

Influence of tensile behaviour of slab on the structural Behaviour of shear connection in composite Beam subjected to hogging moment

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Abstract:-A composite beam is composed of a steel beam and a slab connected by means of shear connectors like studs installed on the top flange of the steel beam to form a structure behaving monolithically. This study analyzes the effects of the tensile behavior of the slab on the structural behavior of the shear connection like slip stiffness and maximum shear force in composite beams subjected to hogging moment. The results show that the shear studs located in the crack-concentration zones due to large hogging moments sustain significantly smaller shear force and slip stiffness than the other zones. Moreover, the reduction of the slip stiffness in the shear connection appears also to be closely related to the change in the tensile strain of rebar according to the increase of the load. Further experimental and analytical studies shall be conducted considering variables such as the reinforcement ratio and the arrangement of shear connectors to achieve efficient design of the shear connection in composite beams subjected to hogging moment.

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

I. INTRODUCTION

A composite beam is composed of a steel beam and a slab connected by means of shear connectors like studs installed on the top flange of the steel beam to realize monolithic behavior. Thanks to the numerous studies that have been conducted to date, the stiffness and deformation characteristics relative to the composite action brought by the shear connector is well known for composite beams subjected to positive moments [1-5]. Besides, research results are relatively poor on the behavior of shear connectors installed on composite beams subjected to hogging moments. The following gives a summary of the survey of dedicated literature.

According to previous studies [6-9], the slip stiffness of the shear connection in hogging moment zone where the slab is in tension is lower than that observed in push-out test, and the maximum shear force sustained by the shear connector is also reduced. Bode [8] reported that this reduction runs around 10% to 20%. Shariati et al. [10] stated that the shear strength and slip stiffness of the shear connection depend not only on the strength of the shear connector itself but also on the cracking behavior and tensile strength of the slab. Furthermore, Johnson [11] reported that the extent of reduction of the shear strength is not significantly great, but the slip stiffness of the shear connection is reduced approximately twice.

In view of this survey, the structural behavior of the shear connector in composite beams subjected to hogging moment is not in agreement with the one that can be obtained through push-out test. It appears that the structural behavior of the shear connector in composite beams subjected to hogging moment is significantly influenced by the cracking and tensile behaviors of the slab.

However, it is difficult to find detailed research analyzing the effects of the tensile behavior of the slab in hogging moment zone on the behavior of the shear connectors as well as on their causes. This can be explained by the extreme complexity in evaluating experimentally the effect of the loss of stiffness of the slab on the composite action of the longitudinally arranged shear connectors with respect to the initiation and propagation of tensile cracks in the slab of the composite beam subjected to hogging moment. In addition, the finite element analysis using the load-slip curves obtained from push-out test evaluates the flexural behavior of the whole structural system assuming that the load-slip relation is known. Consequently, this approach cannot analyze the behavior of the shear connector in a strict sense.

Accordingly, this study develops a 3D-finite element model enabling to analyze the composite action of the composite beam subjected to hogging moment by modeling as realistically as possible the shape and properties of the components of the composite beam that are its slab, steel beam and shear studs. This finite element model is applied to analyze the local and flexural behaviors of the entire composite beam. The corresponding results are compared to the experimental results of previous studies [12, 13] so as to evaluate analytically the influence of the tensile behavior of the slab and structural behavior of the shear connectors on the composite action of the composite beam subjected to hogging moment.

II. COMPOSITE BEAM FOR ANALYSIS

In order to evaluate the effect of the tensile behavior of the slab on the structural behavior of the shear connection by finite element analysis, need is to verify if the analytical model is fitted to this purpose. In this study, results from finite element analysis are compared to previous experimental results [12, 13] for the composite beam B400 as shown in table 1 and Fig. 1.

Table 1: Details of specimen B400 [13].

Details	B400
Steel beam	HEA300 (290×300×8.5×14)
Concrete slab	1200×100
Longitudinal rebar	48Ø8
Traverse rebar	Ø8@200
Reinforcement ratio, ρ (%)	2
Arrangement of studs	1×27
Degree of shear connection (%)	100
Compressive strength of concrete (N/mm ²)	100
Tensile strength of concrete (N/mm ²)	5
Elastic modulus of concrete (N/mm ²)	32673
Yield strength of steel beam (N/mm ²)	525
Tensile strength of steel beam (N/mm ²)	617
Yield strength of rebar (N/mm ²)	616
Tensile strength of rebar (N/mm ²)	679

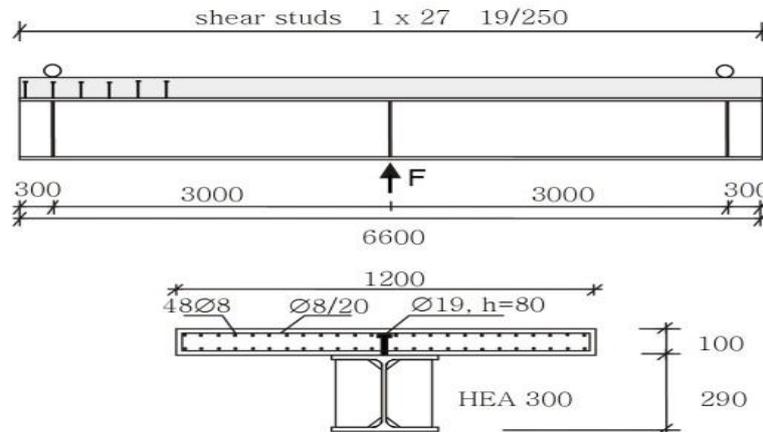


Fig. 1: Composite beam B400 considered in the analysis [13]

III. MATERIAL AND ANALYSIS MODEL FOR FINITE ELEMENT ANALYSIS

A. Material Model

The material model for steel is the common model used in plastic analysis. The concrete model considers the stress-strain relationship of concrete in compressive and tensile states as shown in Fig. 2. Here, a constant stress ($0.4f_t$) is maintained after the initiation of tensile cracks to account analytically for the tension stiffening [14]. The adopted failure criterion shown in Fig. 3 and Eq. (1) is the one proposed by Khan and Saugy [15]. The uni-axial maximum compressive stress is chosen to be the compressive strength under multi-axial stress condition [16]. As pictured in Fig. 4, the maximum strength under pure tension is defined by the failure envelop connecting the points corresponding to the uni-axial compressive strength and uni-axial tensile strength under multi-axial stress condition [17]. Moreover, the failure of the concrete element is set with reference to the failure of smeared model occurring inside the element and not at the nodes of the 3D solid element [18-21].

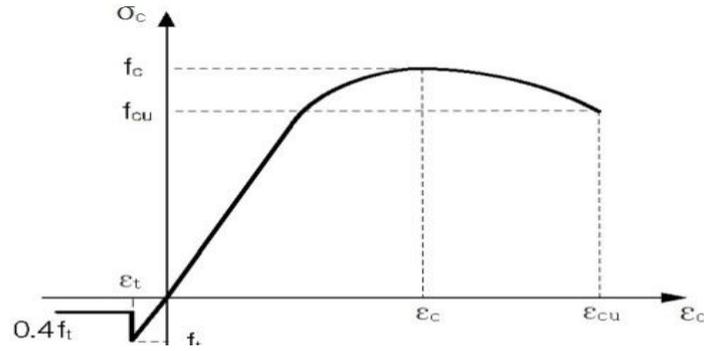


Fig. 2: Stress-strain curve of concrete [18, 21]

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

in which,

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

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

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

where I_1 is stress invariant; J_2 is deviatoric stress invariant; σ_{oct} is octahedral normal stress; τ_{oct} is the deviatoric stress; σ_1 , σ_2 , and σ_3 are principal stress; f_c and f_{bc} are uniaxial and biaxial compressive strength.

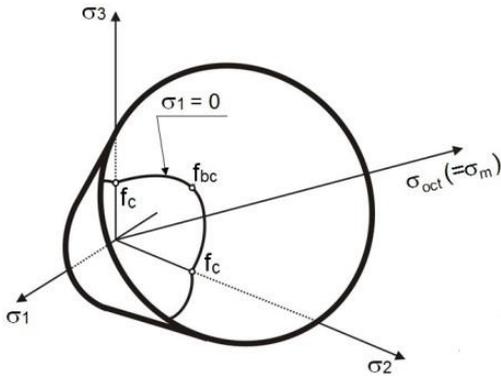


Fig. 3: Compressive failure envelope [15]

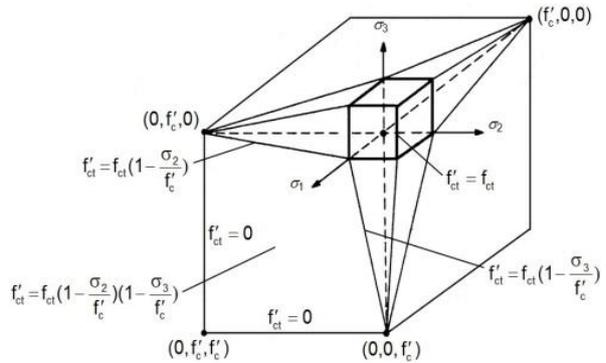


Fig. 4: Tensile failure envelope [17]

B. Analytical Model

In case of the composite beam subjected to hogging moment, the flange of the steel beam buckles through compression, from which the size of the maximum load of the composite beam can be determined. Consequently, local buckling of the steel beam shall be considered to achieve relatively more accurate simulation of the structural behavior of such composite beam by a finite element model. Besides, the overall structural behavior of the composite beam can be evaluated even if the concrete part of the slab is ignored and analysis is conducted only by modeling its tensile reinforcement. However, this approach cannot analyze the change in the flexural rigidity caused by cracking. Moreover, analysis becomes difficult in the absence of technique for modeling the composite action provided by the shear connector established through comparison with experimental results.

In view of these facts, prior to modeling the entire composite beam system, need is to examine first the accuracy of the analytical models in reflecting the actual behavioral characteristics of all the members composing the composite beam. Supposing that the analytical models can reflect the behavioral characteristics of each member, the nonlinear behavior of the structure will be simulated more accurately, which will enable to evaluate analytically the composite action by means of the shear connectors.

(1) Steel Beam Model

The possibility to simulate local buckling by the finite element model of the steel beam to be used in the analysis of the composite beam should be verified. To that goal, finite element analysis is conducted on the steel beam experiencing local buckling similar to the steel beam of the composite beam B400. Comparison is done with the experimental and analytical results of Spangemacher[22]. The steel beam used for the analysis and test of Spangemacher[22] is a 3 m-long HEA280 beam and uses S460 steel ($f_y = 460 \text{ N/mm}^2$) identically to the steel of the composite beam considered in this study.

Fig. 5 shows the analytical model of the steel beam adopted for the simulation of the behavior of the steel beam in the composite beam [22]. Here, initial imperfection is introduced in the shells used for the web and the flange subjected to flexural compression so as to enable the analysis of local buckling due to flexural compression. The conditions at both end supports of the beam are fixed to prevent movement in the loading direction and in the transverse direction. Loading is applied through displacement control method in the analysis by increasing the displacement at mid-span.

Fig. 6 depicts the overall deformed shape of the beam given by the analysis. Fig. 7 compares the analytical results obtained in this study with the analytical and experimental results of Spangemacher[22]. The results are seen to be in good agreement with initial linear behavior until the peak load by buckling and followed by the decrease of the load. This indicates that the finite element model established in this study is able to analyze the local buckling of the steel beam flange under compression, and that this model can be applied for the steel beam in the composite beam subjected to hogging moment.

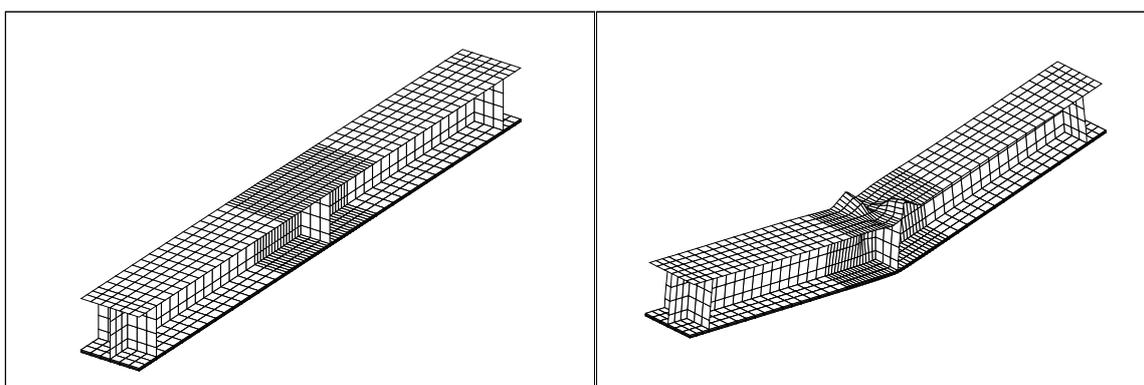


Fig. 5:FE Model of steel beam Fig. 6:Deformed shape of steel beam

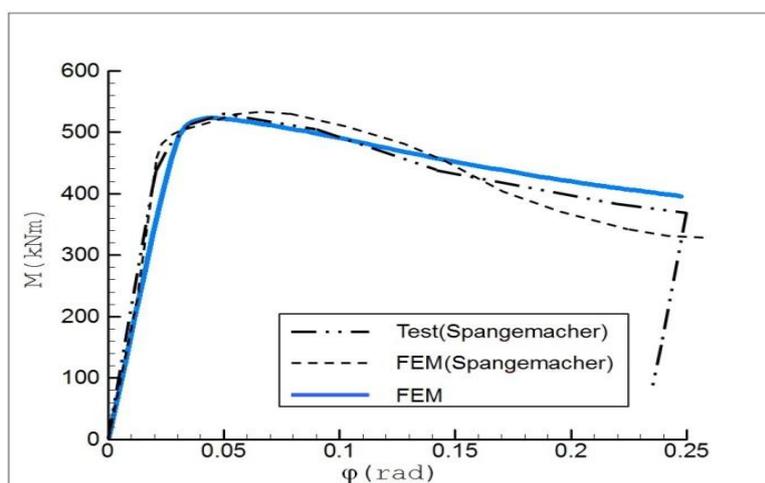


Fig. 7: Moment-rotation curves

(2) Slab Model

In the reinforced concrete member, the tensile force in the cracked zone is mainly sustained by the reinforcement. However, the concrete present between the cracks also sustains the tensile force to a certain extent owing to the bond action between the reinforcement and concrete, and contributes thus to the stiffness of the whole member. In order to search for a modeling method adapted to the analysis of the composite beam subjected to hogging moment, analysis is carried out on a reinforced concrete bar member ($20 \times 20 \times 400$) subjected to uni-axial tension and the results are compared to the experimental results of Bergner [23]. In the

analysis, the compressive and tensile strengths of concrete are respectively 108 N/mm^2 and 3.1 N/mm^2 , the yield strength of the rebar is 500 N/mm^2 with a reinforcement ratio of about 1.55%, and loading is applied through displacement control.

Fig. 8 depicts the finite element model of the reinforced concrete bar. Only the half of the original specimen is modeled considering its symmetry. The concrete part is modeled by three-dimensional 8-node elements. Axial elements are used for the reinforcement to allow only tension or compression, and the nodes are shared with those of the concrete elements.

Fig. 9 compares the analytical and experimental results. It can be seen that the overall tensile behavior is comparatively well simulated by the finite element model with the linear region before the initiation of cracks and the region after deformation of 1.5 mm/m . However, there is some difference in the region between 0.1 to 1.5 mm/m in which cracks develop continuously. The cause of such discrepancy can be found in the impossibility of the simplified model to reproduce the continuous occurrence of brittle and irregular cracks and simulate the corresponding deformation and stress redistribution.

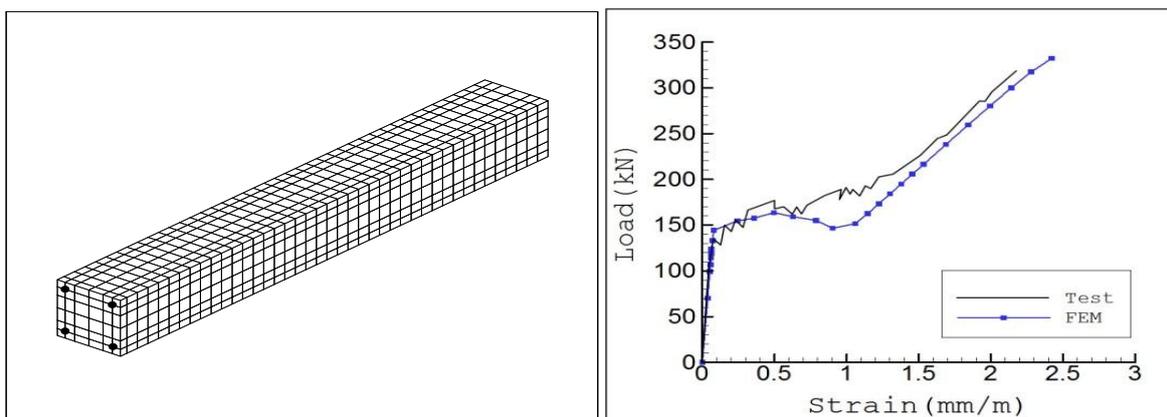


Fig.8: FEM model of RC bar

Fig. 9: FE analysis results.

(3) Model of the entire composite beam including shear connection

The model shown in Fig. 10 and developed for the analysis of the shear composite action in push-out specimen is applied for the shear connection at the interface between the concrete slab and steel beam [18-21]. The studs are modeled by beam elements for simplicity. In addition, the contact area between the stud and concrete in the FEM model is modeled so as to enable interaction by establishing a constraint equation for the displacement occurring at the common node. The verification of the validity of the adopted model is skipped here as it has been already provided in former research results [18-21]. Fig. 11 depicts the three-dimensional finite element model of the entire composite beam including the shear connection. The modeling methods for the steel beam and the slab are those analyzed in sections 3.2.1 and 3.2.2. The composite interface between the slab and the upper flange of the steel beam is modeled by contact surface element so as to enable load transfer through contact between the members.

Figs. 12 and 13 compare respectively the deflection at mid-span and the slip developed between the steel beam and slab at $1/4$ of the span with the experimental results [13]. The comparison of the load-deflection curves reveals the accuracy of the model in simulating the loss of stiffness after the initiation of cracks and the flexural compressive buckling of the upper flange of the steel beam after yielding of the reinforcement.

In Fig. 13, the experimental load-slip curves indicate that slip does practically not occur due to the action of the chemical bond before load of about 290 kN but show comparatively good agreement between the analytical and experimental results after fracture caused by repeated loading. As observed in the preparatory steps of main experiment of Sedlacek et al. [13], the chemical bond developed at the composite interface was seen to fail after 25 cycles under loading corresponding to approximately 40% of the peak load. Accordingly, the composite action provided by this chemical bond is not considered in the finite element analysis.

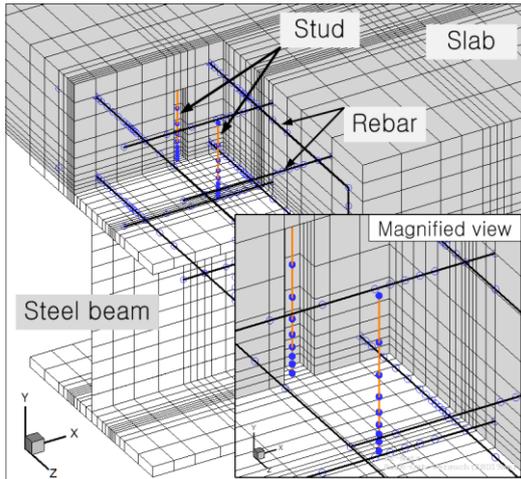


Fig. 10:Model of the shear connection[18-21]

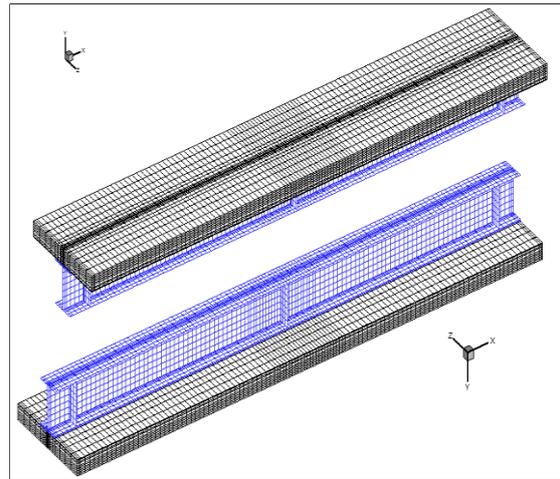


Fig. 11: 3D FE model of the composite beam

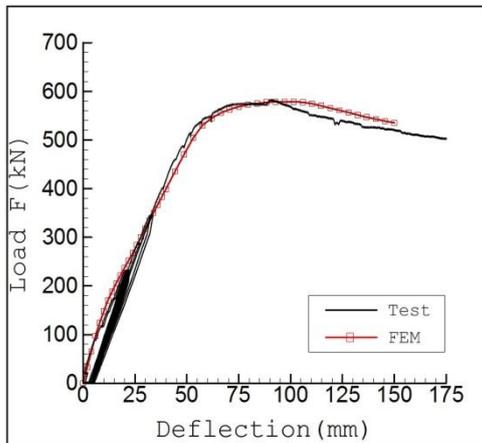


Fig. 12:Comparison of load-deflection curve.

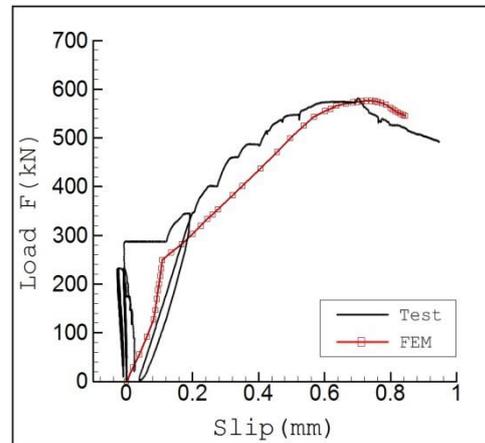


Fig. 13:Comparison of load-slip curve

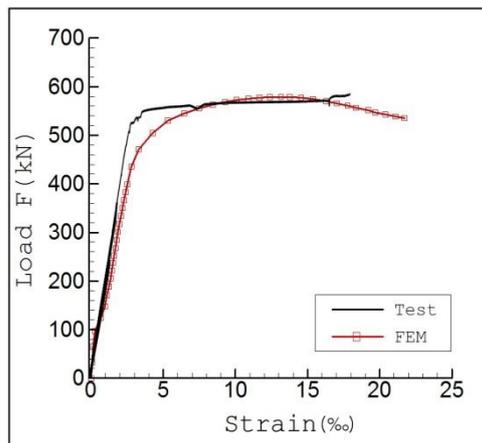


Fig. 14: Comparison of rebar strain

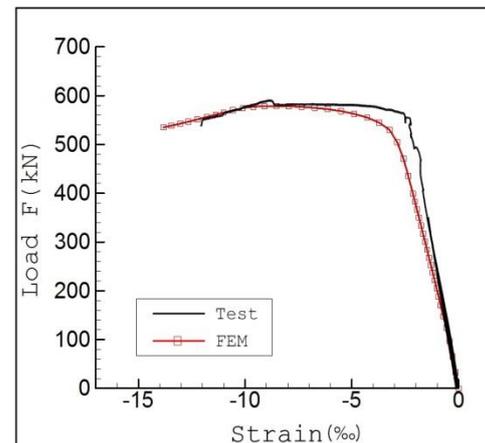


Fig. 15: Comparison of steel beam strain

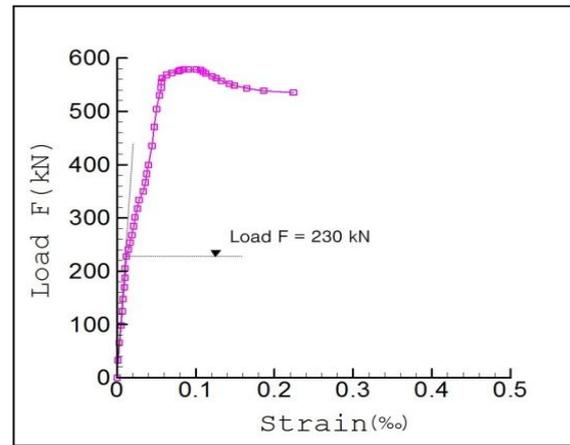
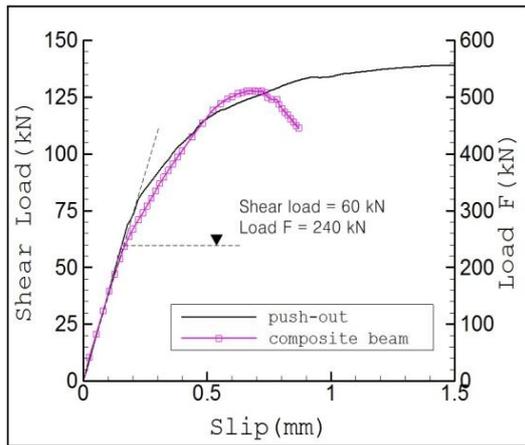
Figs. 14 and 15 compare the strains measured at mid-span in the tensile reinforcement and steel beam to the analytical values. The load-strain curves obtained analytically show relatively good agreement with the experimental results. The error in the ratio of the increase of the load relative to the enlargement of the strain is seen to remain limited indicating that the analytical results are close to the experimental ones.

In view of these observations, we have seen that the analysis is able to reproduce adequately the overall load-deflection behavior of the composite beam as well as the slip behavior at the composite interface. Similarly to the comparison of the strain, local deformation can also be comparatively well simulated by the analysis. Therefore, it can be presumed that the effect of the tensile behavior of the concrete slab on the composite action provided by the studs can be evaluated through the examination of the analytical results.

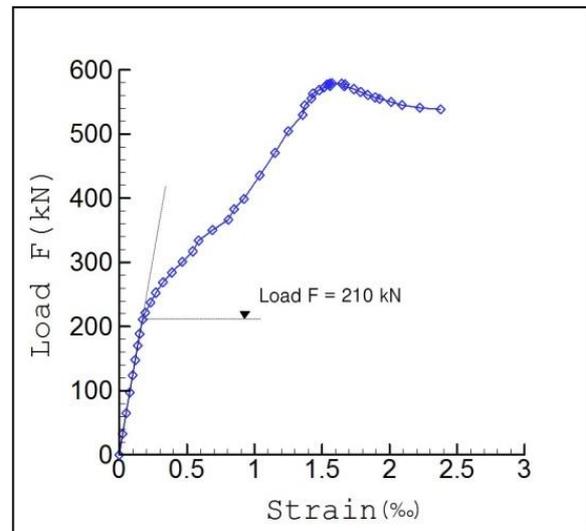
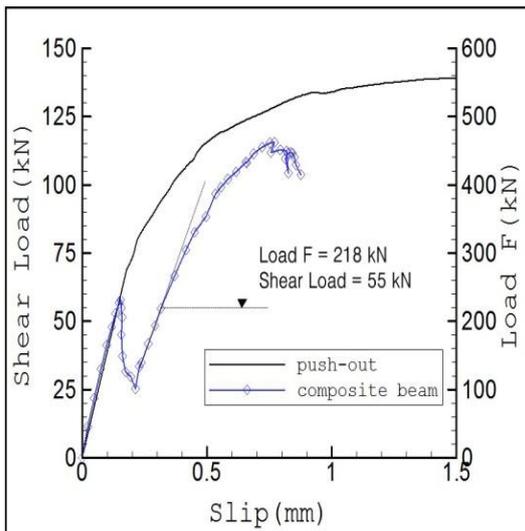
IV. INFLUENCE OF THE TENSILE BEHAVIOR OF THE SLAB ON THE BEHAVIOR OF SHEAR CONNECTION

Since the resultant of the shear force developed in the shear connectors is in equilibrium with the tensile force acting on the slab, the slip behavior of the shear connection is naturally closely related to the tensile behavior of the slab. In order to investigate this relationship, comparison is done between the behavior of the shear studs in the composite beam B400 and the experimental results from push-out test [13]. Figs. 16(a), (b) and (c) compare respectively the analytical load-slip curves of the studs located near the supports, at $L/4$ and at $0.15L$ from mid-span with the push-out test results. Here, the comparison with the push-out test results intends to take the corresponding load-slip relation as reference when comparing mutually the results obtained in this study.

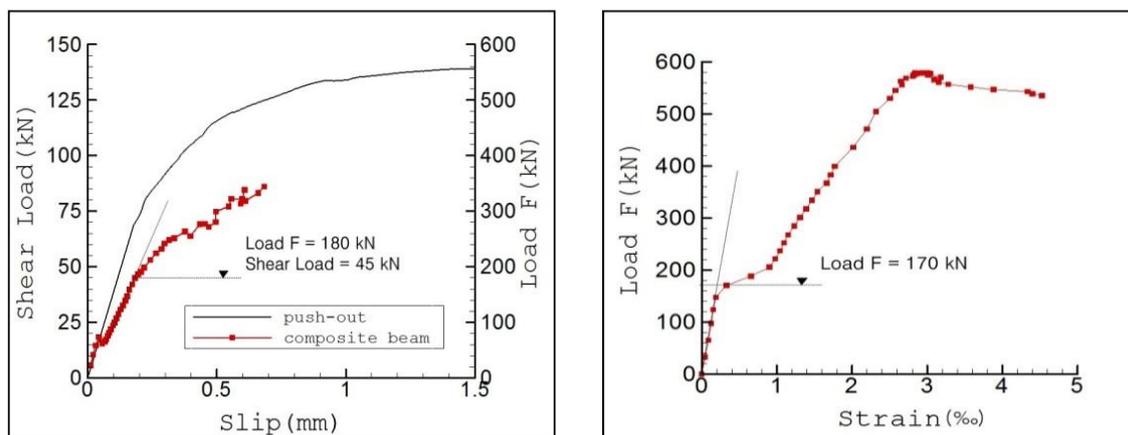
As shown in Fig. 16(a), slip behavior similar to the push-out test is realized for the shear studs located near the supports where there is practically no occurrence of cracks compared to the other regions and with small crack width when cracking occurs. However, in Figs. 16(b) and (c), the shear force sustained by the studs located at $L/4$ and around $0.15L$ from mid-span appears to be comparatively smaller. It can be seen that the shear studs nearby $0.15L$ from mid-span support shear force corresponding to 68% of the push-out test results.



(a) near support of composite beam



(b) at $L/4$ of span



(c) at 0.15L from center of composite beam

Fig. 16: Load-slip curves of studs and load-strain curves of rebar at representative locations in the composite beam

The transient reduction of the load appearing in the analytical results of Figs. 16(b) and (c) can be explained as follows. The load sustained by the concrete part of the slab decreases with the occurrence of cracks in the slab and becomes gradually more supported by the rebar. The transient reduction of the load can be seen as reflecting the tensile behavior of concrete owing to the direct contact between the studs and concrete as shown in the analytical model of Fig. 10. For example, it can be assumed that continuous load-slip relation would be achieved if the studs are modeled by 3D solid elements and if contact surface elements are applied for the interface. However, such modeling method would be unaffordable in term of the efficiency of analysis.

In view of the change in the slip stiffness appearing in the load-slip curve, an initial stiffness of 381.3 kN/mm is developed for the studs at the supports and is similar to that observed for the studs at mid-span and L/4 of the span. However, the stiffness after cracking of the slab drops down respectively to 251.3 and 251.8 kN/mm, which indicates a stiffness loss at identical loading stage. Thereafter and according to the increasing load, the slip stiffness tends to experience clear decrease at each location compared to the initial values. For example, in the push-out test, a stiffness of 140.9 kN/mm corresponding to approximately 37% of the initial stiffness is observed under the action of a shear force of 85 kN. However, a stiffness of 62.6 kN/mm is developed by the studs located near mid-span in loading stage supporting shear force running around 60 to 85 kN. This stiffness corresponds to 16.4% of the initial stiffness and 24.9% of the post-cracking stiffness.

The point to be stressed here is the quasi-synchronous occurrence of the start of the clear decrease in the slip stiffness of the studs and the change in the increase of strain of the rebar as can be observed by comparing the load-slip curves of the studs and load-strain curves of the rebar in Fig. 16. Consequently, the load-slip behavior of the studs in the composite beam subjected to hogging moment appears to be influenced by the tensile behavior of reinforced concrete. Compared to the supports with small bending moment and relatively less occurrence of cracks, the studs located at L/4 and mid-span experience larger loss of stiffness. Especially, the stiffness loss is more pronounced in the studs at mid-span.

In view of these results, the slip stiffness and shear force sustained by the studs appears to be significantly smaller in regions with concentrated occurrence of cracks than in other regions. As reported in the experimental works of Fabbrocino&Pecce [9] and Loh et al. [24], it seems favorable to conduct design so as to avoid the arrangement of shear studs or to achieve partial composition by providing larger spacing between the studs in regions with crack concentration not only in term of the ductility of the entire structure but also in term of design efficiency.

V. CONCLUSIONS

This study developed a 3D finite element model reproducing as possible the actual shape and material properties of the concrete slab, steel beam and shear studs composing the composite beam so as to analyze the behavior of the composite beam subjected to hogging moment. With regard to the verification of the validity of the adopted analytical model, the 3D model appeared to be also appropriate for the analysis of local behaviors like the slip behavior of the shear connection. The analytical model enabled us to examine the influence of the tensile behavior of the slab in the composite beam subjected to hogging moment on the structural behavior including the slip stiffness and maximum shear force of the shear connection. From the analysis results, it was seen that the shear studs located in regions with crack concentration sustained significantly smaller shear force and developed smaller slip stiffness than the studs in other regions. Moreover, the reduction in the slip stiffness of the shear connection appeared to be closely related to the change in the strain of tensile rebar according to the

increase of the load. In the future, experimental and analytical studies shall be conducted considering variables such as the rebar ratio and arrangement of shear connectors to achieve efficient design of the shear connection in composite beams subjected to hogging moment.

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