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Composite and non-composite behaviors of foam-insulated concrete sandwich panels

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A R T I C L E I N F O

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The structural behaviors of foam-insulated concrete sandwich panels subjected to uniform pressure have been evaluated. This study showed that the interface conditions such as composite and non-composite had a significant effect on the response of foam-insulated concrete sandwich panels, indicating that the simulated shear tie resistance should indeed be incorporated in numerical analyses. Finite element models were developed to simulate the detailed shear resistance of connectors and the nonlinear behaviors of concrete, foam and rebar components. The models were then validated using data from static tests performed at the University of Missouri. The modeling approach used here was compatible with the American Concrete Institute (ACI) Code and existing design practices. The results of this study will therefore provide improved methodology for the analysis and design of foam-insulated sandwich panels under both static and blast loadings.

1. Introduction

Generally, static tests are performed in advance in order to define the resistance and failure mode of foam-insulated concrete sandwich panels (FICSP) before the dynamic tests are conducted. Several research programs have sought to evaluate the structural performance of FICSP subjected to static loading [1–8]. It was shown from several researchers [9,10] that FICSPs are also an efficient way to mitigate the impact induced by blast or dynamic loading. Analytical and experimental studies of glass fiber-reinforced polymer/steel concrete sandwich panels under out-of-plane load and the developed analytical method predicted the panel deflections observed in the experiments with reasonable accuracy. However, even though the fundamental static test results provide researchers with the data needed to evaluate the static resistance functions for sandwich walls, most of the results from static tests must be interpreted with caution due to the limitations imposed by the force–displacement history of the samples. It should be noted that FICSPs are constructed from components made of various materials, including concrete, foam, rebar, welded wire reinforcement (WWR) and shear ties, each of which affects the failure mechanism of the structure. Especially the shear ties have significant effects on ultimate flexural strength of the sandwich panels and are used to provide integrity between the interior and exterior concrete sections, referred to as withes [11]. The type and arrangement of the shear tie connectors allowed the panels to act as partially to fully composite. Therefore, the analytical studies to support static tests are a vital part of efforts to efficiently evaluate the structural effects of all components of the FICSP.

The primary objective of this paper was to evaluate the structural behaviors of FICSP subjected to uniform pressure using FE analyses. In this study, finite element (FE) models were developed and then validated by comparing the simulation results with experimental data from static tests performed at the University of Missouri [11]. The FE models in this study offer a useful way of understanding the contribution of each component to the failure mechanism of FICSPs subjected to uniform pressure and should ultimately lead to better design documentation and engineering level predictive tools for blast resistant sandwich concrete walls.

We foresee that in the near future we will continue to design and build civil (not military) defense shelters such as family shelters in homes, common shelters in buildings or public shelters in underground installations for the population in cases of emergency for local envisages threats, levels of protection and rescue procedures. In addition to the structural protection, these tilt-up technologies are the most energy efficient wall systems. Therefore, it is highly anticipated that these results make measurable contributions to the increase of the application to the engineering practice.

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2. Finite element modeling

2.1. Modeling methodology

Concrete is comprised of a wide range of materials, whose properties are quantitatively and qualitatively different. A numerical strategy for solving any boundary value problem with location of fracture, therefore, should consider complex constitutive modeling. Nonlinear concrete models were developed and validated using testing data [11] from reinforced concrete beams and FICSPs. Numerical investigations were executed by a general-purpose FE analysis package, ABAQUS [12]. The concrete damaged plasticity model in ABAQUS takes into consideration the degradation of the elastic stiffness induced by plastic straining both in tension and compression and provides a continuum, plasticity-based, damage model for concrete. It assumes that the two main failure mechanisms are tensile cracking and compressive crushing of the concrete material. The material parameters of the concrete damaged plasticity model used in this study are presented in Table 1. The foam (referred to as XPS hereafter) consisted of extruded polystyrene thermal board insulation. The concrete and foam portions were modeled as solid elements. Rebar and WWR were modeled using beam elements and the embedded element technique in ABAQUS. The stress–strain relationships for rebar, WWR and XPS are shown in Fig. 1.

Geometrically nonlinear static problems may involve buckling or collapse behavior, where the load–displacement response shows a negative stiffness and the structure must release strain energy to remain in equilibrium. The Riks method uses the load magnitude as an additional unknown and solves simultaneously for loads and displacements. In ABAQUS [12], the "arch length," l, along the static equilibrium path in load–displacement space is used, which offers the advantage of providing solutions regardless of whether the response is stable or unstable.

2.2. Concrete code calibration and validation

The data from two test matrix, with two different sizes and/or reinforcement conditions for the concrete beam (Table 2), were employed to verify the concrete code and calibrate the parameters of the nonlinear concrete model. The FE models for the concrete code verification were simply supported and uniformly loaded across a clear span shown in Fig. 2a. The concrete and reinforcements (rebar and WWR) were modeled using solid elements (C3D20; 20-node quadratic brick) and truss elements (T3D3; 3-node quadratic truss), respectively. The interface properties between concrete and reinforcements were assumed to be fully-bonded.

The load–displacement curves from the FE analyses were compared with those of the test matrix. The vertical displacements at the center of the bottom slab were monitored. As Fig. 3a and b show, the results from the FE analyses were in good agreement with those from the test matrix, although the initial stiffness from the FE analyses was a little higher than that of the test matrix. This is probably due to 1) the presence of a crack in the sample at mid-span before testing and/or 2) insufficient information regarding the tensile strength of the concrete.

2.3. Direct shear test

The ultimate flexural capacity of FICSP can highly be affected by the stiffness and failure mode of its shear tie connectors [13]. Direct shear tests were used to evaluate the shear resistance data (shear force–displacement history) for composite and non-composite ties, which was used as an input in the FE modeling in order to simulate efficiently the shear resistance of the tie in the tilt-up sandwich panel model. A multi-point constraints (MPC) approach was used to model each shear tie. The test configuration consisted of three concrete layers, two shear ties, and two layers of foam as shown in Fig. 2b. The symmetrical test configuration was chosen to minimize eccentricity. This study used the same material properties for concrete and rebar as those of the concrete code verification. The axial tensile forces were applied on the rebar in the central concrete panel and then the bottom portions of the rebar embedded in the outside concrete layers were fixed, as shown in Fig. 2b. The interface properties between concrete and XPS were assumed to be frictionless. The resistance on the applied forces was, therefore, provided only by spring elements. The nonlinear SPRING elements in ABAQUS were used to model the actual shear resistances of ties. SPRING1 was used to simulate the shear resistance of coupled nodes between concrete and XPS. As shown in Fig. 2b, SPRING1 serves as the intermediary between a node (coupled nodes) and ground. SPRING2 was used to simulate the axial behavior of the ties, although the axial forces were small relative to the shear forces. The test data used as input data in SPRING1 and SPRING2 for the shear and axial strength are shown in Fig. 3c and d. The shear resistances from the tests were compared with those from the FE models. Figs. 3c and d compares the tested shear resistances with the shear resistance from the FE models and proved that the MPC approach provides an efficient and accurate representation of the shear resistance of various sandwich panel ties without having to explicitly model intricate shear connector systems.

2.4. FE models of FICSP

FE models were developed for a FICSP system subjected to uniform pressure in this study. These sandwich panels can be either

Table 1
The material parameters used for the concrete damaged plasticity (CDP) model.

Concrete		Parameters of CDP model	
E, modulus of elasticity GPa (psi)	24.8 (3.6E+6)	ψ, dilation angle	30°
ν, Poisson's ratio	0.18	ε, flow potential eccentricity	0.1
Density kg/m^3 (pcf)	2403 (150)	σ_{b0}/σ_{c0} [a]	1.16
Compressive strength MPa (psi)	28–34 (4000–5000)	K_c [b]	0.667
Tensile strength MPa (psi)	2.8(400)	μ, Viscosity parameter	0.0
Concrete compression hardening		**Concrete tension stiffening**	
Yield stress, MPa (psi)	Crushing strain	Remaining stress after cracking, MPa (psi)	Cracking strain
24 (3500)	0.0	2 (300)	0.0
28–34 (4000–5000)	0.002	0	0.002
17 (2500)	0.003	–	–

[a] The ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress.
[b] The ratio of the second stress invariant on the tensile meridian, q (TM), to that on the compressive meridian, q (CM).