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Nonlinear Modeling and Analysis of AAC in-filled Sandwich Panels for out of Plane Loads

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Abstract—Sandwich panels are widely used in the construction industry for their ease of assembly, light weight and efficient thermal performance. They are composed of two RC thin outer layers separated by an insulating inner layer. In this research the inner insulating layer is made of lightweight Autoclaved Aerated Concrete (AAC) blocks which has good thermal insulation properties and yet possess reasonable mechanical strength. The shear strength of the AAC infill is relied upon to replace the traditionally used insulating foam and to provide the shear capacity of the panel. A comprehensive experimental program was conducted on full scale sandwich panels subjected to bending. In this paper, detailed numerical modeling of the tested sandwich panels is reported. Non-linear 3-D finite element modeling of the composite action of the sandwich panel is developed using ANSYS. Solid elements with different crashing and cracking capabilities and different constitutive laws were selected for the concrete and the AAC. Contact interface elements are used in this research to adequately model the shear transfer at the interface between the different layers. The numerical results showed good correlation with the experimental ones indicating the adequacy of the model in estimating the loading capacity of panels.

***Keywords*—**Autoclaved Aerated Concrete, Concrete Sandwich Panels, Finite Element Modeling.

I. Introduction

TYPICAL Precast Concrete sandwich panels (PCSPs) are made of two reinforced concrete layers separated by an insulating layer which can take the form of rigid foam or honeycomb insulating core. These types of panels serve as thermally and structurally efficient elements used for exterior walls and roofs. They reduce heating and cooling costs for the structure since they require lower peak loads by about 13 percent for heating and 30 percent for cooling than insulated metal or wood-framed walls having the same U-value subjected to the same heat gradient conditions. They are designed to withstand vertical gravity loads from roofs and floors, lateral wind and seismic loads, insulate the structure and also to provide both an interior and exterior finished surface.

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PCSPs are used extensively worldwide since they provide high quality, proven durability, easy of erection and attractive architectural appearance. The several aspects related to the use, design, manufacturing and detailing of such panels have been covered in depth in the report prepared by the PCI committee on Precast Sandwich Wall Panels [6].

Available PCSP systems are categorized into three major types:

1) Full composite panels – Full interaction between the two concrete wythes is achieved by providing adequate connection to allow transfer of shear between the different panel layers. In this case the two concrete wythes act together as oune unit as would normally occur in solid slabs.
2) Non-composite panels – No interaction exist between the two concrete wythes. These types of panels are mostly used for architectural purposes. Alternatively, these panels could be designed such that the load is supported by one wythe only called the structural wythe.
3) Partially composite panels – Connection between the concrete wythes is developed through friction between concrete and inner insulating material, use of solid concrete zones, bent reinforcing bars and metallic/non-metallic shear connectors. The amount and type of these connectors determine the degree of composite action on a scale from 0 to 100 and such panels behave as partially composite panels. However, it should be noted such connectors would lead to thermal bridges and thereby decrease the thermal efficiency of the panels.

A recent experimental study was performed where autoclaved aerated concrete (AAC) blocks were used in place of the traditional foam [1]. This study examined the behavior of such panels using different types of shear connections. The outcomes of this study showed that the proposed system is very structurally sound. In this paper, a finite element idealization of this system is developed and the results of this finite element model are compared to the experimental results. Close correlation between the model and the experimental results was shown.

II. Literature Review

Several attempts have been undergone to accurately model the behavior of sandwich panels. A previous study [4] to test precast concrete sandwich panels with a hybrid shear connectors made of fiber-reinforced plastic and prestressed steel strands. A finite element modeling was developed using

ANSYS where the slab was modeled using plane stress elements to model the concrete and insulation layers with an assumption of full bond between the layers. Beams elements were used to model the steel strands and truss elements to model the FRP connectors. Cracks were modeled using a combination of interface and control elements. In a different study [2] the concrete wythes were modeled as 3D shell elements and 3D bar elements were used to model the shear connectors and steel reinforcement. The contribution of the foam was ignored and was not included in the model.

In this study a more comprehensive analysis will be done using ANSYS. The effect of sliding between layers is studied using contact elements to model the interface between the layers. A special solid element (Solid 65) is used to model both the concrete and AAC blocks. This element is capable of modeling cracking and crushing failure of concrete.

III. Model Description

Non-linear finite element analysis of reinforced concrete structures has been under extensive research in the recent decades. Several constitutive models have been proposed in addition to a number of numerical techniques to be incorporated into finite element programs. These findings have made it possible to use the finite element idealization with high accuracy in problems that deal with design and analysis of reinforced concrete structures. A commercial finite element package (ANSYS 12.0) was used due to its advanced non-linear capabilities to model reinforced concrete structures. A 3-D model was created to simulate the simply supported sandwich panels under a 4-point loading test. Due to both geometrical and loading symmetry, only one quarter of the panel was drawn to reduce computational time. The FEM mesh used is displayed in Fig. 1.

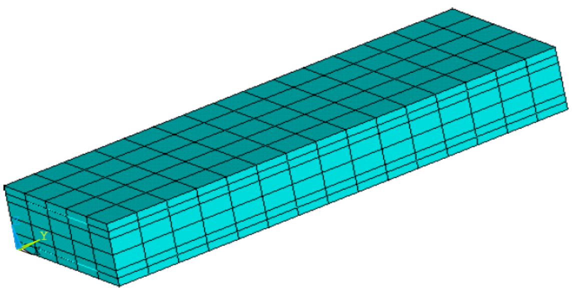

Fig. 1 FEM Model

FEM runs were performed with and without steel shear connectors. Each component of the sandwich panel specimens was modeled separately using the wide range of elements in ANSYS library. Three types of elements were used in this analysis. A brief description of these elements is given below.

A. Types of Elements

1. 3-D Solid Element

Solid65 element is a used to model both the concrete wythes and the AAC blocks. This element has 8 nodes with 3 translational degrees of freedom at each node. Extra displacement shapes are used to correctly model the bending deformation. It also has special cracking and crushing capabilities. In this analysis, both cracking and crushing modes of failure are activated. The failure criterion under a multi-axial state of stress is based on the work done by [7]. A failure surface is defined which is primarily based on the uniaxial tensile and compressive strengths. Whenever a crack occurs, the stress-strain relation is modified by introducing a plane of weakness in the direction perpendicular to the crack. Tensile stress relaxation after cracking is included to help convergence. A shear transfer coefficient is used to reduce the transfer of shear through the crack. A closed and open shear coefficient designates the shear transfer through an open and closed crack respectively.

2. Link Element

Link8 element is used to model both the steel reinforcement and shear connectors as shown in Fig. 3. This element is a uniaxial tension and compression element with 3 degrees of freedom at each node, no bending of the element is considered. The decision to treat the diagonal shear connectors as truss members was a fair assumption since the lateral deformation of the shear connectors is fully restrained by the surrounding concrete and AAC. The shear connectors were assumed to be fully connected to the nodes at mid-thickness of the wythes thus preventing slippage of the shear connectors from the concrete wythe. The discrete representation of steel using link8 element was preferred over using a smeared model, where the reinforcement would be uniformly spread throughout the concrete elements since it yields more accurate results.

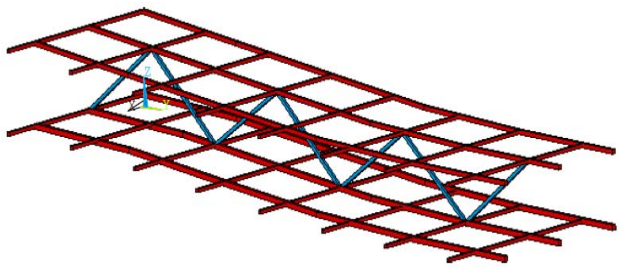

Fig. 2 Link8 Elements for Steel Reinforcement and Shear Connectors

3. Contact and Target Elements

The interface between the concrete and AAC layers was modeled using CONT174 and TARGE170 elements. These two elements together form a contact pair. Contact elements were overlaid on the AAC layer whereas target elements were overlaid on the concrete layers. Contact occurs when the contact surface comes in contact with the target surface. Contact between the two surfaces is treated by defining a value for the contact stiffness between the two surfaces. Both normal and tangential contact stiffnesses are required. The default values works well in most cases and are used in this analysis. To model friction between the two surfaces, ANSYS uses Coulomb friction model. According to this model, the two surfaces start to slide against each other whenever a maximum shear stress is exceeded. This shear stress is a function of the normal stress and an assumed friction coefficient. The friction coefficient used here was 0.001 to simulate the very weak friction bond between the AAC and concrete.

B. Loads and Boundary Conditions

Symmetry boundary conditions were set along the symmetry lines. The nodes along the bottom edge were restrained to simulate the simply supported end condition. The load was applied incrementally through nodal forces. The own weight of the panel was also included in the analysis.

C. Material Properties

The material properties used in the model are shown in Table 1.

Shear transfer coefficients typically range from 0 to 1, with 0 representing a very smooth crack (complete loss of shear transfer) and 1 representing a very rough crack (no loss of shear transfer). The selected values are based on previous research work [5]. The tensile strength is assumed to be 0.1 of the compressive strength.

D. Non-linear Options

A static non-linear analysis was performed. The load was applied incrementally in small steps to achieve a rapid convergence rate. A full Newton-Raphson approach was used with adaptive descent option activated. Adaptive descent is a technique which switches to a secant matrix when convergence difficulties are encountered and switches back to the full tangent matrix when the solution starts to converge. An un-symmetric solver is used since contact problems involving friction produce un-symmetric stiffnessses.

Prior to cracking, the default L2-norm force convergence criterion is used. However, once cracking is initiated, convergence using the default force criterion becomes impossible. Therefore, further to cracking of the panel the force convergence criterion was dropped and a very restrictive displacement criterion was enforced. The reference and tolerance values for the displacement criterion were set to 5 and 0.5 respectively. These two values were multiplied together during the solution to produce a criterion of 0.25

TABLE I
MATERIAL PROPERTIES USED IN THE MODEL

Concrete		AAC		Steel Reinforcement		Shear Connectors	
Linear Isotropic		Linear Isotropic		Linear Isotropic		Linear Isotropic	
EX	25665 MPa	EX	2181 MPa	EX	200000 MPa	EX	200000 MPa
PRXY	0.18	PRXY	0.18	PRXY	0.3	PRXY	0.3
Multi-linear Isotropic		Multi-linear Isotropic		Bilinear Isotropic		Bilinear Isotropic	
Stress	Strain	Stress	Strain	Yield Stress	400 MPa	Yield Stress	250 MPa
0.00054	13.85	0.00054	1.18	Tangent Modulus	20	Tangent Modulus	20
0.001	24.66	0.001	2.1				
0.0015	30.88	0.0015	2.63				
0.002	34.18	0.002	2.91				
0.0027	35	0.0027	2.98				

EX is the modulus of elasticity and PRXY is the Poisson's ratio. A multi-linear stress-strain curve is used to model the concrete and AAC to help with convergence of the nonlinear solution algorithm. The assumed stress-strain curve is based on the work done in [5]. The required parameters to define the failure surface of the concrete and AAC are listed in Table II.

TABLE II
PARAMETERS FOR FAILURE SURFACE

	Concrete	AAC
Open Shear Coefficient	0.3	0.3
Closed Shear Coefficient	0.8	0.8
Uni-axial Compressive Strength	35 MPa	2.98 MPa
Uni-axial Tensile Strength	3.5 MPa	0.298 MPa

which was considered small enough to capture the correct behavior of the panel.

IV. RESULTS AND DISCUSSION

The maximum deflection at mid span was plotted against the applied load. A comparison between the experimental and FEM load deflection curve for the case using no shear connectors is shown in Fig. 3. Panels A1 and A2 are identical panels tested for comparison. For these panels, the AAC blocks were scratched to increase the friction between the concrete layers and AAC. It can be seen that the FEM curve compares very well to the experimental curves especially panel A2.

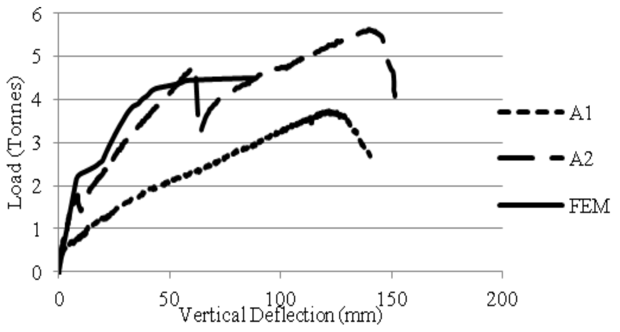

Fig. 3 Load Deflection Curve for the Panels with No Shear Connectors

Panel A1 had an initial separation between the concrete and AAC layers which led to its low stiffness. The near-horizontal portion of the FEM curve at load 2.3 tonnes was due to a separation between the concrete and AAC. This separation was also observed during the actual test at a load slightly lower than 2 tonnes and again at a load of 4.8 tonnes and led to a drop in the experimental curve. The ultimate experimental load obtained in A2 was slightly higher than the FEM load. A comparison between the measured relative sliding between the concrete wythes and the results obtained from the model is shown in Fig. 4. Again, the FEM results show reasonable agreement to slab A2. It can also be noted that there is a close correlation between the relative horizontal sliding and the vertical deflection in the panel. The deflection increases notably when the connection between the two wythes is lost leading to a considerable increase in the relative sliding.

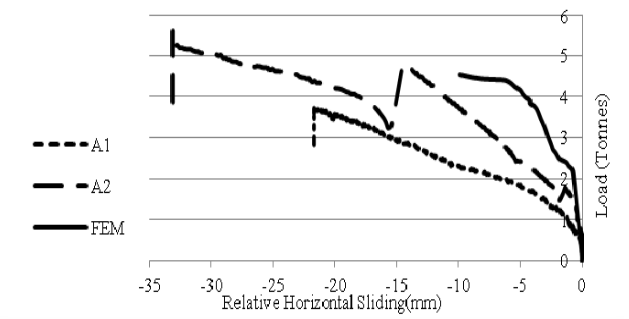

Fig. 4 Relative Horizontal Sliding for the Panels with No Shear Connectors

For the case with steel shear connectors, Fig. 5 shows both the experimental and FEM load deflection curves. B1 and B2 are identical panels tested for comparison. The AAC blocks were not scratched to minimize the friction effect between the concrete layers and the AAC. Two truss shaped steel connectors were used for each panel [1]. Panel B2 had low stiffness possibly due a small embedment length of the steel shear connectors into the concrete wythes leading to ineffective shear connection between the sandwich panel layers. The FEM curve is almost identical to the experimental curve of B1 until a load of about 5 tonnes. According to the analysis given in [1] a disconnection of the steel shear connectors occurred at this load as verified by the strain readings in the shear connectors. However, this behavior was not captured by the finite element model since complete interaction was assumed between the steel shear connectors and the concrete. However, the ultimate load obtained through the model is in close agreement to the experimental load.

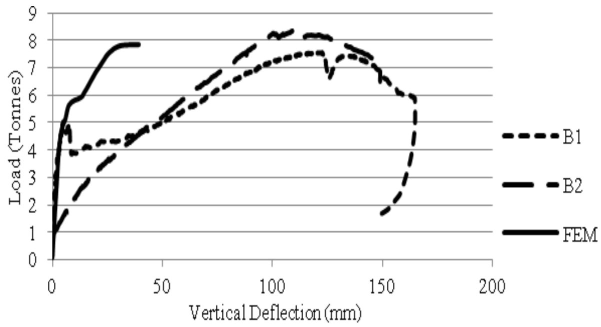

Fig. 5 Load Deflection Curves for the Panels with Steel Shear Connectors

The relative horizontal sliding between the two concrete wythes for the panels using steel shear connectors is shown in Fig. 6. There is also an apparent correlation between the relative sliding and the measured vertical deflection of the panel for this type of panels. The FEM curve aligned perfectly with the experimental curve for slab B2 until a possible disconnection of the steel connectors occurred in the tested specimens.

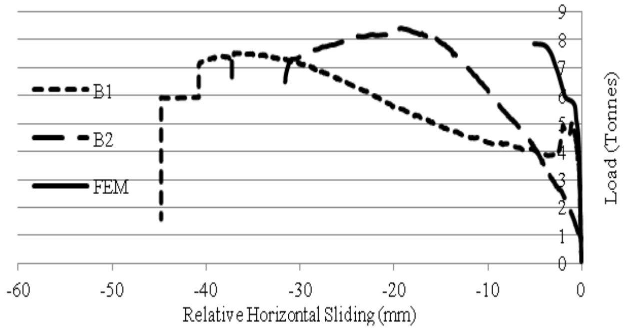

Fig. 6 Relative Horizontal Sliding for the Panels with Steel Shear Connectors

The cracking pattern obtained in the finite element analysis as shown in Fig. 7 shows tensile cracking at the mid span of the panel. This mode of failure was identical to that obtained experimentally where the panels witnessed tensile cracks in both wythes prior to failure. Note that only one quarter of the panel is shown.

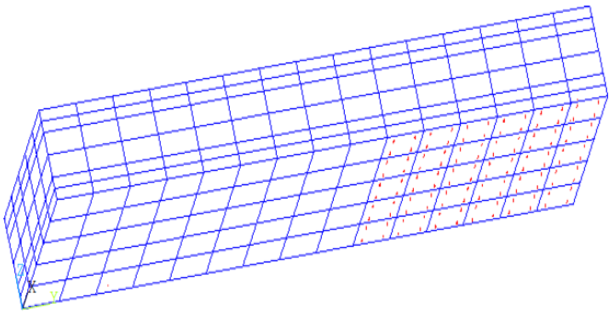

Fig. 7 Relative Horizontal Sliding for the Panels with Steel Shear Connectors

V. Conclusion and Recommendations

The finite element model was able to capture the correct behavior of the sandwich panels. The sliding between the layers was modeled with a reasonable level of accuracy. The pattern of failure obtained through the FEM was similar to that observed experimentally. The developed model can be used for detailed parametric study of the effect of different design parameters on the performance of reinforced concrete sandwich panel with AAC blocks infill. However, further tests need to be performed to determine a better estimate for the different friction parameters to be inputted to the finite element model.

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References

[1] Abdel-Mooty, M., Al-Kashif, M., Fahmy, E., Abou Zeid, M., and Haroun M. (2012). Reinforced Concrete Sandwich Panels with Autoclaved Aerated Concrete Infill, Proceedings of the International Conference on Innovation and Technology for Sustainable Built Environment, April 16-17, Malaysia.

[2] Benayoune, A. et al. (2008). Flexural Behaviour of Precast Concrete Sandwich Composite Panel – Experimental and Theoretical Investigations, Construction *and Building Materials Journal*, *Vol. 22*, pp 580-592.

[3] Fahmy, E., Shaheen, Y., Abou Zeid, M., and Gaafar H. (2006). Ferrocement Sandwich and Hollow Core Panels for Wall Construction, *Journal of Ferrocement, Vol. 36, No. 3*, Thailand, July 2006.

[4] Salmon, D., Einea, A., Tadros, M., and Culp, T. (1994). A New Structurally and Thermally Efficient Precast Sandwich Panel Systems, *PCI Journal, Vol. 39, No. 4*, 90-101

[5] Kachlakev D.I., Miller, T., Yim, S., Chansawat, K. and Potisuk, T. (2001). Finite Element Modeling of Reinforced Concrete Structures Strengthened With FRP Laminates, California Polytechnic State University, San Luis Obispo, CA

[6] Kim E. Seeber et al. (1997). State-of-the-Art Report on Precast/Prestressed Sandwich Wall Panels- PCI Committee Report, *PCI Journal, Vol.42, No.2*, pp 1-61

[7] Willam, K. and Warnke, E. (1975). Constitutive Model for the Triaxial Behavior of Concrete. Proceedings, International Association for Bridge and Structural Engineering, Italy. *Vol. 19*. p. 174.