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FEM Analysis of the Horizontal Shear Behaviour In the Steel-Concrete Composite Beam

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Abstract:- The structural behaviour of the steel-concrete composite beam is governed essentially by the composite action of the shear connector linking the steel beam and the concrete slab. The shear strength of the shear connector is determined through the standard push-out test. In view of recent experimental research results, the composite action of the shear connector observed in the standard push-out test shows clear difference to that observed in real composite beams. Especially, this difference has been found to become extreme in the case of composite beams with partial interaction. This study develops a three-dimensional FEM model for the analysis of the composite beam and the standard push-out test. The validity of the model is verified by comparing the analytic results to those of the tests. Moreover, the so-developed model is used for comparative analysis of the three-dimensional stress distribution within the slab concrete around the shear connector of the push-out test specimen and composite beam. The comparison reveals that the adopted approach can be used as a methodology for the analysis of the differences in the horizontal shear behaviour at the interface of the push-out test specimen and composite beam.

Keywords:- steel-concrete composite beam, push-out test, composite action, horizontal shear behaviour

I. INTRODUCTION

A composite beam is composed of a steel beam and a concrete slab. These two members behave monolithically by means of shear connectors welded on the upper flange of the steel beam. Studs are widely used as shear connector. The structural behaviour of the composite beam depends on the degree of composite action developed by the shear connector at the steel-concrete interface. This composite action mainly governed by the type of shear connector and the degree of shear connection plays a decisive role as much as the material properties of the steel beam and concrete slab on the strength and stiffness of the composite beam. The horizontal shear behaviour at the steel-concrete interface of the composite beam that is, the shear strength and stiffness of the stud, is determined experimentally on a simplified push-out test specimen rather than on the composite beam itself (Fig. 1). A survey of previous research results on this topic reveals the difficulty to compare thoroughly the estimated shear behaviours among the push-out test specimens that have been fabricated in partially different shapes. However, the evaluation method is recently and gradually gaining popularity in USA and several European countries owing to the standard push-out test proposed by Eurocode 4[1].

In view of recent experimental research results, the composite action of the shear connector observed in standard push-out test shows clear difference to that observed in real composite beams. Especially, this difference has been found to become extreme in the case of composite beams with partial interaction[2]-[9]. This can be explained by the simple fact that, in the case of the composite beam subjected to positive bending moment, the concrete slab undergoes larger compressive stress than that of the standard push-out test specimen. The comparison of the design values to those obtained experimentally shows that, in some cases, the composite beam designed with partial interaction exhibits in reality complete interaction as exemplified in the test results.

This study intends to suggest a methodology for the analysis of the differences in the horizontal shear behaviour at the steel-concrete interface of the push-out specimen and the composite beam. To that goal, a three-dimensional finite element model is developed for the FEM analysis of the standard push-out specimen and the composite beam. The validity of the model is verified by comparing the analytic results to those of the tests. The so-developed model is used to obtain the three-dimensional stress distribution within the slab concrete around the shear connector and analyse the behaviour of the connector in the push-out test specimen and composite beam.

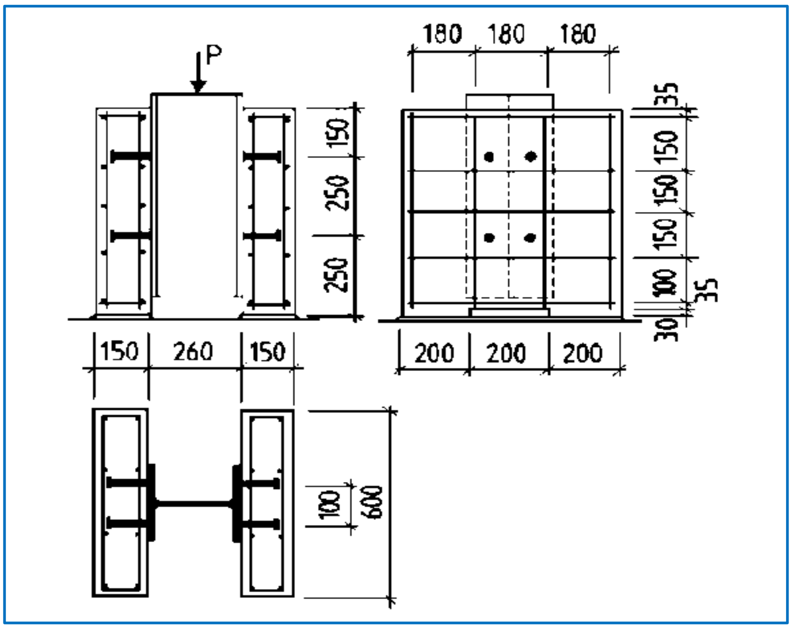


Fig.1: Standard push-out test by Eurocode 4[1]

II. FEM ANALYSIS OF STANDARD PUSH-OUT SPECIMEN

A. Modelling Method: Concrete Material Model

Concrete model used in the FEM analysis is based on the stress-strain curve shown in Fig. 2. At a cracked section of reinforced concrete, tension is carried by rebar. However, the concrete continues to carry tensile stress between the cracks because of bond action. The stress-strain relationship in tensile stress states in Fig. 2 is to consider the tension stiffening effect[10][11].

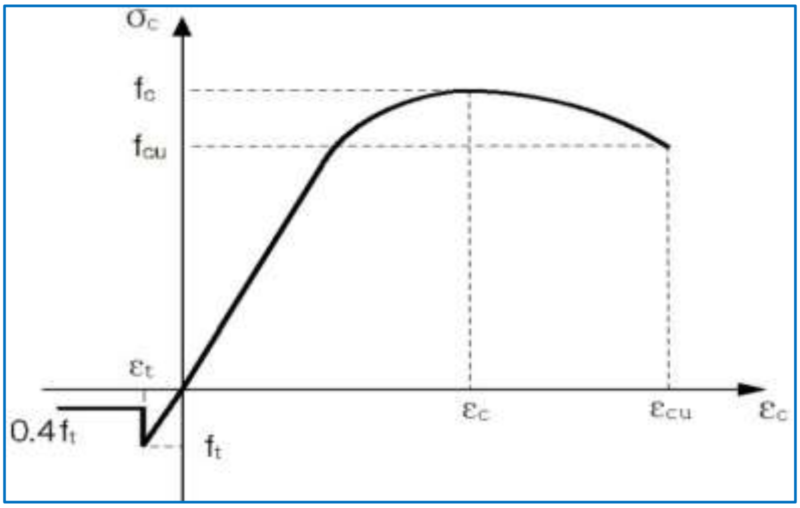


Fig.2: Stress-strain curve of concrete

Compression failure envelope used in the three-dimensional analysis of concrete member is shown in Fig. 3, and expressed by the Equation (1). This triaxial compressive failure envelopeadopted to the concrete model is proposed by Khan and Saugy[12] where f_c and f_{bc} is uniaxial and biaxial compressive strength, σ_{oct} and τ_{oct} is hydrostatic and deviatoric stresses.And tensile and tensile-compressive failure envelop is restricted by uniaxial tensile strength f_{ct} and compressive strength f_c shown in Fig. 4[13][14].

$$\alpha I_1 + \sqrt{J_2} - k = 0 \quad (1)$$

where

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 = 3\sigma_{oct} \quad (2)$$

$$J_2 = \frac{1}{6}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] = \frac{3}{2}\tau_{oct}^2 \quad (3)$$

$$\alpha = \frac{n-1}{\sqrt{3}(2n-1)},\ k = \frac{-n}{\sqrt{3}(2n-1)},\ n = \frac{\sigma_{bc}}{\sigma_c} \quad (4)$$

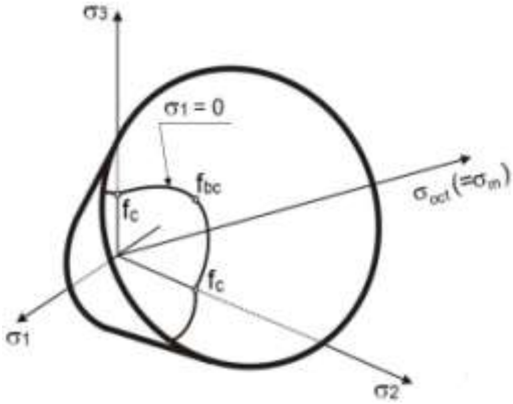


Fig.3:Triaxial compressive failure envelope of concrete model[12]

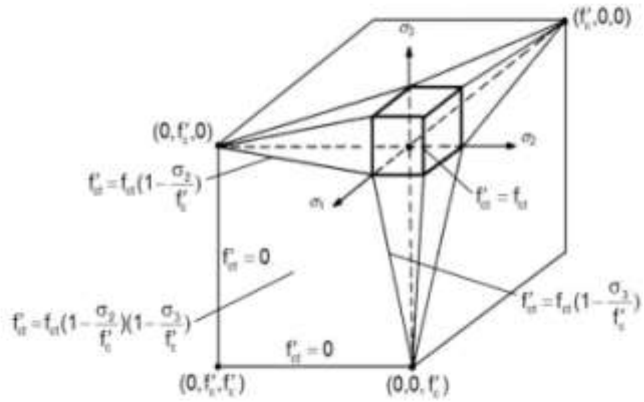


Fig.4:Triaxial tensile failure envelope of concrete model [13]

B. Modelling of Push-Out Test Specimen and Analysis Results

The FE model shown in Fig. 5 is developed for the analysis of the structural behaviour and stress state of the standard push-out test specimen. Only the half of the specimen is modelled for the efficiency of the analysis. Concrete member is modelled by 3D elementusing the concrete material model, and steel beam member mainly by shell element. The flange of the steel beam is modelled by 3D element in order to use contact element between the flange and concrete member. And reinforcement is modelled by one-dimensional element.The material properties adopted for the analysis are a compressive strength of 110 N/mm^2 for concrete, a tensile strength of 536 N/mm^2 for the steel beam and a tensile strength of 550 N/mm^2 for the studs as measured during the material test[15][16].

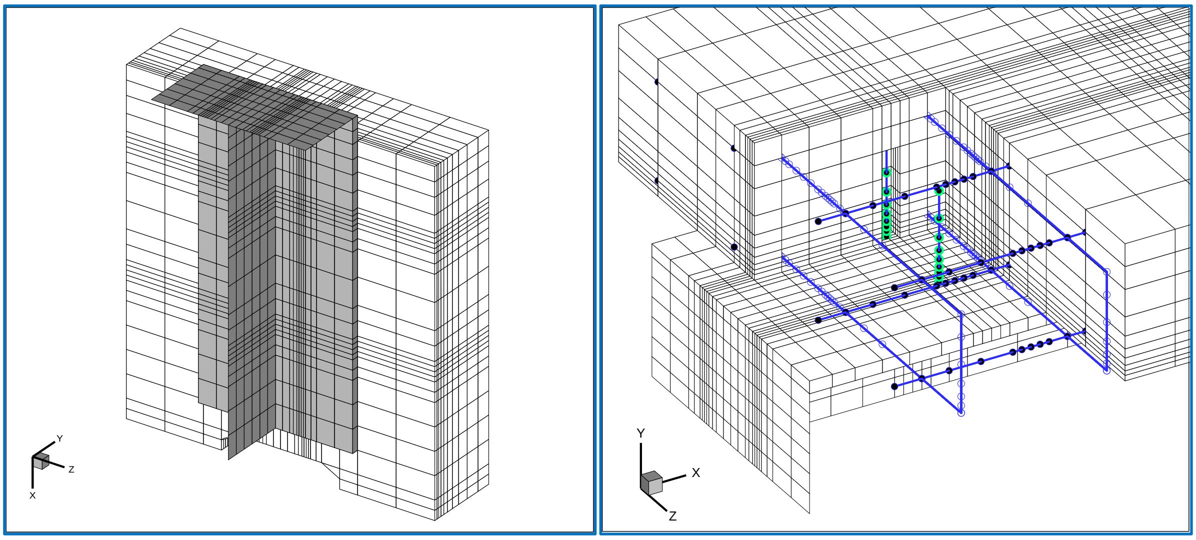


Fig.5: FE model for the push-out test specimen

In a strict sense, the studs as well as the concrete surrounding the studs should also be three-dimensionally modelled according to the shape of the studs in order to achieve exact analysis of the horizontal shear behaviour at the steel-concrete interface. However, applying an identical modelling technique for the composite beam is quasi-impossible considering the computing capacity of the computer and the efficiency of the analysis. Therefore, this study applies beam elements for the studs and models the head, shaft and welded bottom of the studs with their actual section areas. In addition, the contact area between the stud and concrete in the FEM model is modelled so as to enable interaction by establishing a constraint equation for the displacement occurring at the common node. The voids around the stud in Fig. 5 are introduced only for the convenience in the visualization of the details of the shear connection model.

Fig. 6 compares the analysis results and the test results[15][16] (PO1-PO3) for the push-out test specimen using 19 mm-studs. The comparison reveals relatively good agreement between the analysis and test results in which the graphs exhibit a linear part representing elastic behaviour and a part corresponding to the partial failure of concrete and the plastic deformation of the studs.

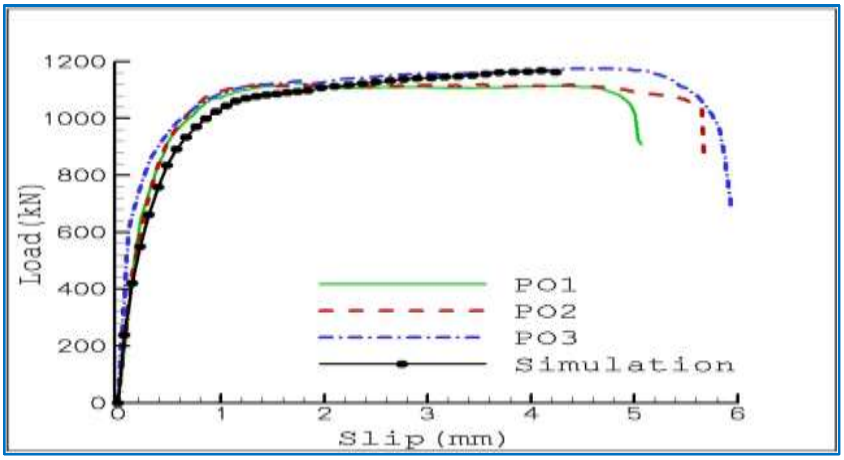
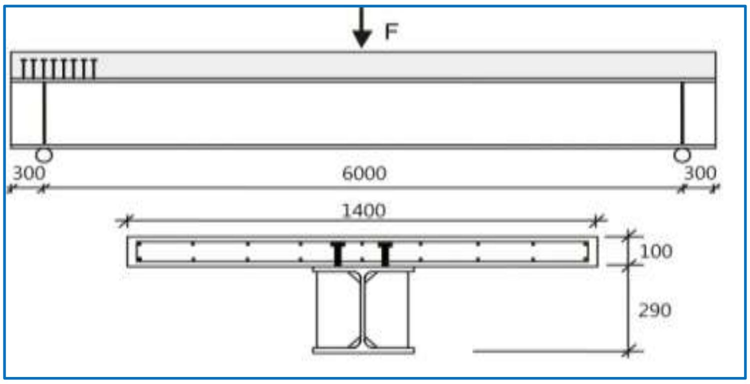


Fig.6: Comparison of analysis and test results

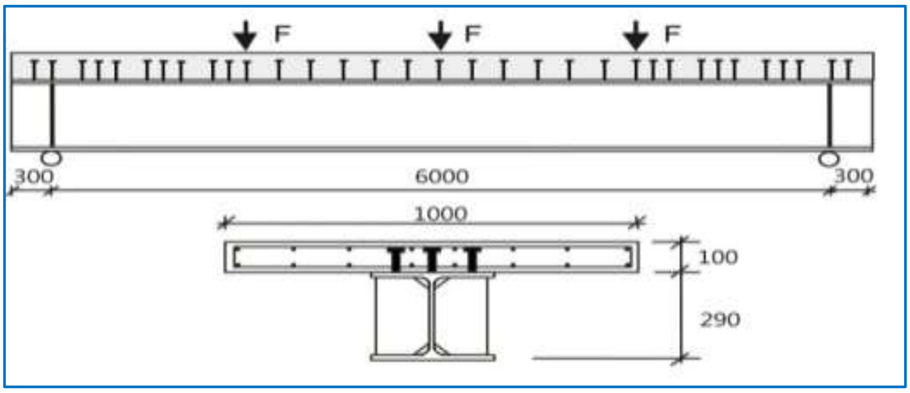
III. FEM ANALYSIS STEEL-CONCRETE COMPOSITE BEAM

As shown in Fig. 7, a single span composite beam of 6 m loaded by a concentrated load at its center and the same single span beam loaded by concentrated loads at every quarter length are selected for the analysis. For the beam loaded at its center, two cases are considered: complete interaction (B100) and partial interaction with a degree of shear connection η of 58% (B300). For the beam loaded at each quarter length, two cases are also considered: complete interaction (B700) and partial interaction with a degree of shear connection η of 42% (B800). The corresponding FEM model is illustrated in Fig. 8. Only the half of the beam is modeled for the efficiency of analysis. The shear connection of the composite section is modeled using the same method to that applied for the standard push-out test specimen in order to enable the comparison of the stress state of the shear connection under identical conditions. The studs are disposed according to the shape of the shear force diagram that is, at regular intervals for B100 and B300, and at irregular spacing for B700 and B800. The material properties adopted for the analysis are a compressive strength ranging from 96 to 114 N/mm^2 for concrete, a tensile strength ranging from 515 to 584 N/mm^2 for the steel beam and a tensile strength of 550 N/mm^2 for the studs as measured during the material test[15][16].

The analysis results and the test results including the deflection of the beam, the slip at the interface between the steel beam and the concrete slab, and the strain at each position of the composite beam are compared for each case in order to evaluate the validity of the developed FEM model of the composite beam. For example, Fig. 9 compares the load-deflection curve, the load-slip curve and the strain at the bottom of the concrete slab for the composite beam B800 obtained analytically and experimentally.



(a) Composite beam B100/B300



(b) Composite beam B700/B800

Fig.7: Composite beams considered in the analysis [15][16]

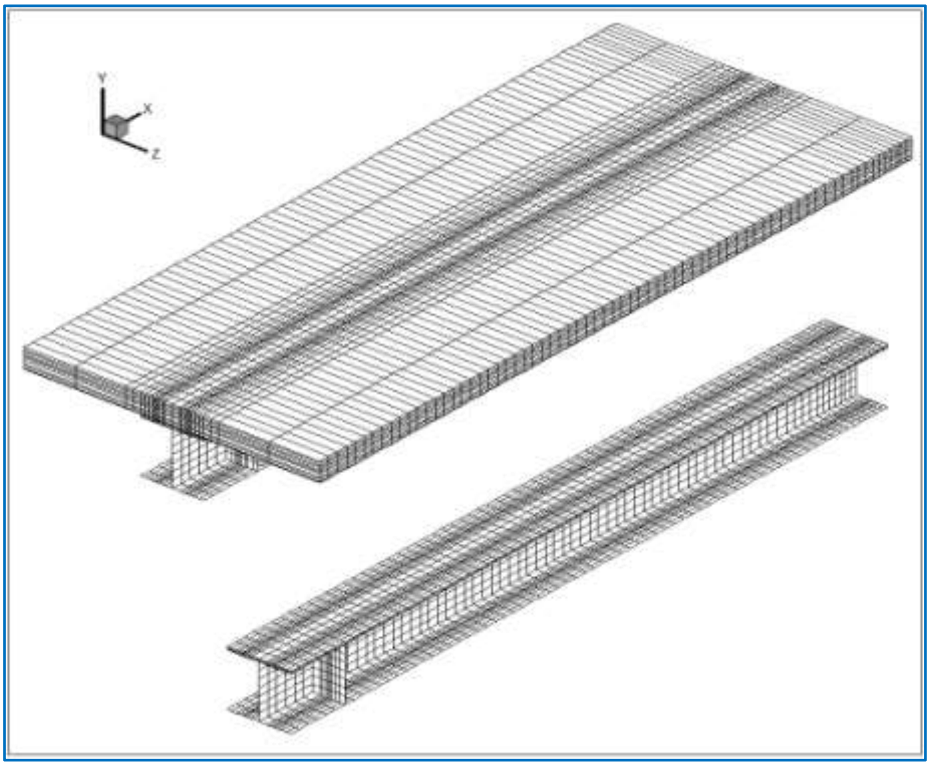
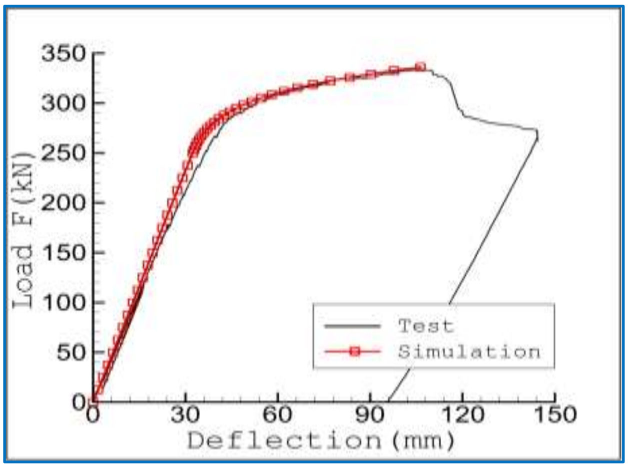


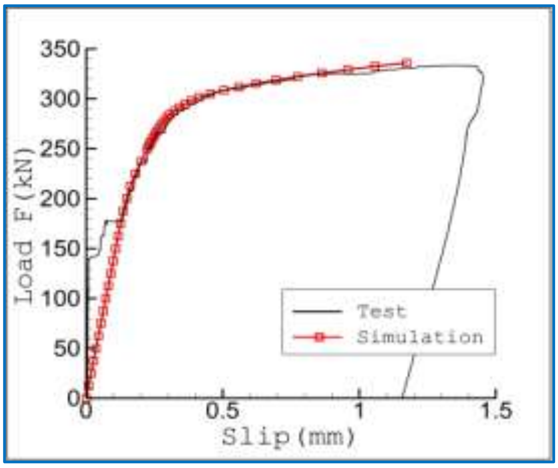
Fig.8: FE model of the composite beam

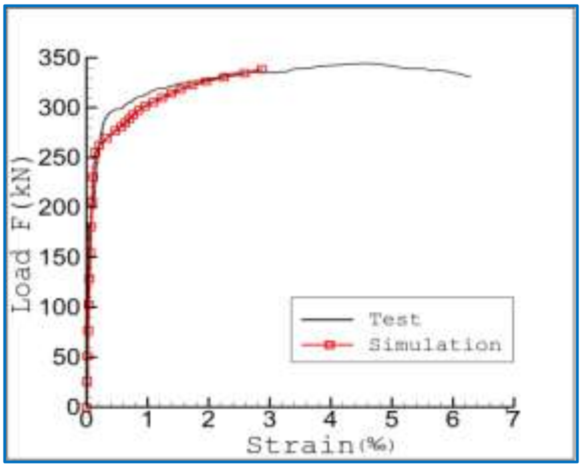
The comparison of the analytic and experimental deflection, slip and strain shows that the analysis results predict the test results with relatively good accuracy. This demonstrates the validity of the FEM model including the shear connection at the steel-concrete interface for the analysis of the structural behaviour of the composite beam. Recalling that the shear connection at the steel-concrete interface was modelled by a method identical to that applied for the push-out test specimen, this allows valid comparison between the horizontal shear behaviour at the steel-concrete interface in the composite beam and their behaviour in the push-out test specimen. For example, the comparison of the analysis results for the studs installed at various positions in beams B100 and B800 with their behaviour observed in the standard push-out test specimens are presented in Figs. 10 and 11.

The positions of the shear connectors presented in Figs. 10 and 11 were selected considering the shear distribution developed in each shear connector in the longitudinal direction of the beam under the maximum loading condition of the composite beam. The positions of 4 and 3 shear connectors, in B100 and B800 respectively, were selected and the horizontal shear behaviour at the steel-concrete interface in the composite beams at the corresponding positions is compared to the behaviour in the push-out test specimens in Figs. 10 (b) and 11 (b).



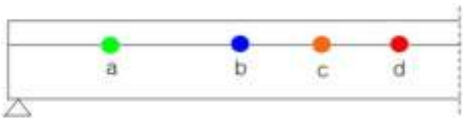
(a) load-deflection curve

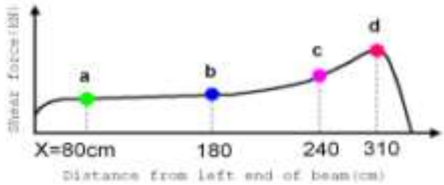




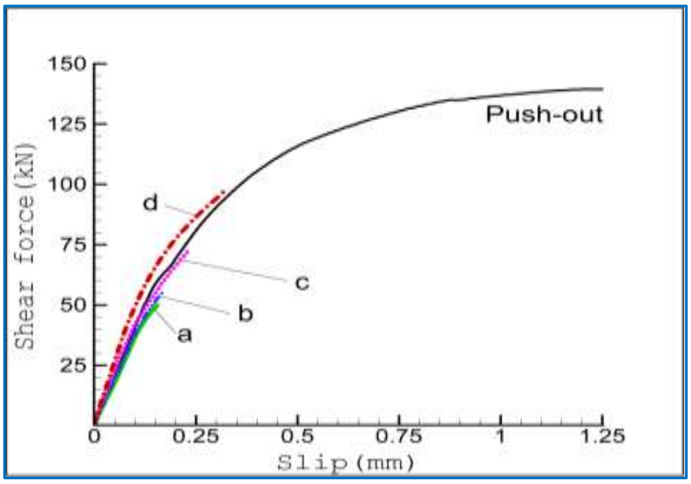
(b) load-slip curve(c) strain at the bottom of the slab

Fig.9: Comparison of analysis and test results (B800)





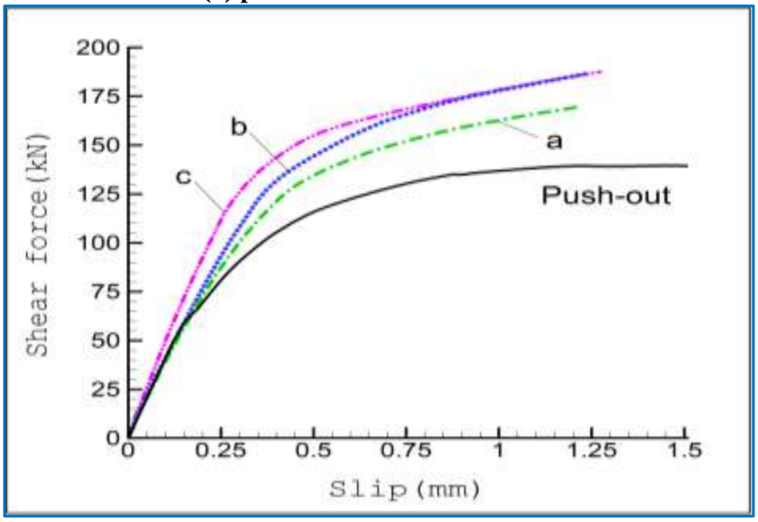
(a) position of considered studs



(b) Shear connection behavior

Fig.10: Comparison of the shear connection behaviour of composite B100 and push-out specimen

(a) position of considered studs



(b) Shear connection behavior

Fig.11: Comparison of the shear connection behaviour of composite B800 and push-out specimen

From the comparison of the behaviour of the shear connectors in the composite beam B100 with complete interaction to the behaviour of the studs obtained from the standard push-out test specimen, it can be observed that the shear connectors in the composite beam support only 70% of the maximum load in the push-out test even if there is some slight difference with respect to the position. Such result indicates that the load bearing capacity of the shear connector is underestimated in the design code and confirms other research results stating that the shear connectors in actual composite beams are designed with a very large margin of safety[2][3][5][8][9]. On the contrary, the shear connectors in the composite beam B800 with 42% of degree of shear connection appear to develop a shear strength larger by 20 to 30%. This means that composite beams designed with partial interaction exhibit in reality larger composite action than assumed in the design, which confirms other experimental results[2][3][15][16] reporting that, sometimes, such beams show a behaviour close to complete interaction.

IV. COMPARATIVE ANALYSIS OF 3-DIMENSIONAL STRESS STATE

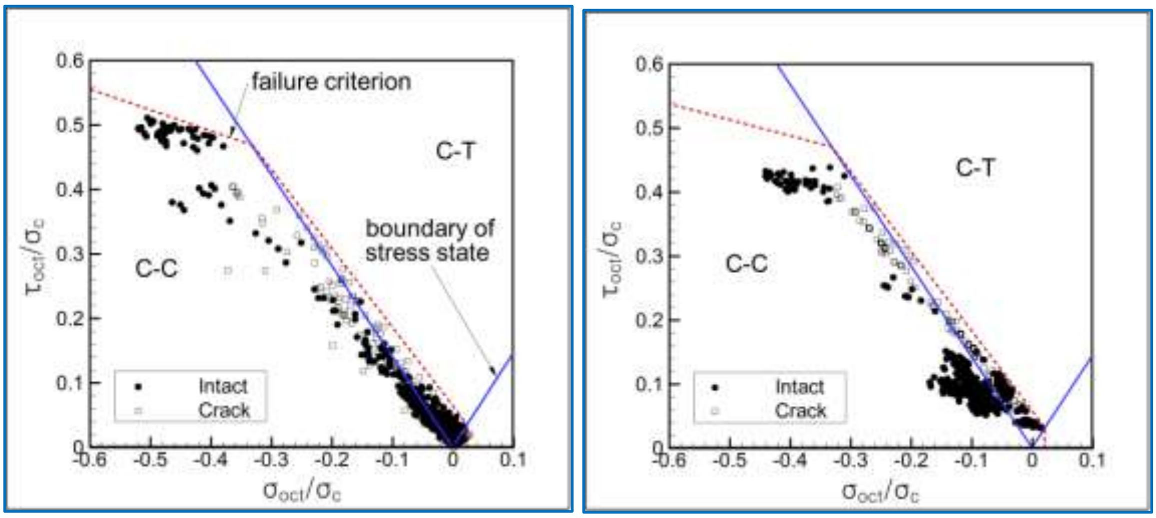
The reason for which the shear connector in real composite beam develops larger strength than that obtained from push-out test can be stated as follows. In the composite beam, the stud is subjected to an axial load caused by the external force acting on the slab, which reduces the flexural tensile stress developed in the stud when large slip occurs and, in turn, increases the strength of the shear connection. However, it can be presumed that this effect will be lesser for the studs positioned outside the area loaded by the concentrated load.

In this study the effects of the bearing stress-induced local failure of the concrete restraining the shear connector on the load-carrying behavior of the shear connector are analyzed by comparing the stress state in the slab concrete around the shear connector according to the external loading conditions of two different structures.

To that goal, the stress state developed in the slab concrete under bearing stress located within the area loaded by the force transmitted through the studs is analyzed as shown in Fig. 12. Here, the stress state is compared for the cases where the shear force acting on the shear connectors is identical in the push-out test specimen and the composite beam. In general, the stress at a point can be divided into the hydrostatic stress (σ_{oct}) and the deviatoric stress (τ_{oct}) in the 3-dimensional principal stress space. The hydrostatic-deviatoric stress space can itself be subdivided into 4 stress states (compression (C) – compression (C), compression (C) – tension (T), tension (T) – compression (C), tension (T) – tension (T)) using (5) and (6). In (5) and (6), I_1 and J_2 are stress invariants.

$$\sqrt{J_2} + \frac{1}{\sqrt{3}} I_1 = 0 \quad (5)$$

$$\sqrt{J_2} - \frac{1}{\sqrt{3}} I_1 = 0 \quad (6)$$



(a) push-out test specimen (b) composite beam B800
Fig.12: Hydrostatic-deviatoricstress states

Besides, this study adopts the Drucker-Prager failure criterion modified by Khan and Saugy[12]as failure criterion for the analysis of concrete. The stress state in the slab concrete around the shear connector as shown in Fig. 12 correspond a stress state prior to complete failure under a given loading condition.

It can be seen that, in the case of the standard push-out test specimen, the stresses in the slab are closer to the boundaries of the stress states whereas the stress in the composite beam are mostly distributed in the compressive stress state (C–C). In addition, the push-out test specimen shows larger portions in deviatoric stress state in the high hydrostatic stress range. This means that the slab concrete around the shear connector of the push-out test specimen stands in more unfavorable stress state than in the composite beam under the same shear load and also that larger portions are likely to fail in the case of load increase.

In order to represent the difference in the stress state more clearly, the deviatoric stress distribution is compared along the length of the shear connector from the bottom of the slab as shown in Fig. 13. It can be observed that a larger part of the slab concrete under bearing stress in the push-out test specimen will experience failure under the same shear load. At early loading, most of the shear load is supported by the weld at the bottom of the shear connector. However, when the slab concrete under bearing stress located in front of the stud reaches its failure state, the shaft of the stud having smaller diameter than the weld starts to develop flexural tensile stress. Thereafter, the shear connector reaches its yielding state as the load increases.

Considering this load transfer mechanism together with the deviatoric stress distribution, the following conclusion can be deduced. In the case of the push-out test specimen in which the slab concrete under bearing stress experiences larger failure under the same load, the load to be sustained by the shaft of the stud is increasing faster and induces its yielding state. Such state results finally in a load-carrying capacity of the shear connector lower for the push-out test specimen than for the composite beam.

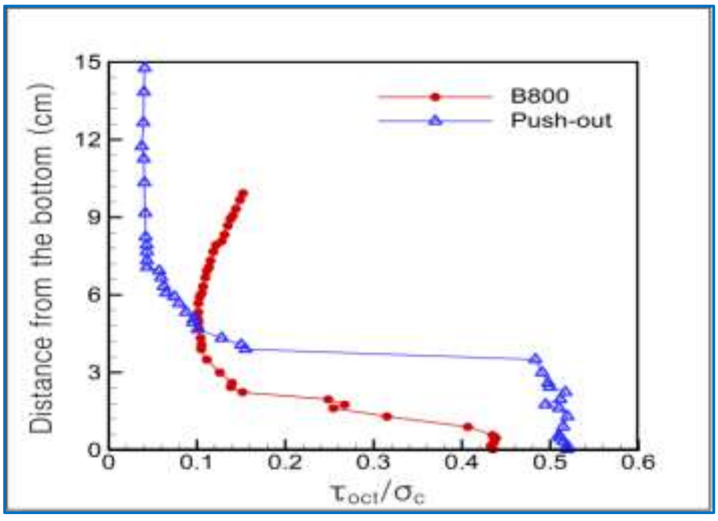


Fig.13: Comparison of the deviatoric stress state

V. CONCLUSIONS

The existing general push-out test methods are widely applied owing to the relative ease in measuring the strength of the shear connector. Moreover, partially different structures are utilized for the push-out test according to the research objectives and test conditions. Since the standard push-out test specimen proposed in Eurocode 4 enables very conservative evaluation of the strength, the empirical equation for the estimation of the strength of shear connection based on this standard specimen could fail in predicting more accurately the composite action of the composite beam, and often result in overdesign. As an example, the composite beams designed with partial interaction are in reality exhibiting a structural behaviour close to complete interaction.

In this study, a FEM model enabling to analyse the horizontal shear behaviour at the steel-concrete interfacewas developed. This model was used to compare the three-dimensional stress state occurring in the slab concrete around the shear connector in the push-out test specimen and in the composite beam. The comparison showed that the slab concrete around the shear connector developed different stress states. Considering the load transfer mechanism of the shear connector, this difference in the stress state was verified to be one cause of the difference in the horizontal shear behaviour. Further research should implement structural mechanics analysis of the shear behaviour using the analytic methodology adopted in this study so as to clarify the causes of the different horizontal shear behaviours more concretely

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