Effects of the Material Constants of Bond
on Stress Distributions for FRP/ALC Sandwich Slabs

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ABSTRACT

The slabs are one of the heaviest structural elements in bridges or buildings, therefore, various lightweight-slab systems, i.e. using lightweight concrete or installing voids, have been proposed for the increase of the seismic load-carrying capacity of these civil structures. However, in these conventional trials, the weight reduction ratios against the same thickness concrete slabs were less than around 20%. The innovative sandwich panel systems for weight reduction, for the increase of the bending rigidity, and for the improvement of corrosion resistance in long-life uses, are studied in this paper. The herein proposed sandwich panels consist of FRP surface skins and an ultra-lightweight ALC (autoclaved lightweight aerated concrete) core the density of which is very small and may be around 0.5g/cm³. The FRP material would be a very suitable material for anti-corrosion, lightweight and high strength, especially when applied to bridge slabs.

In order to grasp the fundamental structural behaviors of these FRP/ALC sandwich slabs, various finite element analyses for four-point bending loading models are performed in this paper. The adopted variables in the FE analysis are Young’s modulus of bond, the thickness and the width of FRP skins. Consequently, it has been shown that the classical simple composite beam theory is available to estimate the deflection behaviors for the Young’s modulus ratio $E_d / E_s \geq 10^{-3}$ which is satisfied by normally used epoxy bonds. In addition, this paper discusses that as the Young’s modulus of FRP increases, the maxima of normal stress and shear stress at the side surface of the ALC core decrease significantly even though stress concentration occurs near the edge of bond layer.

KEYWORD

sandwich slab, FRP skin, ALC core, local stress concentration, effect of bond stiffness
1. INTRODUCTION

The authors of this paper [1] previously proposed “steel/ALC sandwich slab” for lightweight building slabs, consisting of an ALC core adhesively bonded with steel skins, and performed parametric four-pointed bending tests to understand the sandwich composite stiffness and collapse behaviors as shown in Photo 1. The test results have shown that this kind of sandwich slab system has the mechanical benefit of significant reduction of bending deflection and the dramatic increases of load-carrying capacities compared to no-reinforced ALC slabs [2,3]. The bonded steel skins on the surface of the ALC core show no buckling and the shear fracture of ALC core determines the strength of this sandwich system.

Also, the following has been demonstrated: 1) the bending stiffness of steel/ALC sandwich slabs well-adjust to the ideal laminated beams theory. At the same time, shear-lag phenomena are never observed in the adhesive bonding layers. 2) As local buckling of steel skins does not appear, two types of collapse mode of slabs could be identified, i.e., the yielding of steel skins and the shearing collapse of ALC core. 3) The specimens with small quantity of steel skins collapsed by “steel skin yield mode.” As the steel skin quantity increases, the failure mechanism changes to “ALC core shear collapse mode.” 4) In the case of “steel skins yield mode”, the approximate strength of the slabs can be predicted by the yielding condition of the steel skins. 5) Although in the case of “ALC core shear collapse mode,” the effects of the steel skins are observed. There is a tendency that the maximum shear stress in the ALC core increases inversely to the steel skin quantity.

When this steel/ALC sandwich slab is applied to bridge and ocean structures, the steel skin faces some corrosion problems. This paper proposes the use of lightweight thin-walled FRP plates as the skin materials in the place of steel plates.

2. ANALYTICAL MODELS OF FRP/ALC SANDWICH SLABS

The analytical models in this paper are exactly the same as the previous experimental specimens except for the skin material; FRP skin plates are used instead of steel plates. The ALC panels sandwiched by skins with adhesive bonding with 1mm thickness are shown in Fig.1. Two types of ALC core panels are selected; the small size, S-type model is 600mm in length (span L =540mm), 100mm wide (b_c) and 50mm thick (t_c); the long size, L-type model is 3,000mm in length (span L =2,700mm), b_c =600mm and t_c =150mm, respectively.

Photo.1 Steel/ALC sandwich panel tests [1]

The FRP skins on the upper and lower ALC surface in this paper are the same length as ALC (3,000mm), and the thickness t_f is 1.2mm so as also to be the same as the steel skins adopted in the experiments [1] and width b_f is varied as the analytical parameters.

As for the mechanical properties of ALC cores from the coupon tests in [1], the compressive strength is 5.4N/mm², bending strength 1.3N/mm², Young’s modulus E_c = 1.91kN/mm², Poisson’s ratio 0.21, and density 0.49g/cm³. The 1.2mm steel skin [1] has the yield stress 212N/mm², Young’s modulus E_s =205kN/mm², and Poisson’s ratio 0.30.

For Young’s modulus of the presently used t_f =1.2mm FRP skins, three kinds of FRP are adopted; the high rigid stiffness FRP which may be made from carbon fibers is of Young’s modulus E_f =100kN/mm², the middle rigid stiffness FRP which may be made from hybrid glass/carbon fibers 50kN/mm², and the low rigid GFRP
30kN/mm². The Poisson’s ratios in these FRPs are adopted to be 0.36.

The mechanical properties of the epoxy adhesive bond in [1] were listed as having the compressive strength 49.9N/mm², tensile strength 25.2N/mm², tensile/shear strength 25.3N/mm², Young’s modulus 2.14kN/mm², Poisson’s ratio 0.36, and density 1.38g/cm³. In this paper, only the Young’s modulus $E_a$ varies from $E_s/10^8$ to $E_f$ as an analytical parameter considering its capability of selection for various bond materials (mortal, polymer or silicon type). The bonded thickness $t_a = 1.0$mm has been adopted as referred from the actual one in [1].

3. PRELIMINARY CONSIDERATIONS OF BUCKLING-RESTRAINED SKINS

In the sandwich panel systems composed of multiple materials, several collapse modes can be predicted. For the combination of thin surface skin and relatively massive ALC core, the following representative collapse modes have first been estimated:

[Mode1] elastic local buckling of skin
[Mode2] yielding or failure of the skin material
[Mode3] shear collapse of ALC core
[Mode4] peeling of skin plate accompanying ALC surface adhesion

In Mode 1, complicated design treatment would be needed as that in Tateishi and Yamada [4] where the elastic local buckling of FRP skin plate on relatively lower Young’s modulus core made of urethane was shown experimentally. Yamada et al. [5] studied the effects of the core rigidity of sandwich panels on the elastic local buckling of their skins. The stationarity of total potential energy has been used and the local buckling modes have been adopted as the harmonic expressions including core deflections. As the core rigidity increases, the buckling stress of the skin increases and the buckling restraint zone of core in thickness direction decreases. Through the comparison of this local buckling stress and the failure stress for skins, the minimum of core rigidity to restrain the local buckling $E_{cr}$ are given using the strength of skin $F_f$ and $E_f$ as simply

$$\left( \frac{E_{cr}}{E_f} \right)^2 = \frac{8 (F_f/E_f)^3}{3}$$

The authors have clarified the combination of conditions between surface skin and core materials on strength and Young’s modulus inducing the buckling of skin using Eq. 1, and the ALC core has sufficiently large Young’s modulus to restrain the elastic bucking of steel skins. That is, in the present sandwich slab, the local buckling of skin is negligible.

4. FINITE ELEMENT ANALYTICAL RESULTS AND DISCUSSIONS THEREOF

The commercially available finite element software, NX Nastran, has been used in this study; the solid finite elements with eight-nodes are adopted for ALC core, FRP surface skins, and adhesive bond layers. The linear elastic stress and deflection analyses considering three dimensional effects have been performed.

Fig.1 Loading Condition and Analytical Models
Figure 2 shows the effects of the Young’s modulus of the adhesive bond \( E_a \) on the center deflection at \((X, Y, Z) = (L/2, 0, 0)\) in Fig.1 in the fully covered case of \( b_f = b_c \). Four solid curves in Fig.2 show the present FEA results for the Young’s modulus of the skins \( E_f = 30\text{kN/mm}^2, 50\text{kN/mm}^2, \) and \( 100\text{kN/mm}^2 \) for FRPs and \( 205\text{kN/mm}^2 \) for steel. The dotted curves are the results based upon the well-known composite beam theory considering bending and shear deflections as,

\[
\delta_c = \frac{23pl^3}{1296E_fI_e} + \frac{PL}{5A_cG_c}
\]

where \( I_e \) is the effective moment of inertia for the composite slab beam, \( A_c \) the cross sectional area of ALC core, and \( G_c \) the shear modulus of ALC core. The center deflection value \( \delta \) in Fig. 2 is normalized by that for no-reinforced ALC slabs \( \delta_0 \)

\[
\delta_0 = \frac{23pl^3}{108E_fI_e} + \frac{PL}{5A_cG_c}
\]

Figure 3 shows the variation with \( E_a / E_s \) on the normal stress \( \sigma \) of the center of the span at point A (surface of upper FRP skin), B (surface of lower FRP skin), C (upper bond layer), D (lower bond layer), E (upper side of ALC core in center), F (lower side of ALC core in center), G (upper side of ALC core in edge), and H (lower side of ALC core in edge). The vertical axis is normalized by the maximum normal stress for no-reinforced ALC slabs \( \sigma_0 = \frac{PL}{ht^2} \); that is, \( \sigma_0 = 1.3\text{N/mm}^2 \) (bending strength of ALC material) is related to \( P_b = 6.5\text{kN} \) in the case of L-type.

For example, the ratios of \( E_a / E_s \) for mortal, epoxy and silicon bonds are around \( 10^{-1}, 10^{-2} \) and \( 5 \times 10^{-6} \), respectively. Shown in these figures are that the composite beam theory in solid lines is available to estimate deflection behaviors for \( E_a / E_s \geq 10^{-3} \) which is satisfied in various normally used epoxy bonds. But when a very soft silicon type bond is adopted, the composite beam theory yields dangerous estimations; the shear deflection in the bond layers should be considered and an alternative FEA may be recommended.

In Fig.3 for \( b_f=0.5b_c \), the tensile stress of the ALC core at point G varies with \( E_a / E_s \) or \( E_f \). Various parametric FEA results for \( E_a / E_s \geq 10^{-3} \) including those of S-type show that as \( E_f \) increases the maximum of \( \sigma \) decreases and the associated bending failure load \( P_b \) would be expected to increase.

Figure 4 shows the variation with \( E_a / E_s \) on the shear stress \( \tau_{xy} \) of \( X = 350\text{mm} \) at various points of ALC core; A is the cross section center, B side surface, and C near the edge of upper bond layer. 
Fig. 3 Normal Stresses in the case of $b_l = 0.5b_c$ (L-type, $X = L/2 = 1350$ mm)
The vertical axis is normalized by the average shear stress for no-reinforced ALC slabs $\tau_0 = P/(2A_c)$; that is, $\tau_0 = 0.0364\text{N/mm}^2$ and $P_0=6.5\text{kN}$ in the case of L-type. The allowable shear stress for sustained loading according to Japanese ALC Association (2004) is $0.08\text{N/mm}^2$. Even though the stress concentration occurs near the edge of the bond layer, $\tau_{xy}$ at the point B decreases as $E_f$ increases.

5. CONCLUSIONS

In this paper, various finite element analyses for the structural behaviors of FRP/ALC sandwich slabs subjected to the four-point bending load have been performed. It has been shown that the classical simple composite beam theory is available to estimate the deflection behaviors for the Young’s modulus ratio $E_f/E_s \geq 10^{-3}$ which is satisfied in normally used epoxy bonds. In addition, this paper has discussed that as the Young’s modulus of FRP increases, the maxima of normal stress and shear stress at the side surface of ALC core decrease significantly even though stress concentration occurs near the edge of the bond layer.

REFERENCES