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The Combined Finite-Discrete Element Analysis of Precast Lightweight Foamed Concrete Sandwich Panel (PLFP) Under Axial Load

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Abstract—**This paper presents a comprehensive study on structural and damage behaviours of Precast Lightweight Foamed Concrete Sandwich Panel (PLFP) under axial load. The 3D models were developed using the finite-discrete element method (FDEM) with different material nonlinearities of concrete cracking/crushing and steel bar plasticity, and geometrical nonlinearities of large load-deflection. The precast lightweight foamed concrete sandwich panel consists of double lightweight foamed concrete wythes and a polystyrene insulation layer. The concrete panels are reinforced with bars and tied to each other through the insulation layer by shear connectors. The material models of concrete capping and foamed concrete are based on the Mohr-Coulomb with Rankine cut-off and Rotating Crack. Meanwhile, the steel reinforcement and truss connector were modelled using the Von-Mises plasticity criterion. The damage mechanisms of PLFP were numerically observed and validated using experimental results. The structural behaviour in term of load-deflection profiles from numerical results were compared with results obtained from the similar panels of experimental test. The damage mechanism and load-deflection profiles show a good agreement.**

Keywords—**Combined Finite-Discrete Element Method, Structural Behaviour, Damage Mechanism, Lightweight, Foamed Concrete, Sandwich Panel.**

I. Introduction

The computational modelling of composite structures has greatly dependent on two numerical schemes; finite element and discrete element methods. Finite element method (FEM) is almost invariably based on a continuum failure which although permitting the development of crack fields to be simulated in a smeared sense, however that, do not allow discrete fracture to be traced. The finite element method is nowadays old fashion due to the result that depending on the continuum failure pattern. It is suitable for problem which are linear or in which the extent of cracking is limited. It is not a common solution route for multi-fracturing situations whereby individual material particles are formed, such as the simulation of reinforced concrete as composite structure. On the other hand, the discrete element method is relatively computational intensive where the elements are structurally arranged, whereas in reality the propagation of cracks within an isotropic, brittle material, such as concrete follows near random unpredictable paths which have been used for simulation of fracture of reinforced concrete structure. The combined finite–discrete element method is newly developed numerical method aimed for failure, fracture and/or fragment of reinforced concrete structure [1]. The method combines aspects of both finite elements and discrete element. It is paramount to employ the latest technology which is the combined finite-discrete element method (FDEM) to ensure the accuracy and the credibility of the numerical results. Especially for the foamed concrete structures that behaves in a complex manner. Therefore, this study has been focused on numerical investigation of structural behaviour and damage mechanism of precast lightweight foamed concrete sandwich panel under axial load using the FDEM.

A. *Precast Lightweight Foamed Concrete Sandwich Panel*

The concept of industrialization has been emerged on the building technology and become preferred option in the construction projects. This includes the numerical application of newly developed Precast Lightweight Foamed Concrete Sandwich Panel (PLFP) as composite materials and building components. The precast concrete sandwich panel usually consists of two layers of high strength wythe and separated by a low strength of core layer as can be seen in Fig. 1.

The precast concrete sandwich panels have been used for many years in buildings and recently being used as load bearing members in naval structures [3]. Therefore, it is not surprising that the precast concrete sandwich panels have gained popularity and attention to be used as an effective structural form in the buildings and construction industries. Sandwich construction form has distinct advantages over conventional structural sections because it has comparatively low cost, high stiffness and high strength to weight ratios [4-7]. The combination of wythe and core layer is therefore produce so-called quasi-composite behaviour. In addition, the quasi-composite behaviour of the precast sandwich panel is also formed by the reinforced concrete capping at the both

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ends of the panel and the truss connectors. Such behaviours of composite structure have been observed by Gara et al. [8] through intensive investigations of experimental tests and numerical modelling of wall sandwich panels. Meanwhile, Mohamad et al. [7] have performance an investigation of the structural behaviour of precast lightweight foamed concrete sandwich panel under axial load with single shear truss connectors. It was observed experimentally that the achieved ultimate strength is affected by the compressive strength of the foamed concrete that used as wythes, the presence of concrete capping and the slenderness ratio. Specimens with capping at both ends recorded higher ultimate loads with no premature crushing. Failure of panels with slenderness ratio, H/t < 18 were happen by premature buckling near the supports whereas for panels with higher H/t ratio, slight bending was observed in the middle zone.

B. *Computational Modelling of Foamed Concrete*

A number of researches have been carried out to model foamed concrete using numerical methods. Previous investigation reported that the results of a research study concerning the mechanical behaviour of syntactic foam employed as core material for sandwich composite panels. Experimental and numerical results are presented and compared at the macroscopic scale. The main features observed in the uniaxial, biaxial and Three Point Bending (TPB) tests were highlighted by Rizzi et al. [9]. This resulted in the bimodulus constitutive model of the Drucker-Prager type was chosen for modelling biaxial stress states with diffused damage of foamed concrete. Since the Drucker-Prager is stress-dependent material model, thus the Mohr-Coulomb and Rankine criteria can also be used in a simplified form of the constitutive law of foamed concrete.

Experimental tests and numerical simulations on both sandwich composite and its separate components have been performed by Corigliano et al. [10] in order to characterize the complex mechanical behaviour of such a highly heterogeneous material. All the numerical simulations have been performed with the commercial finite element code ABAQUS. In the numerical scheme, a Rankine criterion was assumed for the simulation of damage in the core and the skins, while a control on the maximum shear stress was adopted for the strip of elements at the boundary core/lower skin for the simulation of skin debonding. In the simulation, the core and the skins was considered as homogeneous and isotropic, while the presence of piles was neglected. The models chosen for the numerical simulations are the best models to correctly describe the real material behaviour and of offering a cost-effective analysis tool for numerical simulations in a real industrial environment.

An extensive investigation involves fourteen PLFP specimens of experimental tests and numerical finite element simulations with single shear truss connector under axial load have conducted by Mohamad. [11].

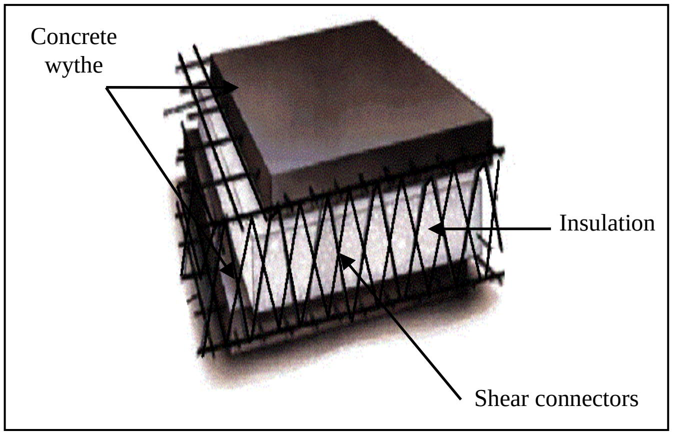

Figure 1: Typical Precast Sandwich Panel [2].

All the numerical simulations have been performed with the finite element code LUSAS using a 2D plane stress. In the numerical simulations, a multi-crack concrete (model 94) has been chosen for foamed concrete wythes. It was found that the results of ultimate strength from experimental are not reliable with finite element method with different percentage between these two results are high as 19%.

II. The Combined Finite-Discrete Element Model

A. *Physical Model*

The modelling of precast lightweight foamed concrete sandwich panel consists of foamed concrete as outer wythes and polystyrene as core layer. The wythe is reinforced with steel bars. In addition, shear steel truss connectors are used to tie the reinforcements from the bottom to top panel. The function of shear connector is to transfer the applied load from one wythe to the other. There are two models with different dimensions, slenderness ratios and sizes of truss connectors as described in TABLE I.

The designed reinforcement used in the foamed concrete wythes are circular 9 mm diameter bars. It used as the longitudinal reinforcement for the inner and outer wythes. Meanwhile, the shear connectors are continuous truss-shaped connectors made of 6mm diameter mild steel bar and bent to an angle 45°. The shear connectors are used to tie the inner and outer wythes together so that the panel acts as an unit of composite structural elements. Five connectors are used over the width of panel. Each row of the shear connectors is continuous and differences height with the panel.

TABLE I. DETAILS OF SPECIMENS FOR PANELS PA-1 AND PA-2

Model	H x W x t	H/t	Diameter of Shear Connectors	Vertical Reinforcement
PA-1	1800 x 750 x 100	18	6 mm	9 mm
PA-2	2500 x 750 x 100	25	9 mm	9 mm

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B. *Finite-Discrete Element Model*

To numerically investigate the structural behaviours and damage mechanism of PLFP, the combined finite-discrete element program so-called ELFEN is employed to ensure the accuracy of cracking/crushing and load-deflection profile. The foamed concrete wythes are modelled using unstructured triangular-noded elements whilst the steel reinforcement bar and shear connecters are discretized as two-noded 2D Simo beams. The values of the second moment area, product moment of area, the effective shear area of the steel are used to represent the geometric and deformation of bar elements. For geometric bar element, the bond between foamed concrete and steel reinforcement is assumed as fully-perfect bonded.

The boundary conditions for axial loading on PLFP model was pinned in x-direction at the top and at the bottom was pinned in both x and y direction. The top panel is restraint in x-direction only whereas it is frees in both y and z direction. The bottom panel is restraint in x and y-directions. Both top and bottom was free in z-direction and also free to rotate. A ramp load of face loading was loaded axially on the top of PLFP panel. The applied load and the boundary conditions are shown in Fig. 2. The load factor of 1.0 was assigned initially and the increased gradually until the failure stage.

The constitutive laws of concrete capping and foamed concrete are based on the Mohr-Coulomb with Rankine cut-off and Rotating Crack. The properties include elastic and plasticity properties of concrete capping and foamed concrete. The concrete capping has elastic modulus, E = 26MPa, density, ρ = 2400kg/m^3 and Poisson's ratio, v = 0.2. On the other hand, the elastic modulus, density and Poisson's ratio of foamed concrete are 11.03MPa, 1625kg/m^3 and 0.2 for panel PA-1 and 12.06MPa, 1595kg/m^3 and 0.2 for panel PA-2. The plastic properties of concrete capping and foamed concrete are displayed in TABLE II below, where f_c = compressive strength, f_t = tensile strength, $Ø$ = friction angle, C = cohesion stress, and G_f = fracture energy per unit area.

Meanwhile, the steel reinforcement and truss connector are modelled using the Von-Mises plasticity criterion. The material model represents a ductile behaviour of materials that exhibit little volumetric strain which is limited to metals and isotropic plastic material. The properties of steel are displayed in TABLE III below.

TABLE II. PLASTIC PROPERTIES OF CONCRETE CAPPING AND FOAMED CONCRETE.

Panel	F_c (MPa)	F_t (MPa)	Ø (°)	C (MPa)	Gf (N/m)
Capping	30	3.54	45	15	100
PA-1	12	0.56	31	1.67	15.82
PA-2	12	0.53	30	1.67	15.82

TABLE III. PROPERTIES OF STEEL USED FOR REINFORCEMENT AND SHEAR CONNECTORS.

Parameters/Steel	Mild Steel, Ø 6mm	High Tensile, Ø 9mm
Initial yield stress, σ_y	518 MPa	560 MPa
Ultimate stress, P_t	544.28 MPa	626.5 MPa
Young's modulus, E_s	203.6 MPa	209 MPa
Density, ρ	7700 kg/m^3	7800 kg/m^3
Poisson's ratio, v	0.3	0.3

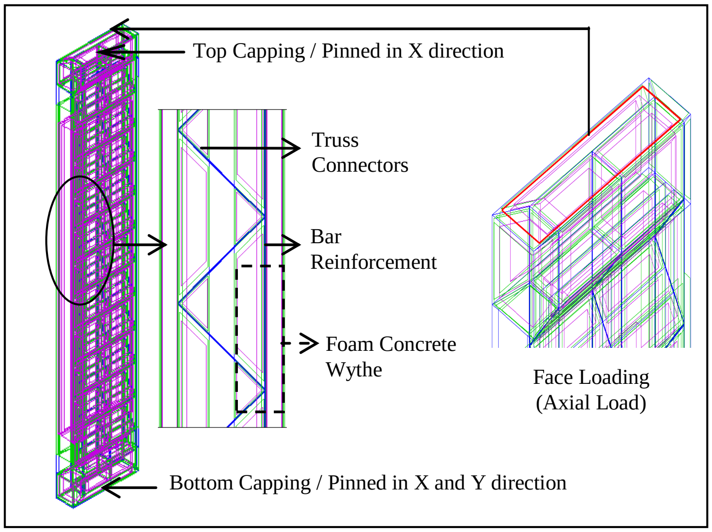

Figure 2: Finite-Discrete Element Model of PLFP.

III. Results and Discussion

A. *Damage Mechanism*

From the experimental and numerical studies, the load was applied on the panels incrementally until failure. Crack was observed and remarked on the panels occurred at every load increment. The ultimate loads corresponding to the appearance of first crack were recorded. Cracks were observed in either or both concrete wythes and the specimen finally failed by the crushing of foamed concrete. Fig. 3 and Fig. 4 show damage behaviour of panels PA-1 and PA-2 respectively. A comparison of numerical results with that obtained from experimental results show a favourable agreement. The crack and crush are noticed appear at the lower part of the panel near the bottom capping of panel PA-1. The crack then propagates to the upper part of the panel. After the panel totally loses the tensile strength, it is found that the panel experience fracture and crushing. For panel PA-2, crack and crushing are observed occur at the top half of panel, the same location where the maximum deflection is recorded.

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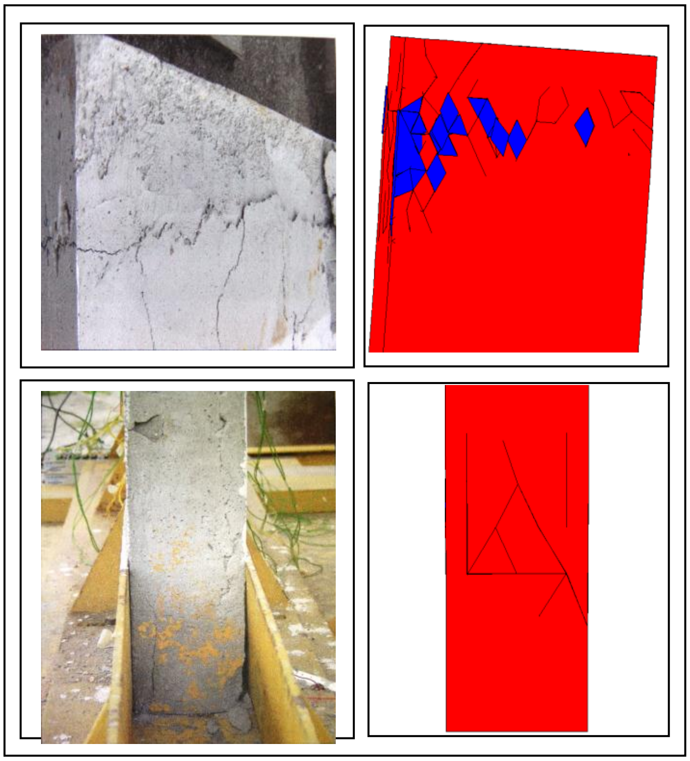

Figure 3: Damage behaviour of PLFP panel PA-1. Experimental results (left) and numerical results (right).

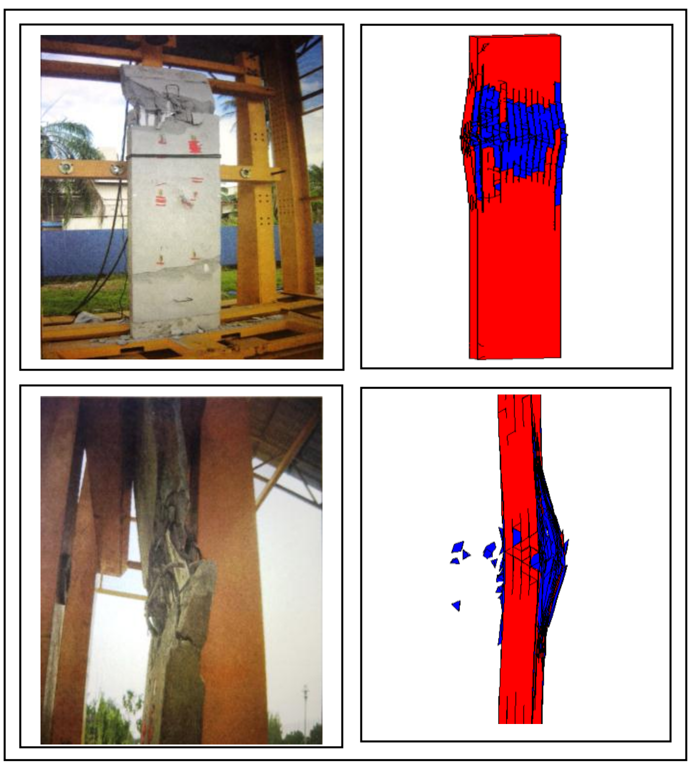

Figure 4: Damage behaviour of PLFP panel PA-2. Experimental results (left) and numerical results (right).

B. Load-Deflection Profiles

Fig. 5 and Fig. 6 show load-deflection profiles of panels PA-1 and PA-2 respectively. The results of ultimate load and deflection for panel PA-1 and PA-2 can be seen in TABLE IV and TABLE V. Both results of ultimate load and deflection have only 5% error between FDEM and Experimental results. After reaching this ultimate load the stress-strain profile change to non-linear behaviour. The ultimate load was recorded at the hardening curve of the stress profile during the first duration of micro-cracks. Unlike normal concrete that shows catastrophic failure in ideal stress-strain profile, the precast lightweight foam concrete sandwich panels displays softening phase that governed by fracture energy. This shows similar behaviour of composite structures under quasi-static loads. It is found that, the numerical results from the combined finite-discrete element method are slightly higher than experimental results. This happens due to isotropic homogeneous of foamed concrete that employed in the models.

TABLE IV. ULTIMATE LOAD FOR PANELS PA-1 AND PA-2

Panel	Experiment	FEM	FDEM
PA-1	280kN	345kN	295kN
PA-2	441kN	445kN	448kN

TABLE V. DEFLECTION FOR PANELS PA-1 AND PA-2

Panel	Experiment	FEM	FDEM
PA-1	2.165mm	2.20mm	1.95mm
PA-2	2.82mm	2.87mm	2.76mm

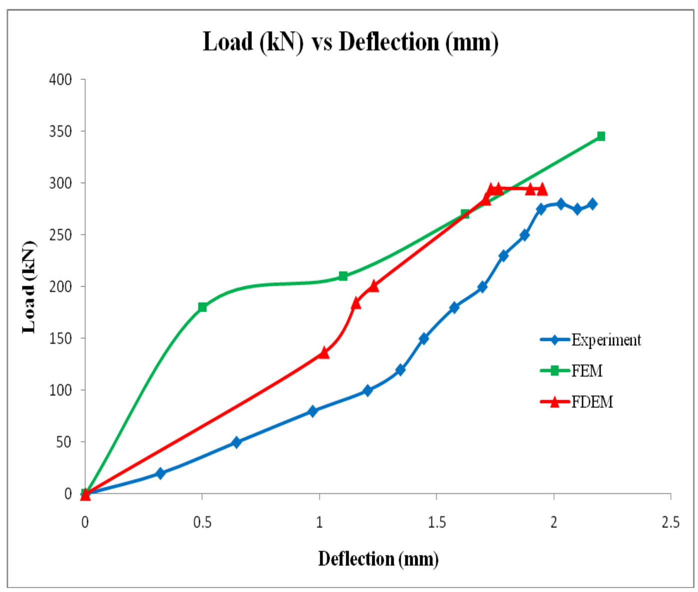

Figure 5: Experiment, FEM and FDEM simulation result of Load versus Deflection for Panel PA-1

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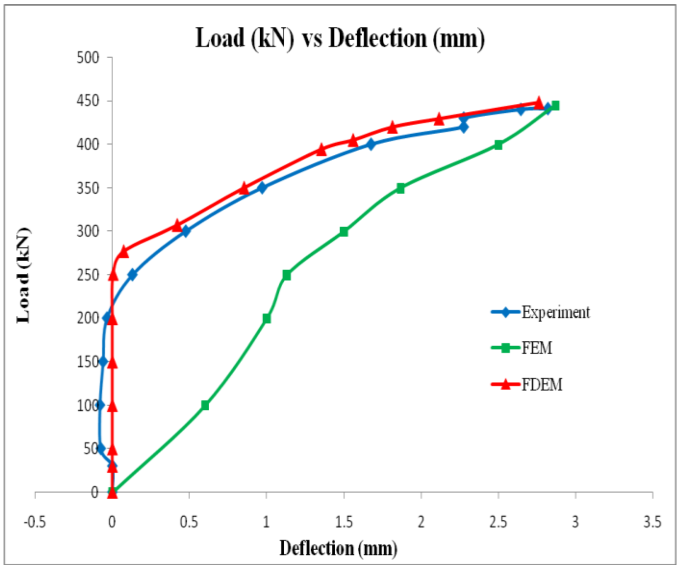

Figure 6: Experiment, FEM and FDEM simulation result of Load versus Deflection for Panel PA-2

IV. Conclusion

Based on the numerical investigation, it can be concluded that the precast lightweight foamed concrete sandwich panels under axial load can be accurately modelled using the combined finite-discrete element method. The PLFP panels were modelled using the Mohr-Coulomb with Rankine cut-off and Rotating Crack for the concrete capping and foamed concrete wythe. Meanwhile, the steel bar was employed the Von-Mises criterion. These material models have proved as the best constitutive laws to correctly describe the real material and steel behaviour, and damage mechanism of PLFP panels. The numerical results show a good agreement with that obtained from experimental studies in term of damage mechanism and load-deflection profile. It is proven from the FDEM results that the models of PLFP panel using the combined finite-discrete element shows a better accuracy compared to FEM method, where the results is not only based on continuum but also fracture failure.

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