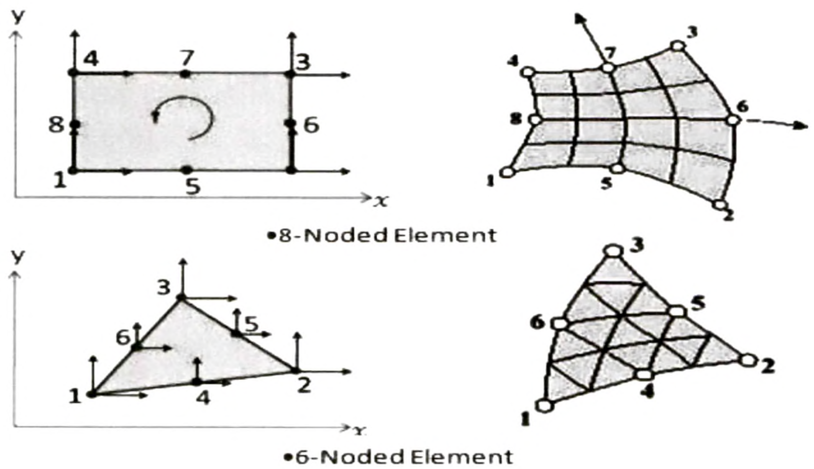


Fig. 11.5 Higher Order Two Dimensional Plane 183 Elements

The symmetry of the push-out test is taken into account, hence only half of the setup is modeled. The base of the concrete slab in the direction of loading is constrained. The steel beam is restricted in X-direction along the axis of symmetry.

The meshing as shown in **Fig. 11.6** is carried out which satisfies the limits and aspect ratio of the elements. The concrete slab is divided into 6 elements in X-direction and 18 elements in Y-direction. The shank of the stud has 3 elements in X-direction and 1 element in Y-direction. The head of the stud has 1 element in X-direction and 3 elements in Y-direction. The steel beam flange and web have 1 and 3 elements in X-direction respectively while they have total 18 elements [107].

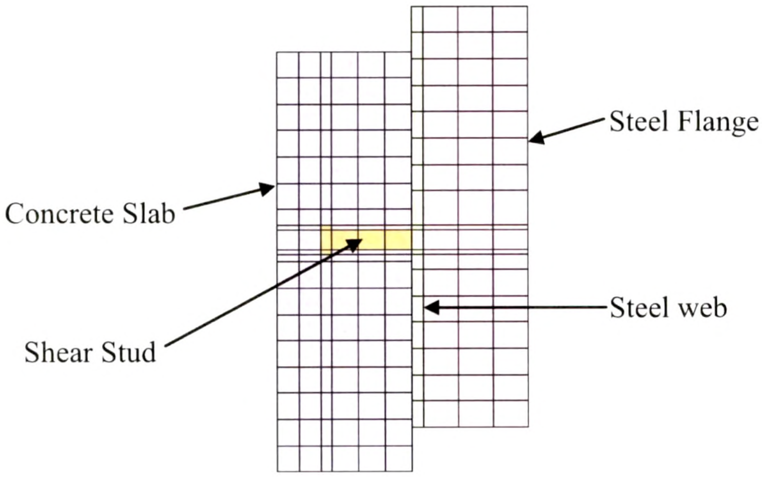


Fig. 11.6 Finite Element Mesh of 2D Model

11.5.2 MATERIAL MODELLING

Modelling of shear connection between steel and concrete requires successful representation of all the components associated with connection. The region around the stud is a region of severe and complex stresses. The shear forces are transferred across the steel-concrete interface by the mechanical action of shear connectors. The shear stud is modelled as a bilinear stress strain model. The stud material behaves as a linearly elastic material up to the yield point and then becomes completely plastic. The modulus of elasticity and yield stress considered are $E_s = 2 \text{ X } 10^5$ N/mm^2 and $f_{ys} = 470.8$ N/mm^2 respectively.

The stress-strain curve of the headed stud is shown in **Fig. 11.7** which is a simulated bi-linear stress-strain model with yield stress of 275 N/mm^2. The main function of steel beam is to allow the transmission of applied load to the connectors. It is considered that the effect of the steel beam is insignificant in a push-off test. Yahya and Kasim [67] studied the effects of concrete nonlinear modelling on the analysis of push out test by ANSYS. The material model suggested by them is used for simulating the concrete.

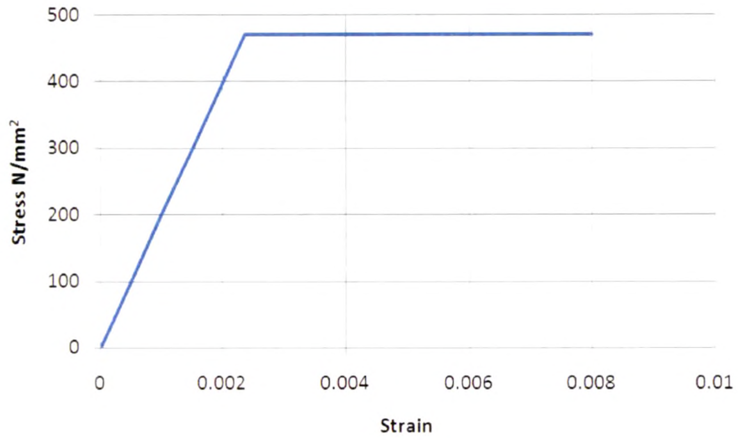


Fig. 11.7 Bilinear Stress-Strain Curve for Headed Stud Model

The uni-axial stress-strain relation simulating the compressive behaviour of concrete is used. The multi-linear isotropic material is considered, using the formula given below in Eq. (11.3) and Eq. (11.4).

For $0 < \varepsilon \leq \varepsilon_0$,

$$f_c = f'_c \left[2\left(\frac{\varepsilon}{\varepsilon_0}\right) - \left(\frac{\varepsilon}{\varepsilon_o}\right)^2 \right] \qquad \text{...(11.3)}$$

For $\varepsilon_o < \varepsilon \leq \varepsilon_{cu}$,

$$f_c = f'_c - 0.15f'_c \left[\frac{\varepsilon - \varepsilon_o}{\varepsilon_u - \varepsilon_o}\right] \qquad \text{...(11.4)}$$

where, f_c = stress in concrete, f_c' = peak stress in concrete, ε = strain in concrete, ε_0 = peak strain in concrete, and ε_{cu} = ultimate concrete strain.

11.5.3 Verification of FE Model

The comparison of results of two dimensional model is done with the results of three dimensional model and experimental results given by Lam and El-Lobody [76] in **Fig. 11.8.** The displacement contours obtained using 2D mode are as shown in **Fig. 11.9.**

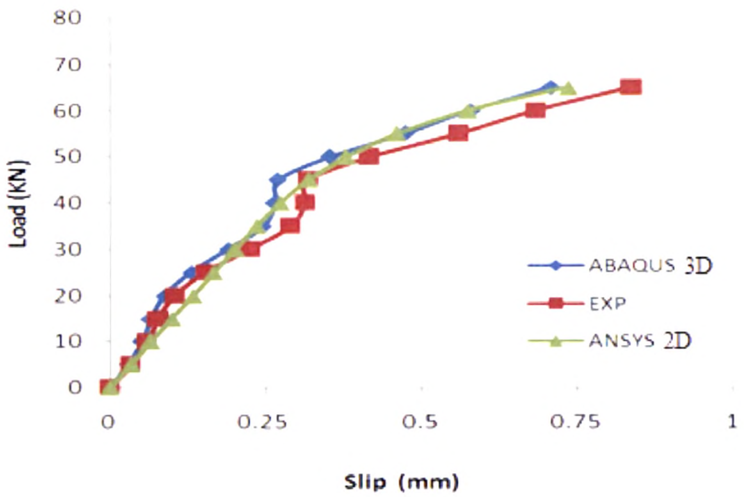


Fig. 11.8 Comparison between Experimental, 3D and 2D Model

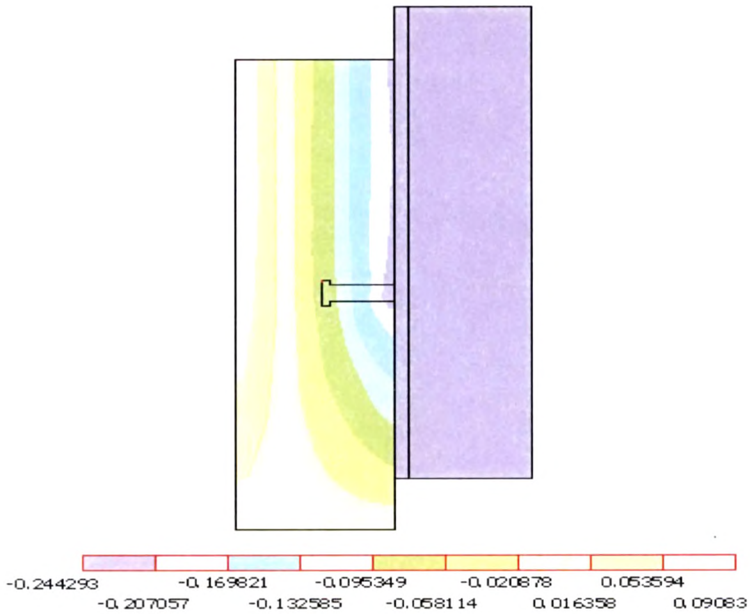


Fig. 11.9 Displacement Contour Plot (2D Model)

11.5.4 Parametric Study

The strength of connector and the concrete are the main factors affecting the behavior of shear connectors. To investigate the effect of the shear capacity of the headed stud with the variation in concrete strength and stud diameter, the parametric study is carried out for the different grades of concrete i.e. 25, 30, 35 and 40 N/mm^2 and the stud diameters as 13, 16, 19 and 22 mm. The results for 4 different size of studs are depicted in **Figs. 11.10, 11.11, 11.12** and **11.13** respectively. The results are compared with the characteristic resistance of the headed stud specified by EC4 [7].

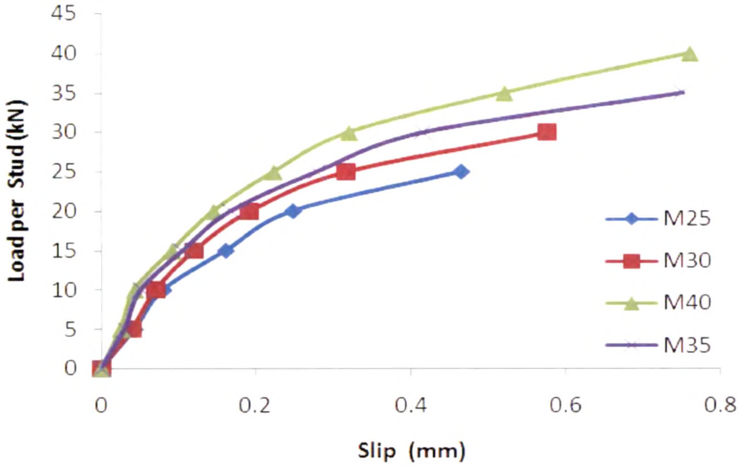


Fig. 11.10 Load-Slip Curve of 13 x 65 Headed Stud

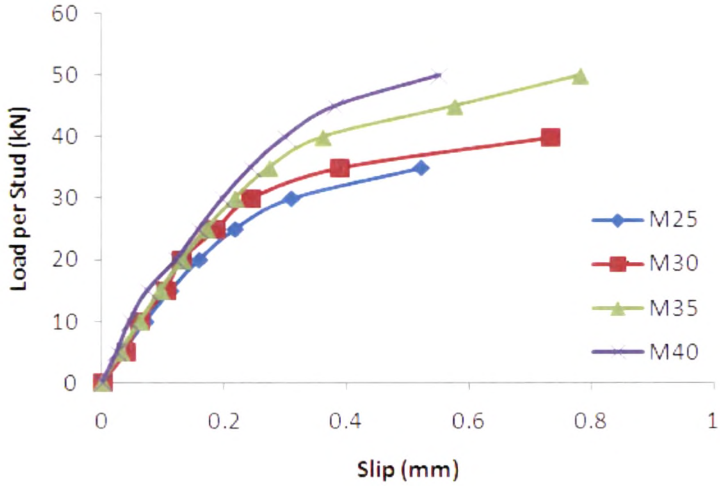


Fig. 11.11 Load-slip curve of 16 x 75 Headed Stud

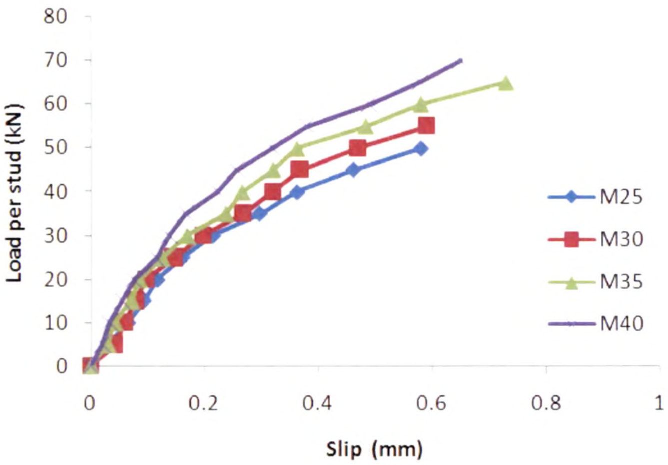


Fig. 11.12 Load-slip curve of 19 x 100 Headed Stud

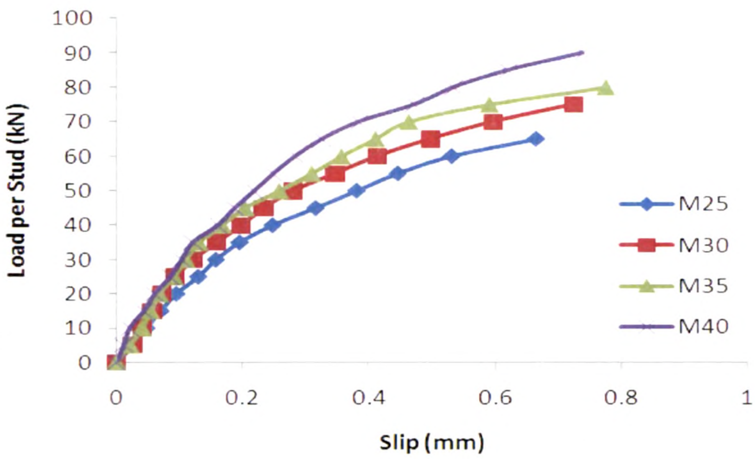


Fig. 11.13 Load-slip curve of 22 x 100 Headed Stud

11.5.5 Comparison of Resistance of Stud Results

The behavior of the stud in terms of load versus slip is required for the proper modelling and analysis of the composite beam and slab. The load versus slip values of the stud up to the ultimate resistance of stud connectors (P_R) are given by EC4 [7]. The values obtained for 16 mm headed stud using 2D FE model are compared in **Table 11.2** with those given in EC4.

Table 11.2 Comparison of Resistance of Stud Results

Diameter of Headed Stud (mm)	Concrete Compressive Strength (N/mm^2)	FE Model Results (kN)	Resistance of Shear Connection as per EC4 (kN)
16	25	35	33.85
16	30	40	38.82
16	35	45	45.70
16	40	50	48.17

11.6 FE Modelling of Push-Out test With Deck Slab

11.6.1 Finite Element Modelling

The behaviour of headed studs in composite beams with profiled steel sheeting depends on many factors including strength and dimensions of headed stud shear connectors, geometries and direction of profiled steel sheeting, reinforcement area and position, compressive strength of concrete and location of the stud within the ribs of the profiled steel sheeting. Usually to determine the capacity of shear connection and load-slip behavior of the shear connector push-out test are used.

Two models are developed as shown in **Figs. 11.14** and **11.15**. Model A represents the actual trapezoidal geometry of the profiled steel sheeting. It is suitable for investigating the behavior of headed studs through profiled steel sheeting with mild side slopes. In this case, the concrete within the ribs of the profiled steel sheeting can be modelled properly. Model B represents the trapezoidal shape of the rib by an equivalent rectangular shape. It is used to investigate the behavior of headed studs welded through profiled steel sheeting with stiff side slopes.

To investigate the behavior of headed studs in push-out tests conducted by Kim et al., [108] model A was used where as to investigate the behavior of headed studs in push-out tests conducted by Lloyd and Wright [17] model B was used. The circular cross-sectional area of the reinforcement is simulated by the equivalent rectangular cross-sectional area in the finite element modelling. It is assumed that the effect of separation of the profiled steel sheeting from the concrete slab at certain load level has little effect on the concrete slab. Hence, the nodes of the concrete elements are attached to the nodes of the profiled steel sheeting elements.

As per the observations made by Jayas and Hosian [109], the separation of the concrete behind the shear connector occurs at a low load level. Thus, the nodes behind the stud, in the direction of loading are detached from the surrounding concrete nodes with the other nodes of the stud connected with the surrounding concrete.

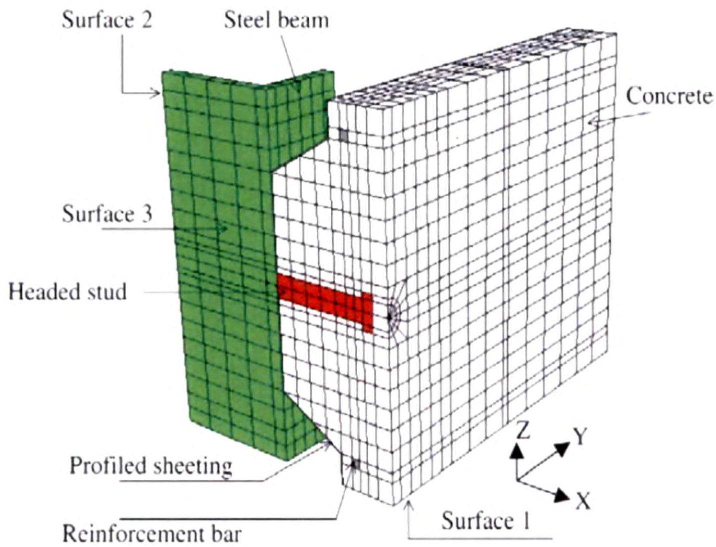


Fig. 11.14 Mesh of 'Model A' using 3D Elements

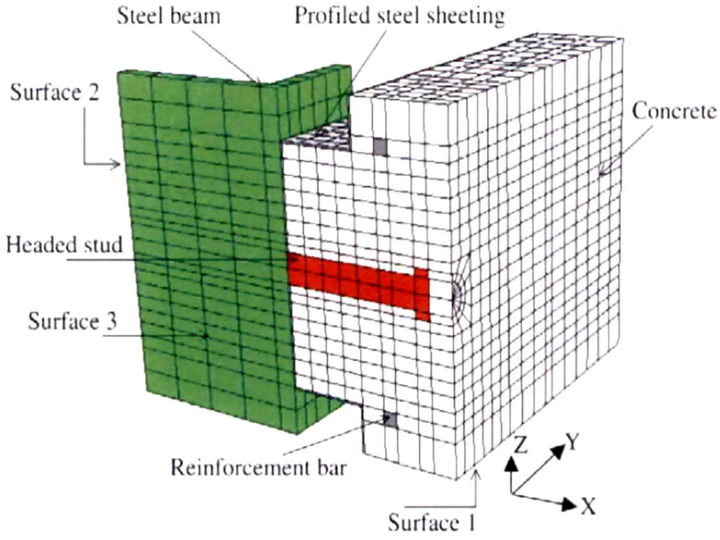


Fig. 11.15 Mesh of 'Model B' Using 3D Elements

Lam and El-Lobody developed three dimensional finite element model using ABAQUS to investigate the behaviour of shear connector in composite beams with profiled steel sheeting. They used three dimensional eight-noded element (C3D8), six-noded (C3D6) solid elements for meshing. The meshed model is as shown in **Figs. 11.14** and **11.15.**

Here, to investigate the behaviour of shear connection in composite beams with profiled steel sheeting the finite element program ANSYS is used. Modelling of shear connection between steel and concrete requires successful representation of all the components associated with the connection. The region around the stud is a region of severe and complex stresses. The shear forces are transferred across the steel-concrete interface by the mechanical action of shear connectors. The main components affecting the behavior of shear connection in composite beams with profiled steel sheeting are concrete slab, steel beam, profiled steel sheeting, reinforcement bars and shear connectors. Assuming that the load is transferred equally from the steel beam to each shear connector, modelling of only a single stud welded to each flange of the composite beam is carried out.

Here also Plane 183 element is used for modelling of shear stud, steel beam, concrete slab and profiled steel sheeting. It has plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities. The shear capacity obtained is independent of number of shear connectors used in the investigation and it can be obtained for different stud diameters by adjusting the finite element mesh. Due to symmetry only a quarter of the push-out test arrangement is modelled.

Finite element mesh for model A and model B using 2D elements is shown in **Fig. 11.6** and **Fig. 11.7** respectively. The meshing is carried out which satisfies the limits and aspect ratio of the elements. The shank of the stud has 8 elements in X-direction and 2 elements in Y-direction. The head of the stud has 1 element in X-direction and 4 elements in Y-direction. The steel beam flange and web have 1 and 9 elements in X-direction respectively while they have 26 elements in Y-direction. The reinforcing bar is meshed as a single element.

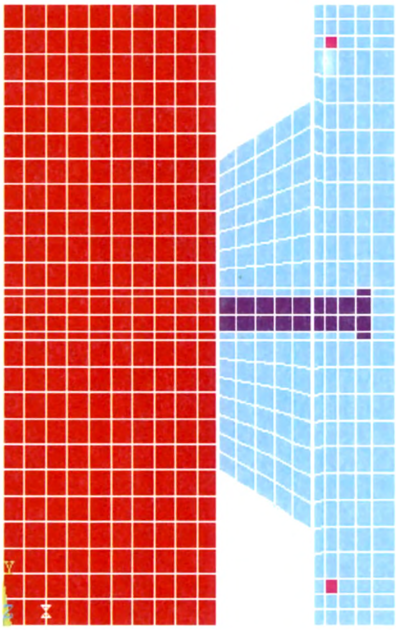


Fig. 11.16 2D FE Mesh of 'Model A'

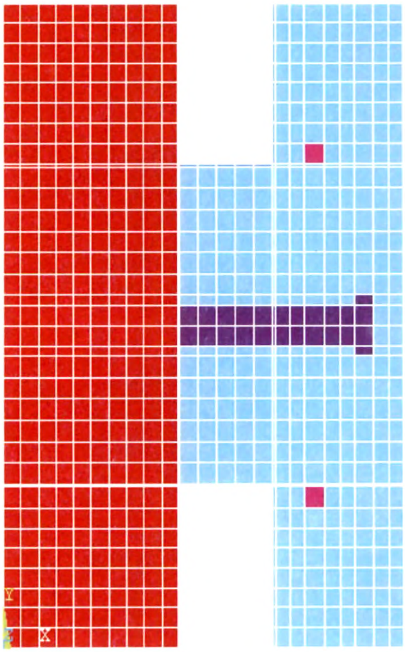


Fig. 11.17 2D FE Mesh of 'Model B'

All the nodes of the profile steel sheeting and the concrete slab in the opposite direction of loading are restricted from moving in the Y- direction to resist the applied compression load. When the slip becomes significant, the stud is subjected to tensile forces and simultaneously the stud deformations produce some uplift of the concrete slab in the surroundings of the stud foot, which may have an effect on the failure mode of the connection. To overcome this problem while modelling, the shear connection is loaded by applying longitudinal constant downward displacement to the steel flange so that there is slip between the concrete and the steel elements but there is no separation.

11.6.2 MATERIAL MODELLING

To model the nonlinear behavior of the concrete slab, the equivalent uniaxial representation for the stress-strain curve of concrete as shown in **Fig. 11.18** is used. This stress-strain curve is linearly elastic up to 30% of the maximum compressive strength. Above this point the curve increases gradually up to about 70-90% of the maximum compressive strength. Eventually it reaches the peak value which is the maximum compressive strength σ_{cu}. Immediately after the peak value, this stress-strain curve descends because of material softening. After the curve descends, crushing failure occurs at an ultimate strain ε_{cu}. A numerical expression was developed by Hognestad which treats the ascending part as a parabola and descending part as a straight line. For numerical expressions, see Eqs. (11.3) and (11.4).

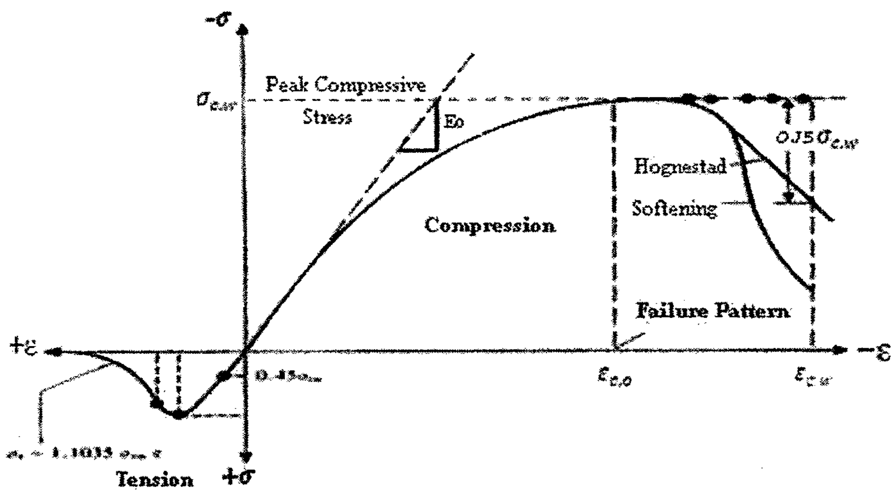


Fig. 11.18 Typical Uniaxial Stress-Strain Curve for Concrete

For, material modelling of headed shear stud here, bilinear stress and strain model, explained earlier in clause 11.5.2, is used.

The steel beam and profiled steel sheeting are modeled using bilinear stress-strain curve with yield stresses of 288 MPa and 308 MPa and initial Young's modulus of 189 GPa and 184 GPa, respectively. The reinforcement bars are also modeled as a bilinear stress-strain curve with a yield stress of 460 MPa and initial Young's modulus of 200 GPa.

11.6.3 VERIFICATION OF FINITE ELEMENT MODEL

To verify the developed finite element models push-out test results obtained by Kim et al. [108] and Lloyd and Wright [17] are used. **Table 11.3** summarizes the measured dimensions and concrete cube strengths of the tested specimens. The load-slip behavior of the headed shear stud and failure modes are investigated along with the shear connection capacity per stud. **Table 11.4** shows a comparison of the capacities of shear connection obtained experimentally and numerically; a good agreement can be seen.

Table 11.3 Dimensions and Concrete Strength of Push-Out Specimen

Specimen	Dimensions					Concrete Strength f_{cu} (MPa)	Tested By
	Sheeting Type	Stud		Slab			
		d (mm)	h (mm)	B (mm)	D (mm)		
SP	(a)	13	65	450	75	34.5	Kim et at [108]
S1	(b)	19	100	675	115	44.8	
S2	(b)	19	100	900	115	35.3	
S3	(b)	19	100	1125	115	39.5	
S4	(b)	19	100	1350	115	46.3	
S5	(b)	19	100	900	115	43.6	Lloyd & Wright [17]
S6	(b)	19	100	900	115	43.8	
S7	(b)	19	100	900	115	37.3	
S8	(b)	19	100	900	115	39.6	
S9	(b)	19	100	600	115	39.8	

Table 11.4 Comparison of Shear Connection Capacities

Specimen	P_{test} (kN)	P_{FE} (kN)
SP1	39.2	40.9
S1	95.3	94.0
S2	81.8	88.1
S3	89.9	93.2
S4	95.8	94.1
S5	102.9	97.3
S6	98.8	94.0
S7	94.9	92.0
S8	87.3	93.2
S9	88.4	93.3

The experimental load-slip curve, the numerical curve given by three dimensional modelling in ABAQUS are compared with the numerical curve obtained by two dimensional modelling in ANSYS in **Fig. 11.19**. It shows that the model successfully predicts the shear connection capacity, stiffness as well as the load-slip behaviour of headed shear stud.

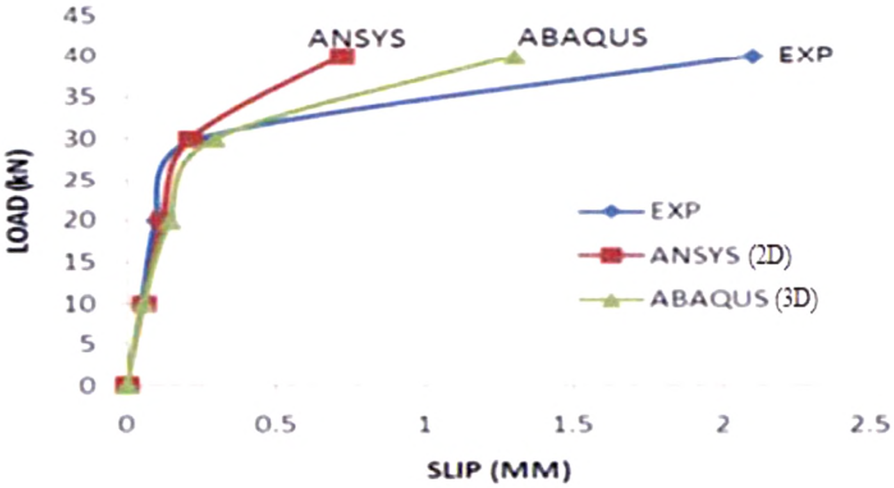


Fig. 11.19 Load-Slip Behaviour of Headed Shear Stud in SP1

The failure mode observed experimentally was combination of concrete conical failure and stud shearing, which is confirmed numerically here. **Figures 11.20** and **11.21** show the contour plots of specimens SP1 and S1.

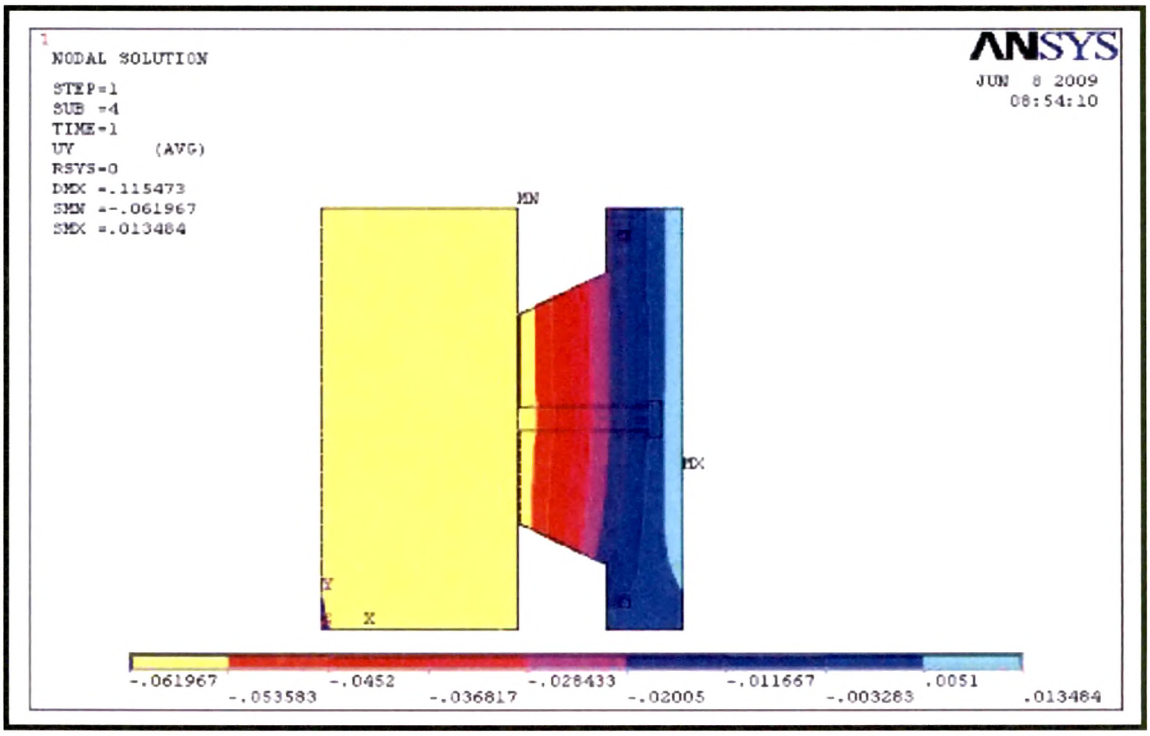


Fig. 11.20 Displacement Contour for Specimen SP1

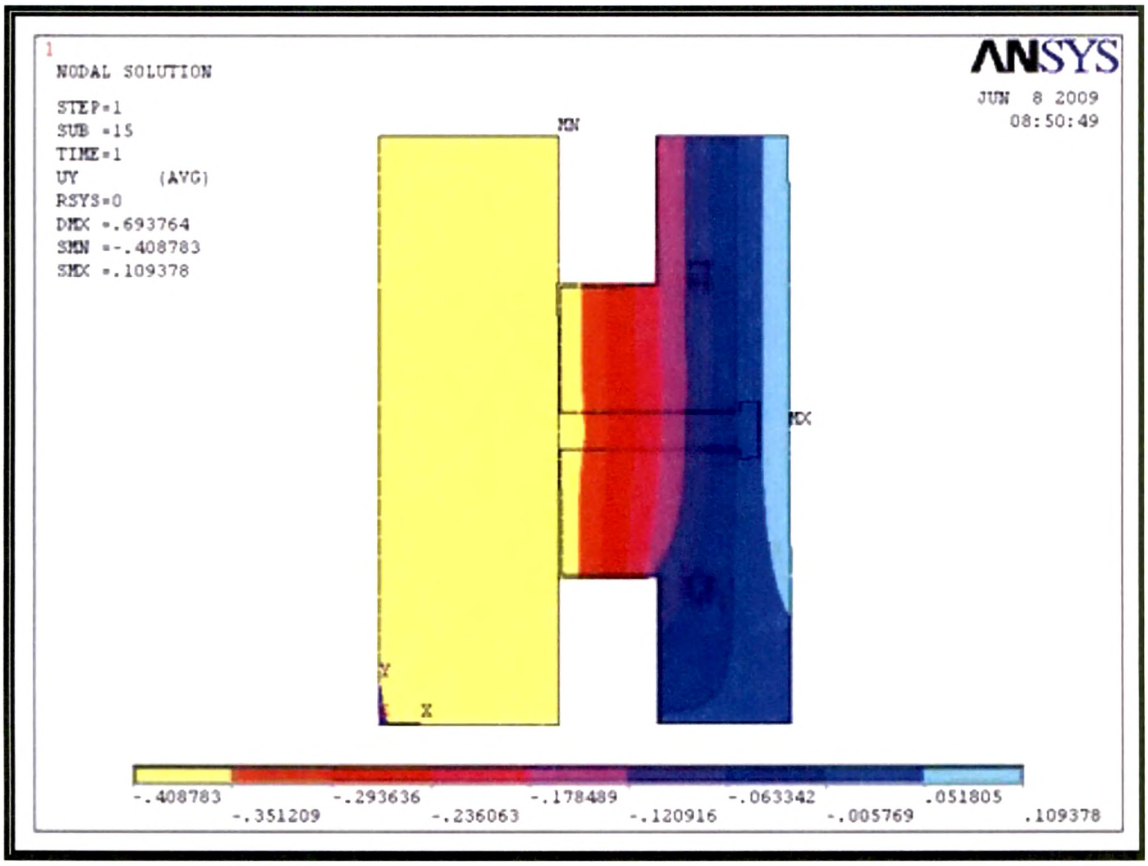


Fig. 11.20 Displacement Contour for Specimen S1

The maximum stresses in the concrete are in the regions around the stud forming a conical shape. The conical concrete failure is also known as concrete pull-out failure since the tensile force acting on the shear stud forces the slab to move up and leave a cone of concrete around the stud.

11.6.4 Parametric Study

The proposed finite element model accurately predicted the behavior of the headed shear stud in composite beam with profiled steel sheeting. Hence, a parametric study is conducted to study the effects on the capacity and behavior of shear connection by changing the concrete strength, height of the headed shear stud and the profiled steel sheeting geometry. Eleven groups (G1-G11) having 4 specimens each, having the same dimensions but with different concrete strengths, are investigated. The different concrete cube strengths considered are 25, 30, 35 and 40 MPa. The width of the concrete slab is taken as 600 mm while the depth of the concrete slab is equal to the stud height plus 25 mm of concrete cover. The steel beam used in the push-out specimens is 254 x 254 UC 73 and the reinforcement bar mesh was 10 mm diameter with 200 mm spacing between two bars. The difference between the stud height (h) and the rib depth (h_p) is greater than or equal to 35 mm. The push-out specimens in groups G1, G2 and G3 had the profiled steel sheeting dimensions of type (a), shown in **Fig. 11.22**, with plate thickness of 0.68 mm, and it is modeled using Model A. The push-out specimens in the groups G4–G11 has the profiled steel sheeting geometries of type (c), shown in **Fig. 11.23**, with plate thickness of 0.91 mm and they are modeled using Model B. The push-out specimens in groups G1, G2 and G3 have 13× 75, 16×75 and 19× 100 mm headed studs, respectively. The push-out specimens in groups G4 to G7 have 19 × 127 mm headed studs, while the push-out specimens in groups G8 to G11 have 19 × 100 mm headed shear studs. The push-out specimens in groups G4 and G5 have the same average rib width of 224.5 mm with different rib depths of 76 and 40 mm respectively. Similarly, the push-out specimens in groups G6 and G7 have the same average width of 143.5 mm with different rib depths of 76 and 40 mm, respectively. The push-out specimens in group G8 have the same dimensions as those in group G5, except that 19 × 100 mm headed studs are used instead of 19 × 127 mm. Finally, the push-out tests in groups G9, G10 and G11 have the same headed stud and dimensions, except with different rib depths of 65, 50 and 40 mm, respectively. **Table 11.5** summarizes the dimensions of the push-out specimens and concrete cube strengths considered for the parametric study.

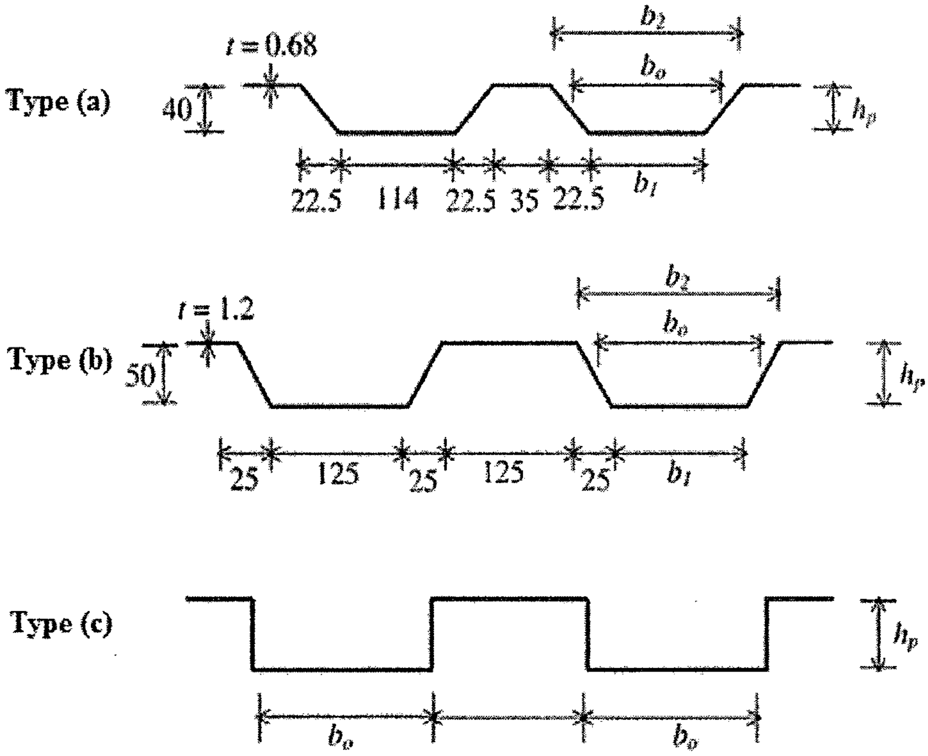


Fig. 11.22 Definitions of Symbols for Profiled Steel Sheeting

Table 11.5 Dimensions and Concrete Strength Considered for Parametric Study

Group	Specimen	Dimension								Concrete Strength F_{cu} (MPa)
		Sheeting				Stud		Slab		
		Type	B_o (mm)	h_p (mm)	T (mm)	D (mm)	H (mm)	B (mm)	D (mm)	
G1	P1	(a)	136.5	40	0.68	13	75	600	100	25
	P2	(a)	136.5	40	0.68	13	75	600	100	30
	P3	(a)	136.5	40	0.68	13	75	600	100	35
	P4	(a)	136.5	40	0.68	13	75	600	100	40
G2	P5	(a)	136.5	40	0.68	16	75	600	100	25
	P6	(a)	136.5	40	0.68	16	75	600	100	30
	P7	(a)	136.5	40	0.68	16	75	600	100	35
	P8	(a)	136.5	40	0.68	16	75	600	100	40
G3	P9	(a)	136.5	40	0.68	19	100	600	125	25
	P10	(a)	136.5	40	0.68	19	100	600	125	30
	P11	(a)	136.5	40	0.68	19	100	600	125	35
	P12	(a)	136.5	40	0.68	19	100	600	125	40
G4	P13	(c)	224.5	76	0.91	19	127	600	152	25
	P14	(c)	224.5	76	0.91	19	127	600	152	30
	P15	(c)	224.5	76	0.91	19	127	600	152	35
	P16	(c)	224.5	76	0.91	19	127	600	152	40
G5	P17	(c)	224.5	40	0.91	19	127	600	152	25
	P18	(c)	224.5	40	0.91	19	127	600	152	30
	P19	(c)	224.5	40	0.91	19	127	600	152	35
	P20	(c)	224.5	40	0.91	19	127	600	152	40
G6	P21	(c)	143.5	76	0.91	19	127	600	152	25
	P22	(c)	143.5	76	0.91	19	127	600	152	30
	P23	(c)	143.5	76	0.91	19	127	600	152	35
	P24	(c)	143.5	76	0.91	19	127	600	152	40
G7	P25	(c)	143.5	40	0.91	19	127	600	152	25
	P26	(c)	143.5	40	0.91	19	127	600	152	30
	P27	(c)	143.5	40	0.91	19	127	600	152	35
	P28	(c)	143.5	40	0.91	19	127	600	152	40
G8	P29	(c)	224.5	40	0.91	19	100	600	125	25
	P30	(c)	224.5	40	0.91	19	100	600	125	30
	P31	(c)	224.5	40	0.91	19	100	600	125	35
	P32	(c)	224.5	40	0.91	19	100	600	125	40
G9	P33	(c)	143.5	65	0.91	19	100	600	125	25
	P34	(c)	143.5	65	0.91	19	100	600	125	30
	P35	(c)	143.5	65	0.91	19	100	600	125	35
	P36	(c)	143.5	65	0.91	19	100	600	125	40
G10	P37	(c)	143.5	50	0.91	19	100	600	125	25
	P38	(c)	143.5	50	0.91	19	100	600	125	30
	P39	(c)	143.5	50	0.91	19	100	600	125	35
	P40	(c)	143.5	50	0.91	19	100	600	125	40
G11	P41	(c)	143.5	40	0.91	19	100	600	125	25
	P42	(c)	143.5	40	0.91	19	100	600	125	30
	P43	(c)	143.5	40	0.91	19	100	600	125	35
	P44	(c)	143.5	40	0.91	19	100	600	125	40

11.6.5 Comparison of FE Results with Design Strengths

The shear connection capacities of the 44 push-out specimens analyzed in the parametric study using the two dimensional finite element models are summarized in **Table 11.6.** The shear connection capacities obtained from the parametric study are compared with the nominal unfactored design strengths of headed stud shear connectors predicted by the American Specification (AISC) [110], British Standard: 5950 [93] and Euro Code 4 [7]. The AISC equation for the calculation of the design strength of headed stud shear connector (P_{AISC}) in composite beams with profiled steel sheeting perpendicular to the steel beam is given by:

$$P_{AISC} = r_1 \times 0.5 \times A_S\sqrt{f_c E_c} \leq A_S f_u \qquad \text{... (11.5)}$$

and

$$r_1 = \frac{0.85}{\sqrt{N}}\left(\frac{b_0}{h_p}\right)\left[\left(\frac{h}{h_p}\right) - 1\right] \leq 1.0 \qquad \text{... (11.6)}$$

where, A_s = Cross-sectional area of the headed stud shear connector, f_c = Compressive cylinder strength of concrete, E_c = Initial Young's modulus of concrete, f_u =Specified minimum ultimate tensile strength of the stud shear connector, r_1 = reduction factor, N = Number of shear connectors in one rib, b_o = Average width of b1 and b2, and h_p = Depth of the rib and h is the height of the headed stud.

As per BS 5950 by multiplying the tabulated values in the Standard by a reduction factor, design strength can be determined.

EC4 [7] and AISC [110] specifications took similar approach for determining the design strength of the headed stud in composite beam. P_{EC4} is taken as the lesser value calculated from Eq. (11.1) and Eq. (11.2) multiplied by a reduction factor (r3) that is calculated using Eq. (11.5) but replacing the factor 0.85 by 0.7.

It is found that the AISC, BS 5950 and EC4 overestimate the design strength of headed studs except for EC4 the design strength of specimen P1 and P2 in group G1.

Table 11.6 Comparison of Results for Shear Capacities

Group	Specimen	P_{FE} (kN)	P_{AISC} (kN)	P_{BS} (kN)	P_{EC4} (kN)
G1	P1	38.5	43.0	44.0	37.3
	P2	44	49.3	47.0	41.9
	P3	46.8	55.4	49.0	46.4
	P4	48.5	61.2	52.0	50.7
G2	P5	55	65.2	70.0	56.5
	P6	60	74.7	74.0	63.5
	P7	65	83.9	78.0	70.3
	P8	70	92.7	82.0	76.9
G3	P9	85	91.9	95.0	79.7
	P10	87	105.4	100.0	89.6
	P11	92	118.3	104.0	99.1
	P12	97	130.8	109.0	108.4
G4	P13	86	91.9	95.0	79.7
	P14	93	105.4	100.0	89.6
	[15	99	118.3	104.0	99.1
	P16	106	130.8	109.0	108.4
G5	P17	93	91.9	95.0	79.7
	P18	98	105.4	100.0	89.6
	P19	101	118.3	104.0	99.1
	P20	107	130.8	109.0	108.4
G6	P21	83	91.9	95.0	70.7
	P22	89	105.4	100.0	79.4
	P23	95	118.3	104.0	87.9
	P24	98	130.8	109.0	96.1
G7	P25	93	91.9	95.0	79.7
	P26	99	105.4	100.0	89.6
	P27	103	118.3	104.0	99.1
	P28	106	130.8	109.0	108.4
G8	P29	85	91.9	95.0	79.7
	P30	94	105.4	100.0	89.6
	P31	102	118.3	104.0	99.1
	P32	100	130.8	109.0	108.4
G9	P33	69	91.9	95.0	66.3
	P34	86	105.4	100.0	74.5
	P35	93	118.3	104.0	82.5
	P36	94	130.8	109.0	90.2
G10	P37	77	91.9	95.0	79.7
	P38	88	105.4	100.0	89.6
	P39	95	118.3	104.0	99.1
	P40	97	130.8	109.0	108.4
G11	P41	80	91.9	95.0	79.7
	P42	91	105.4	100.0	89.6
	P43	96	118.3	104.0	99.1
	P44	104	130.8	109.0	108.4

11.6.6 PARAMETERS AFFECTING THE SHEAR CAPACITY

11.6.6.1 Effect of concrete strength

From load per stud versus slip relationship for the push-out specimens in group G5, it can be seen from **Fig. 11.23** that the stiffness and capacity of the shear connection increase with the increase of concrete strength.

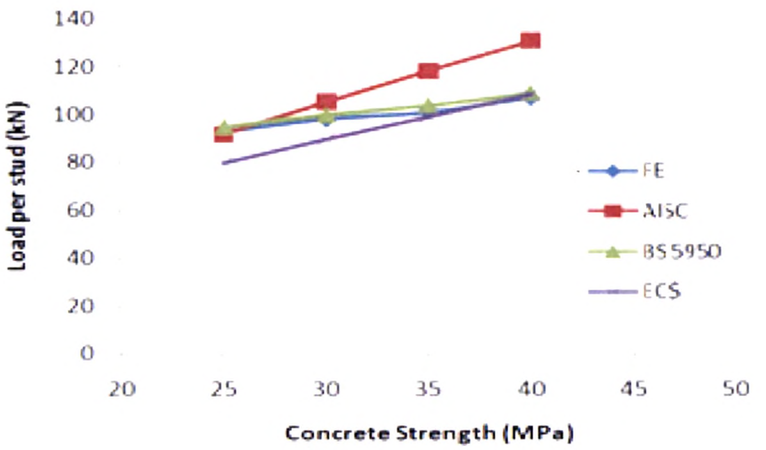


Fig 11.23 Effect of Change in Concrete Strength

11.6.6.2 Effect of change in rib depth on the capacity of shear connection

It can be seen from **Fig. 11.24**, for 19 x 127 headed stud of group G6 and G7, both AISC and BS 5950 predictions are unconservative and do not consider the effect of the change in rib depth from 40 to 76 mm on the strength of shear stud. The EC4 took into consideration the effect of change in rib depth. EC4 gives conservative design strength for rib depths as 76 and 40 mm.

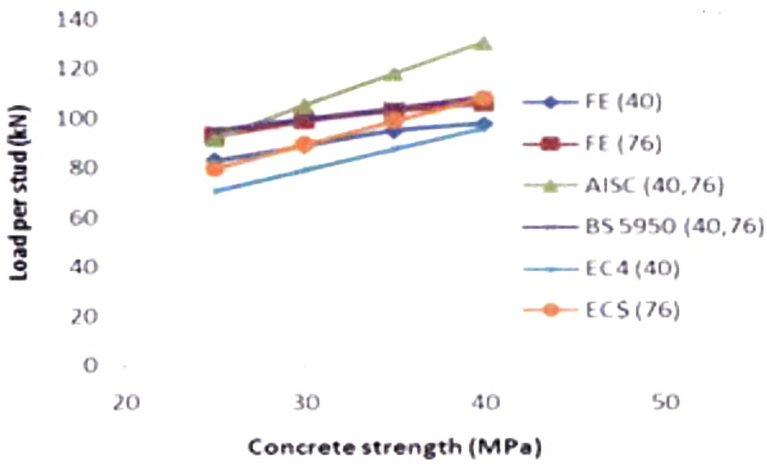


Fig. 11.24 Effect of Change in Rib Depth (h_p)

11.6.6.3 Effect of change in rib width

Considering the groups G5 and G7, having the rib width 224.5 and 143.5 respectively, it can be seen from **Fig. 11.25** that the change in rib width has negligible effect on the shear connection capacity for 19 x 127 mm headed stud of groups G5 and G7.

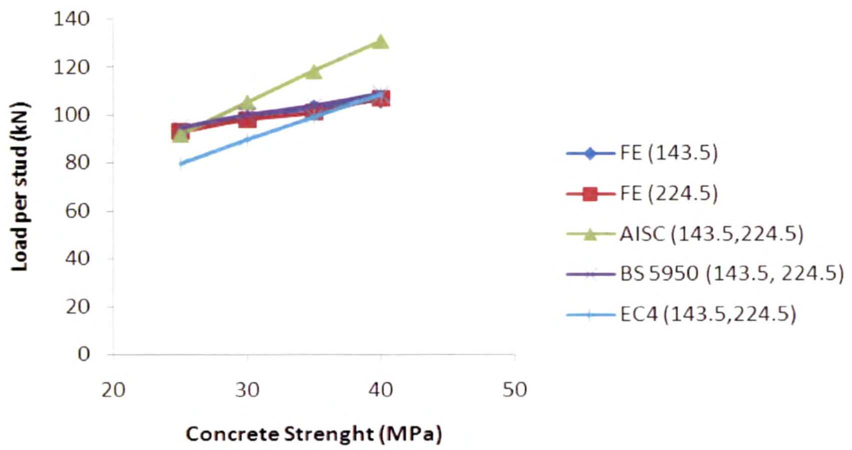


Fig. 11.25 Effect of Change in Rib Width (b_o)

11.6.6.4 Effect of change in stud diameter and height

The shear capacities obtained from the FE analysis and the design rules specified in the AISC, BS 5950 and EC4 specifications increase with the increase in stud diameter as shown in **Fig. 11.25** for 19 mm diameter headed stud of groups G7 and G11.

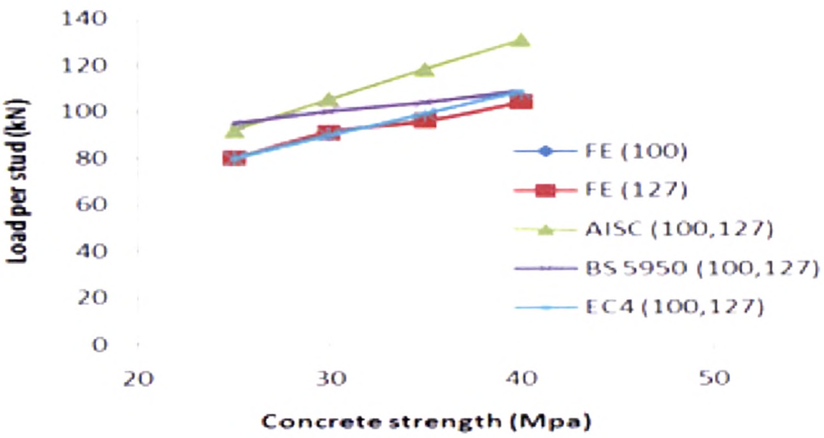


Fig. 11.26 Effect of Change in Stud Height (h)