3D FEM ANALYSIS OF OPEN SANDWICH BEAMS

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ABSTRACT: In the numerical analysis of engineering problems, it is often necessary to properly model the behavior and effects of discontinuities and interfaces. For non-linear analysis of steel-concrete composite structures bond-slip interface plays a crucial role. In this study, the authors develop a three-dimensional (3D) model to simulate the behavior of steel-concrete composite slabs using Finite Element Method (FEM). The aim is to clarify the applicability of the developed model for the relation between the transferred shear force and the relative displacement of stud shear connector by comparing the FEM results with corresponding experimental results on beam type specimens with stud shear connector.
KEYWORDS: transferred shear force, open sandwich beams, stud shear connector, FEM.

1. INTRODUCTION

Composite steel-concrete structures are used widely in modern bridge and building construction. A composite member is formed when a steel component, such as an I-section beam, is attached to a concrete component, such as a floor slab or bridge deck. In such a composite T-beam the comparatively high strength of the concrete in compression complements the high strength of the steel in tension. In the composite T-beam the steel top flange that the studs have been attached to has no deformation (local bending) because the web prevents the deformation from taking place in the flanges. Meanwhile, in the case of steel-concrete composite slab (or open sandwich slab) the steel plate may be affected by the local bending at the position of the studs because there is no web underneath. Throughout this study, the steel-concrete composite slab will be studied and will refer to the steel and concrete as the components of the member.

2. OUTLINE OF ANALYSIS

2.1. FINITE ELEMENT PROGRAM

The non-linear three-dimension finite element program used in this study was developed to analyze the composite members. Element's types used in the program are 20-nodes isoparametric element with 8 integration points, and 16-nodes isoparametric element with 4 integration points. Material types for the element are plain/reinforced concrete, steel, and bond element. For non-linear computation, Newton-Raphson method was applied. Iteration was continued until the convergence for residual displacement caused by unbalanced force was satisfied. For constitutive law of concrete before cracking, three-dimensional elasto-plastic and fracture model [1] was applied. A three-dimensional failure criterion in tension-tension and tension-compression was developed by modifying an existing two-dimensional failure criteria [2]. Also, constitutive model for concrete after cracking has been applied [3]. Furthermore, solution of bond link problems for steel-concrete composite slab was developed. The proposed model that adopts the transferred shear force-relative displacement relationship for stud shear connector was verified in this study.

2.2. ANALYTICAL METHOD

Fig. 1 shows the Finite Element mesh. Because of symmetry, quarter of the open sandwich beams was analyzed. Prescribed displacements were given at the loading point directly.

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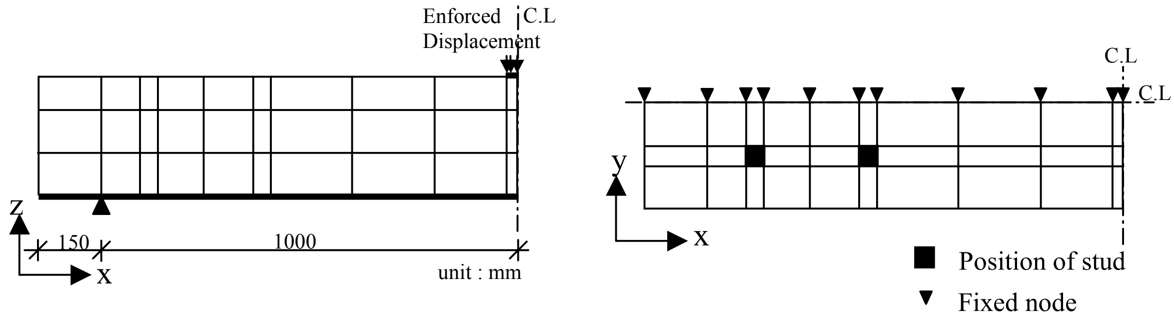


Fig. 1 – Finite Element Mesh

3. EVALUATION OF EXPERIMENTAL RESULTS BY ANALYSIS

The stud shear connectors are required to transfer the shear force between concrete and steel element in order to develop the composite action. In the analysis of the steel-concrete composite beam structures, the composite action between steel plate and concrete should be considered using a transferred shear force-relative displacement relationship of the stud shear connector.

Researches on the stud shear connector were merely conducted by direct pull-out tests [4][5]. In actual sandwich structures the shear connector is not only subjected to the transferred shear force but also compressive force and local bending deformation of the steel plate. The behavior and load carrying capacity of the shear connector may be different from those obtained by the direct pull-out test.

The transfer capacity for the shear connector has been studied [4][5]. Meanwhile, there is no study on the relation between transferred shear force and relative displacement of the stud shear connector except the studies by Saidi [6][7][8] in which shaped steel 'angle' shear connector was used.

Considering this point, the present study was conducted on a series of simply supported beams with symmetric one-point load, and attempted to predict experimentally the relationship between transferred shear force and relative displacement of the stud shear connector in steel-concrete composite beams.

3.1. SPECIMEN DESCRIPTION AND TESTING PROCEDURE

Beam loading experimental program was conducted with the aim of studying the mechanical behavior of stud shear connector for steel-concrete composite beams with emphasis on relationship between the transferred shear force and the relative displacement of stud shear connector [9][10].

Ten steel-concrete composite beams were cast and tested. The parameters of the experimental program were; concrete compressive strength ($f_c^{'}$ = 20.5, 32.1, 47.1 MPa), height of the stud (h_s = 50, 100, 150 mm), spacing between studs in loading direction (s = 150, 200, 250 mm), spacing between studs in direction normal to loading (b = 150, 200 mm), and thickness of steel plate (t_s = 6, 9, 12 mm).

Stud shear connectors were provided at the interface between concrete and steel plate. The shear connectors were welded perpendicular to the steel plate. The specimens were designed to fail due to failure of the shear connector in one side of the beams. The details of specimens and their shear connector are given in **Table 1** and **Fig. 2**.

Table 1 - Details of Specimens

Specimen	$f_c^{'}$ (MPa)	h_s (mm)	s (mm)	b (mm)	t_s (mm)
S-1	20.5	100	200	150	9
S-2				200	
S-4	47.1	100	150	200	9
S-5			200		
S-6			250		
S-7	32.1	50	200	200	9
S-8		100			
S-9		150			
S-10	20.5	100	200	200	12
S-11					6

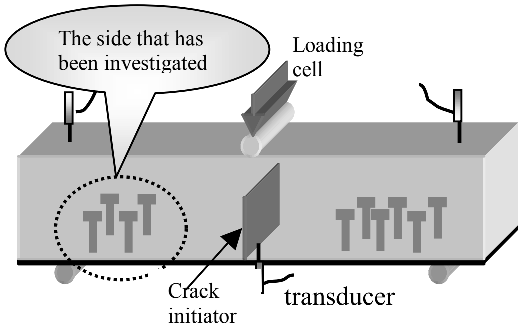


Fig. 2 – Test Set-up

3.1.1. Procedure of calculating transferred shear force

From the strain gauges located on the lines **a**, **b**, **c**, **d**, as shown in **Fig. 3,** the stresses before and after the studs can be calculated using the stress-strain relationship of the steel plate (σ = Eε). From the calculated stresses, the force transferred by each stud can be calculated after knowing the area, which is the multiplication of thickness of steel plate (t_s) by the half of the width of the beam (b/2) (it is assumed that, each stud has its own effective zone which is the half of the width of the beam). For stud **1**, the transferred shear force is the subtraction of the calculated force at the half of line **a** (F_2) from the calculated force at the half of line **b** (F_1), in other words (F_1-F_2), while the other half is used for stud **2**. Same procedure is applied for studs **3** and **4** using the calculated force at lines **c** and **d**.

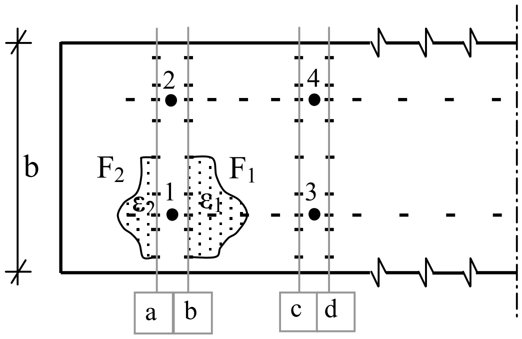


Fig. 3 – Procedure of calculating transferred shear force

3.1.2. Procedure of calculating relative displacement

The relative displacement for studs **1** and **2** will be the relative displacement δ between the steel plate and the concrete block which has been measured by using displacement transducer as shown in **Fig. 4**. In the case of stud **3** the relative displacement will be the relative displacement δ plus the elongation of steel plate between stud **1** and **3**. In the case of stud **4** the relative displacement will be the relative displacement δ plus the elongation of steel plate between studs **2** and **4**.

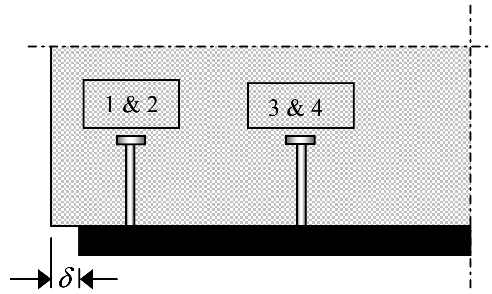
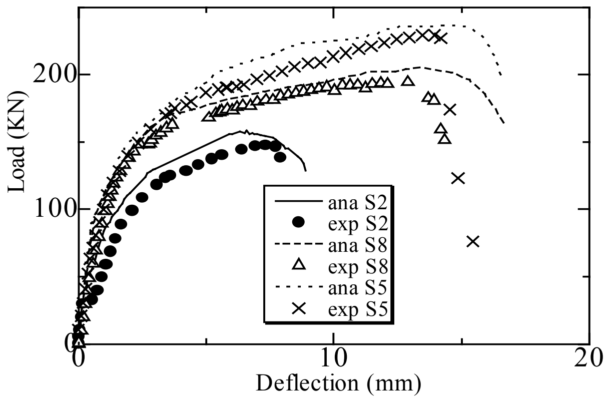


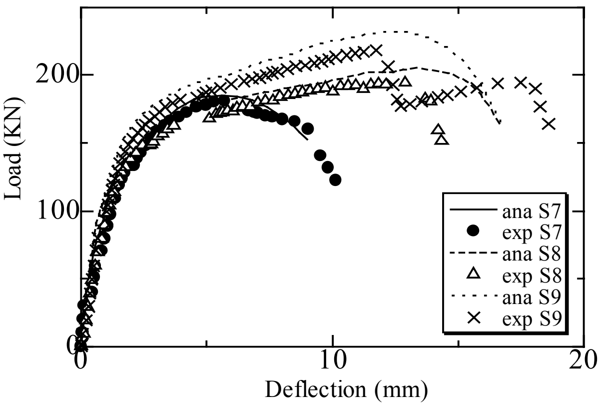
Fig. 4 – Procedure of calculating relative displacement

Table 2 – Ultimate Loads

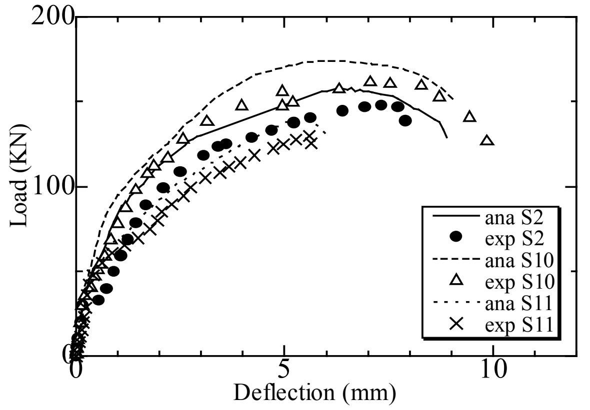
Specimen	Exp. (KN)	Ana. (KN)	Exp./Ana.
S-2	147	158	0.93
S-5	229	237	0.97
S-7	181	185	0.98
S-8	194	205	0.94
S-9	218	232	0.94
S-10	161	174	0.93
S-11	129	139	0.93



(a) – Effect of f_c'



(b) – Effect of h_s



(c) – Effect of t_s

Fig. 5 – Load-Deflection curves

3.2. COMPARISON OF EXPERIMENTAL AND ANALYTICAL RESULTS

3.2.1 Ultimate Load

The ultimate load, in experiment, was reached due to failure of the concrete surrounding the shear connector in all specimens except specimen S-10. Ultimate loads for all specimens are shown in **Table 2** except those for specimens S-1, S-4, and S-6, which were eliminated from the analysis due to indistinct experimental behavior. The FEM calculation was stopped after the peak load was observed. It is clearly seen that predicted loads agree with experimental ones.

3.2.2 Deflection

Experimental and predicted relationships between applied load and deflection of analyzed specimens are shown in **Fig. 5**. The predicted applied loads are slightly higher than the experimental results. It can be said, however, that the analysis can estimate the experimental behavior reasonably. **Fig. 5** (a) and (c) show that, concrete compressive strength '$f_c^{'}$' and thickness of steel plate 't_s' have an effect on the Load-Deflection experimental curves. Meanwhile, height of stud 'h_s', **Fig. 5** (b), has no effect on Load-Deflection curves. By comparing the analytical results with the experimental ones, we can find that the Load-Deflection curves for analysis have the same behavior as the experimental curves.

4. SHEAR FORCE-RELATIVE DISPLACEMENT RELATIONSHIP

4.1. PROPOSED MODEL FOR TRANSFERRED SHEAR FORCE-RELATIVE DISPLACEMENT RELATIONSHIP

Based on the experimental study, a numerical model which simulates the relationship between the transferred shear force and relative displacement of the stud shear connector was proposed.

The proposed formula is a non-linear relationship between transferred shear force (Q) and relative displacement (Δ) as shown in Eq. (1).

$$Q = Q_u \frac{3.15\,\Delta}{1 + 3.15\,\Delta} \tag{1}$$

The proposed model presents the effect of each parameter on the transferred shear force relative displacement relationship. From the analysis of the experimental results we can find that the effect of the parameters as follow; the transferred shear force increases with the increases of concrete compressive strength, height of stud, and thickness of steel plate. For the two parameters, spacing between studs in loading direction 's' and in direction normal to loading direction 'b', their effect could not be clarified, therefore, they were eliminated from the proposed model.

In order to obtain a mathematical relationship between Q_u and the parameters affecting $Q-\Delta$ relationship multiple regression analysis (least square fit) were made. Q_u was used as the dependant variable and the parameters were considered as independent variables. A general experimental model given by Eq. (2), which considered all the parameters, was initially selected.

$$Q_u = g \cdot f_c^{'a} h_s^{\,b} t_s^{\,c} \tag{2}$$

Result of regression analysis, using all possible combinations of the parameters as independent variables, was found to be as given in Eq. (3).

$$Q_u = 0.974\, f_c^{'1.05} . h_s^{\,1.5} . t_s^{\,1.5} \tag{3}$$

where;

Q Transferred shear force (KN),

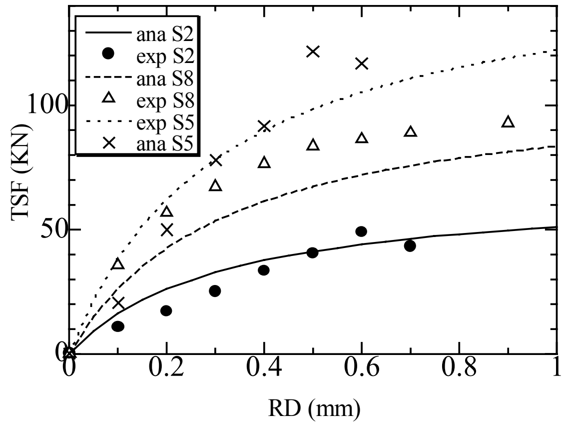
Δ Relative displacement (mm),

$f_c^{'}$ Concrete compressive strength (MPa),

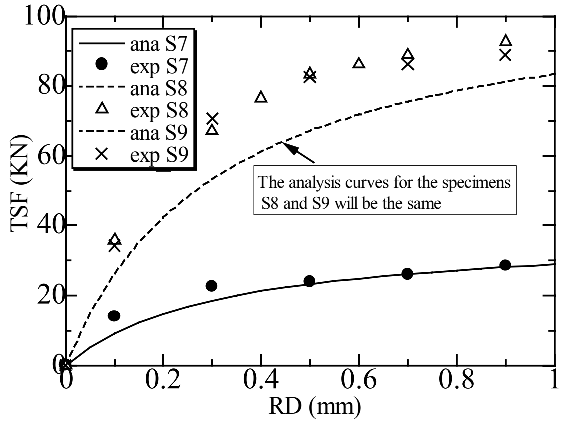
h_s Height of stud (cm), and t_s Thickness of steel plate (cm).

4.2. COMPARISON OF THE PROPOSED MODEL WITH EXPERIMENT

In **Fig. 6**, the proposed model has been compared with the experimental result considering all the parameters that affect the transferred shear force-relative displacement relationship. It was confirmed that the predicted transferred shear force and relative displacement relationship is in agreement with the experimental results. Meanwhile, due to the small difference, which may happen, in the Transferred Shear Force (TSF) and Relative Displacement (RD) relationship between the analytical result and the experimental one, as shown in **Fig. 6**, we got such slight small differences in the corresponding Load-Deflection curves as shown in **Fig. 5**.

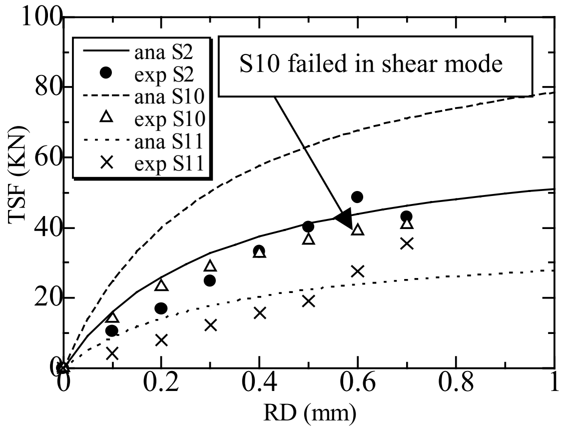


(a) – Effect of $f_c^{'}$



(b) – Effect of h_s

From illustration of **Fig. 6** we can say that the proposed model represents the effect of each factor in some extent. Meanwhile, in the study of the effect of t_s, there are some differences between the experimental result and the proposed model for 12 mm steel plate thickness. The compressive strength of the concrete for the three specimens that have been conducted to study the effect of t_s was not high ($f_c^{'}$ = 20.5 MPa). Therefore, we can say that the specimen with 12 mm steel plate thickness (S-10) was over-reinforced and due to that the specimen failed in shear.



(e) – Effect of t_s

Fig. 6 – TSF-RD relationship

Furthermore, the proposed model has to have some limitation for the effect of height of stud (h_s) that the stud height has an effect on the transferred shear force-relative displacement relationship until an effective height. The portion of the stud more than that effective height has no effect on the transferred shear force-relative displacement relationship. This effective height can be predicted by calculating the curvature of the stud [10]. The curvature of portions at height equal to or lower than 60 mm becomes larger with increasing the load, however the curvature of portions at height equal to or higher than 80mm is almost zero. It was assumed that 70mm is the effective height of stud. Namely, if a stud is higher than 70mm, its performance is almost same as a stud with 70 mm height. Therefore, Eq. (3) was modified as follow;

$$\left.\begin{array}{ll} Q_u = 0.974 f_c^{'1.05} . h_s^{1.5} . t_s^{1.5} & \text{if } h_s \le 7\,\text{cm} \\ Q_u = 18.03 f_c^{'1.05} . t_s^{1.5} & \text{if } h_s \ge 7\,\text{cm} \end{array}\right\} \quad (4)$$

5. CONCLUSION

The present study was conducted on a series of tests on stud shear connector in simply supported open sandwich beam with symmetric one-point load. The aim was to study the effect of concrete compressive strength, height of stud shear connector, spacing between studs in loading direction, spacing between studs normal to loading direction, and thickness of steel plate on the transferred shear force-relative displacement relationship of the stud shear connector. From the analysis of the experimental results we can conclude the effect of the parameters as follow; transferred shear force increases with the increase of concrete compressive strength, height of stud, and thickness of steel plate.

Based on the experimental study, a numerical model which simulates the relationship between the transferred shear force and relative displacement of the stud shear connector was proposed. Also, the proposed model presented the limitation of the effect of height of stud, in which, the effective stud height was assumed 70 mm. The results of the 3D FEM analysis of the open sandwich beams, in which the numerical model for stud shear connector was applied, indicate the reliability of the 3D FEM analysis.

Further experimental study is necessary to clarify the effect of the two parameters, stud spacing in loading direction, *s*, and stud spacing in direction normal to loading, *b*.

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