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등분포하중에 종속된 폼내장 콘크리트 샌드위치패널의 유한변위거동

Large displacement behaviors of foam-insulated concrete sandwich panels subjected to uniform pressure

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ABSTRACT

This study examined the structural behaviors of foam insulated concrete sandwich panels subjected to uniform pressure. Finite element models were used 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. Both composite and non-composite action had a significant effect on the response of the foam insulated concrete sandwich panels, indicating that the simulated shear tie resistance should indeed be incorporated in numerical analyses. The modeling approach used here conveniently simulated the structural behaviors during all loading stages (elastic, yielding, ultimate and post-failure) and was compatible with the American Concrete Institute (ACI) Code and existing design practices. The results of this study will therefore provide useful guidelines for the analysis and design of foam insulated sandwich panels under both static and dynamic loadings.

요 지

본 연구는 등분포 하중에 종속된 폼내장 콘크리트 샌드위치 패널 (foam insulated concrete sandwich panel)의 구조거동특성을 파악하였다. 유한요소모델이 콘크리트, 폼 그리고 철근의 비선형거동과 연결부재 (connector)의 상세 전단저항거동을 모사하기위해 사용되었다. 개발된 모델은 미주리대학 (University of Missouri)에서 수행된 정적실험자료를 사용하여 검증되었다. 합성 및 비합성 거동이 샌드위치패널의 구조거동에미치는 영향을 정확히 모사하기 위해 전단연결재의 저항력을 모델에 정확히 반영하는 것이 중요하다. 본 연구에서 개발된 모델은 구조물의 극한강도및 좌굴이후의 거동까지 모사하였고 미국콘크리트 학회 (ACI)의 설계예제와 비교하였다. 본연구의 결과는 정적 및 동적하중에 종속된 폼내장 콘크리트 샌드위치 패널의 해석및 설계에 유용한 정보를 제공할것이다.

Key Words: insulated sandwich panel; Finite element model; Composite; Non-composite

1. Introduction

This study investigated the failure mechanisms of foam insulated concrete sandwich panel (FICSP) subjected to uniform pressure. The use of foam-insulated concrete and insulated tilt-up concrete sandwich panels for exterior walls is common practice in the United States. These forms of construction provide a thermally efficient and high-mass wall that enhances the energy efficiency and blast resistance of the building making it ideal for military and government facilities (Naito et al. 2011). A common type of modern exterior wall

주요어 : 폼내장 샌드위치판, 유한요소모델, 합성, 비합성

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construction, the sandwich panel, contains two concrete wythes separated by a layer of foam insulation. The concrete wythes can be either conventionally reinforced or prestressed. Reinforcement allows the concrete to reach its full flexural strength and resist lateral, construction, and handling loads. It should be noted that FICSPs are constructed from components made of various materials, including concrete, foam, rebar, welded wire reinforcement (WWR), composite and non-composite shear connectors. Therefore, it's c omplex to develop the analysis and design methodology considering the contributions of each components on the failure mechanism of the sandwich structures.

The most common design approach for sandwich panels subjected to blast loads is to develop a single-degree-of-freedom (SDOF) system that will represent the displacement response of the structure. The difficulty in developing a SDOF prediction model for sandwich panels subjected to blast loads arises from the ambiguity in describing the resistance of the sandwich panel system. Static tests, therefore, are performed in advance in order to define the resistance and failure mode of FICSP before the dynamic tests are conducted. Several research programs (PCI 2011; Salmon et al. 1977; Pantelides et al. 2008; Naito 2007) have sought to evaluate the structural performance of FICSP subjected to static loading, and showed that FICSP is an efficient way to mitigate the impact induced by blast or dynamic loading. However, even though the fundamental static tests 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. Furthermore, the high costs are associated with full-scale static tests. The use of FE models, therefore, is very effective to understand the failure modes of FICSP.

2. Objective

The objective of this study was to evaluate the failure mechanisms of FICSP subjected to uniform pressure using the FE analyses. In this study, the FE models incorporating with concrete damaged plasticity model were developed and then validated by comparing the simulation results with experimental data from static tests performed at the University of Missouri (Naito et al. 2011; Newberry et al. 2010).

3. Finite element modeling

Table 1. The material parameters used for the concrete damaged plasticity model in Abaqus

Concrete		Parameters of CDP model	
E, modulus of elasticity GPa (psi)	24.8 (3.6E+6)	, dilation angle	30°
ν Poisson'sratio	0.18	ϵ, flow potential eccentricity	0.1
Density Kg/m^3(pcf)	2403 (150)	σ_0/σ_{c0}*	1.16
Compressive strength MPa (psi)	28 ~ 34 (4,000 ~ 5,000)	$_c$**	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 (3,500)	0.0	2 (300)	0.0
28 ~ 34 (4,000~5,000)	0.002	0	0.002
17 (2,500)	0.003	-	-

This study used a general-purpose FE analysis package, ABAQUS (SAMURAI 2007), in numerical analyses. Nonlinear static problems involve buckling or collapse behavior, where the load-displacement response shows 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. For unstable problems, the load and/or the displacement may decrease as the solution evolves. In ABAQUS (SIMULIA 2007), the arch length 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.

The concrete damaged plasticity model used in this study 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 Abaqus are presented in Table 1. Compressive testing results of insulating foams was used to define the stress/strain material property input for foam elements in Abaqus as shown in Figure 1. The extruded expanded polystyrene foam (referred to as XPS hereafter) was used as thermal board insulation. The concrete and foams (rebar and WWR) were modeled using solid elements (C3D20; 20-node quadratic brick) as shown in Figures 2 and 3. Reinforcement in concrete structures is typically provided by means of rebar, which are modeled as one-dimensional rods that can be defined singly or embedded in oriented surfaces. Rebar is typically used with metal plasticity models to describe the behavior of the rebar material and is superposed on a mesh of standard element types used to model the concrete. With this modeling approach, the concrete behavior is considered independently of the rebar. Effects associated with the rebar/concrete interface, such as bond slip and dowel action, are modeled approximately by introducing “tension stiffening” into the concrete modeling to simulate load transfer across cracks through the rebar. In this study, rebar and welded wire reinforcement (WWR) were modeled using truss elements (T3D3; 3-node quadratic truss) as shown in Figure 3 and the embedded element technique in Abaqus. The stress-strain relationships for rebar and WWR are shown in Figure 1, which were used as the material input parameters in Abaqus.

Table 2 Concrete beam dimensions

Name	Depth, cm (in.)	Width, cm (in.)	Reinforcement
Concrete Beam	29 (11.5)	46 (18)	Welded-Wire W4 x W4 @ 25.4 (10) # 8’s @ 24 (9.5)

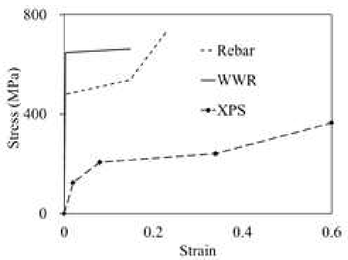

Fig. 1. Input for material properties of rebar, WWR, and XPS in Abaqus

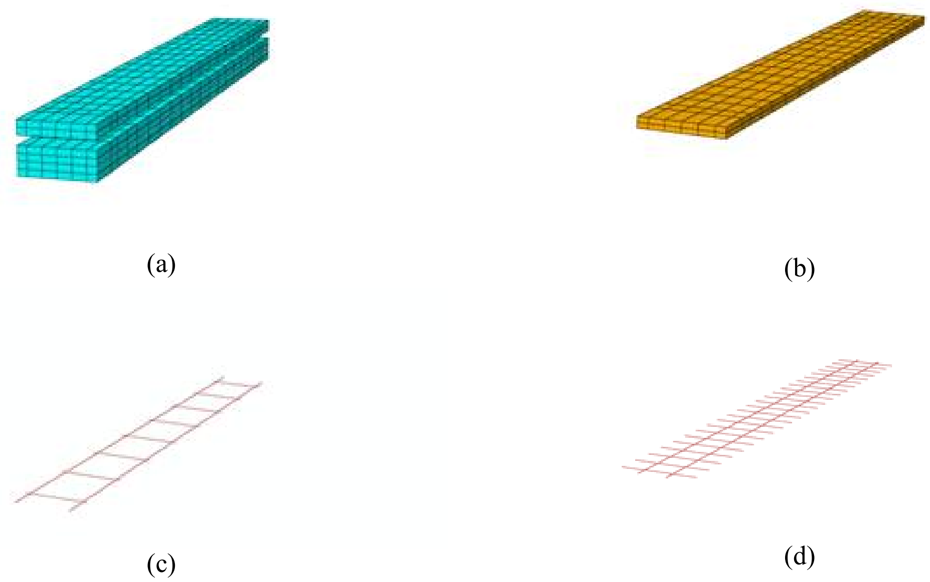

Fig. 2 FE models: (a) concrete; (b) foam; (c) rebar; and (d) WWR.

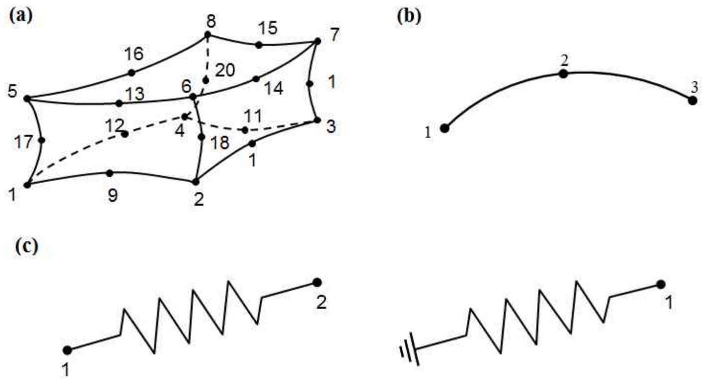

Fig. 3. Types of elements used in FE models: (a) solid element (C3D20; 20-node quadratic brick); (b) truss element (T3D3; 3-node quadratic truss); and (c) spring elements.

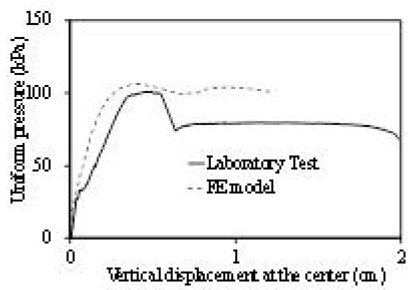

Fig. 4. Test results (Newberry et al. 2010) versus FE models for concrete code verifications.

4. Calibration and validation

The test data (Newberry et al. 2010) as shown in Table 2 was employed to verify the concrete code and calibrate the parameters of the nonlinear concrete model. The interface properties between concrete and reinforcements were assumed to be fully-bonded.

The load-displacement curves from the FE analyses were compared with that of the test beam. The vertical displacements at the center of the bottom slab were monitored. As Figure 4 shows, the results from the FE analyses were in good agreement with those from the test data, although the initial stiffness from the FE analyses was a little higher than that of the test matrix. This is probably due to 1) imperfection of the sample at mid-span before testing and/or 2) insufficient information regarding the tensile strength of the concrete (Newberry et al. 2010).

5. Multi-Point Constraints (MPC) approach

Especially the shear connectors 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 (Newberry et al. 2010). The type and arrangement of the shear tie connectors allowed the panels to act as partially to fully composite. Composite connectors, however, do not reach allow panels to achieve full composite action under large displacements. FICSP using composite shear connectors will act composite while under service loads, but when subjected to large displacement, full composite action between concrete wythes does not occur. The modeling of such composite and non-composite behaviors is the key to predicting sandwich panel behavior. The shear resistance data (Naito et al. 2009) for composite and non-composite connectors was used as an input in the FE modeling in order to simulate efficiently the shear resistance of the connectors in the tilt-up sandwich panel model. A multi-point constraints (MPC) approach was used to model each shear tie. The resistance on the applied forces was, therefore, provided only by spring elements as shown in Figure 3. The nonlinear spring elements in ABAQUS were used to model the actual shear resistances of connectors. The MPC approach provides an efficient and accurate representation of the shear resistance of various sandwich panel connectors without having to explicitly model intricate shear connector systems.

6. FE models of FICSP

The MPC approach described above was incorporated into the sandwich panel models. TCA non-composite 6-2-3 sandwich panel (Naito et al. 201!) shown in Figure 6 was used to validate the FE models of FICSP. The interface properties between concrete and foam are assumed to be frictionless since the resistance data of spring used in the MPC approach indirectly included friction resistance. The shear resistance for all concrete sandwich panels, therefore, was provided by nonlinear spring elements that represent each individual shear tie. The FE models for FICSP were simply supported and uniformly loaded across a clear span as shown in Figure 7.

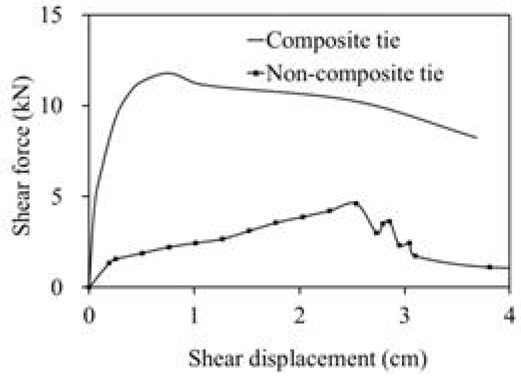

Fig. 5. Force-displacement relationships for shear connectors (Naito et al. 2009)

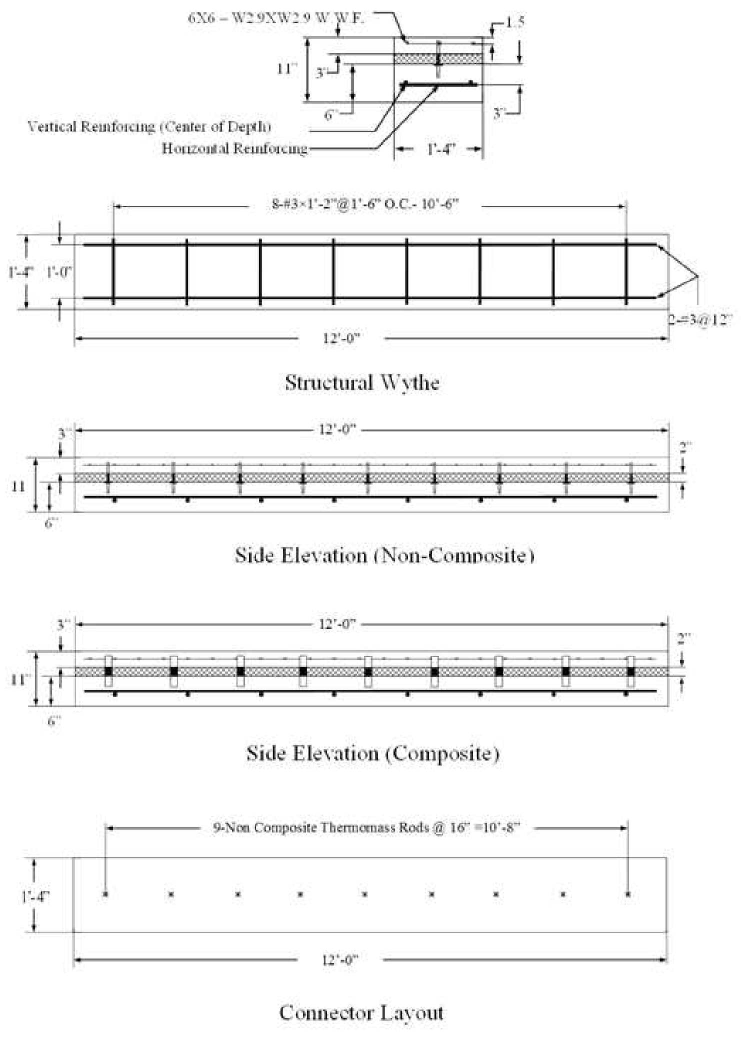

Fig. 6. TCA Non-Composite 6-2-3 Single Span Static Specimen Details (Naito et al. 2011)

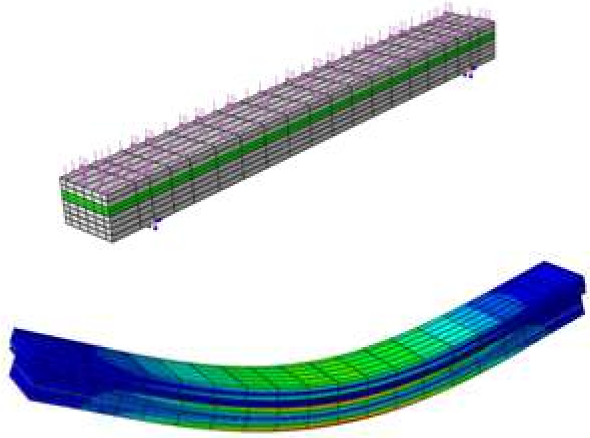

Fig. 7. FE model and deformed shape of 6-2-3 FICSP.

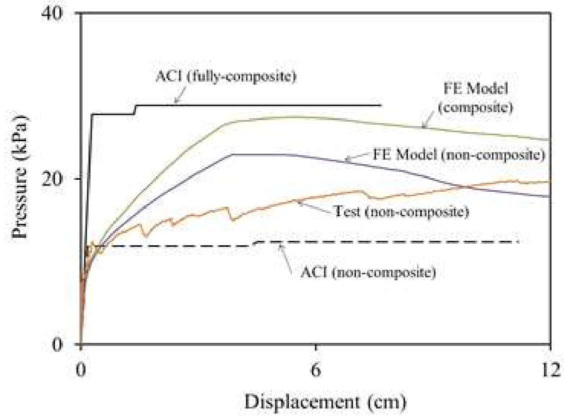

Fig. 8. Test data (Naito et al. 2011) versus FE results for 6-2-3 FICSP subjected to uniform pressure.

7. ACI code versus FE results

The ACI Code definitions and design practices for the nominal flexural strength are presented for the comparison with the FE models and testing data. Moment-curvature relationships from the ACI Code and design practices will be used to describe and discuss the flexural behavior of composite and non-composite FICSPs. The failure of concrete in tension involves the propagation of cracks (Nilson et al. 2004). The initial cracking moment can be predicted by the following equations:

$$_{r} \quad \frac{f_r \bullet I_{ut}}{y_t} \tag{1}$$

$$f_r = 19.7 \quad f'_c \tag{2}$$

where M_{cr}= the cracking moment, f_r= the modulus of rupture, I_{ut}= the moment of inertia of the uncracked section, y_t= the distance from the neutral axis to the tension face, and f'_c= the compressive strength of concrete (kPa). The yielding moment was calculated based the elastic concrete stress distributions as follows:

$$M_y = A_s f_y \; d - \frac{kd}{3}\Big) \tag{3}$$

where M_y= the yielding moment, A_s= the entire steel area, f_y= the yielding stress of the steel, d= the effective depth of the beam, and kd= the distance from the compression face to the cracked elastic neutral axis. The nominal moment capacity (M_n) was calculated using the following expression:

$$M_n = A_s f_y \left(d - \frac{a}{2} \right) \tag{4}$$

$$a = \frac{f_y A_s}{0.85 f_c{}' b} \tag{5}$$

$$c = \beta_1 a \tag{6}$$

where M_n= the nominal moment capacity, a= the depth of the equivalent constant stress, b= the width of the beam, and c= the distance to the neutral axis.

Figure 8 illustrates the comparison between the ACI Code, the FE models, and the static tests results of FICSPs. The vertical displacements at the center of the bottom slab were monitored. Pressure-displacement histories were compared relatively well, especially in the early stages of loading where the initial stiffness of the models impacts behavior. After loss of initial stiffness, there is some disparity between static testing results and FEM models. This is primarily due to approximations involved in simulating composite action between concrete wythes; much is still unknown about the effectiveness of shear transfer connectors and the effect of insulation type and surface roughness on the degree of composite action (PCI 1997). The natural variance of failure in discrete shear connectors within a system, especially those connectors designated as creating a non-composite panel, is another area that makes modeling of such systems difficult. For instance, it was noted in static testing that often shear connectors would begin to fail on one side of the panel, creating unsymmetrical stresses on the panels. Although creating the nonsymmetrical tie condition described above provided failure modes that better compared with the failure of test samples, the approach is highly approximate. Furthermore, although the static shear connector test data proved to be helpful in understanding shear transfer of connectors, the tests only took into account direct shear. Uncertainty from the use of this data arises from the fact that shear connectors are part of a flexural system and not only subjected to direct shear.

As shown in Figure 8, the ultimate strength of FICSPs is highly affected by the interface properties between concrete and foam. It can be explained from the fact that the stress distributions of composite sections are totally different from those of non-composite sections. Figure 8 also showed that the uniform pressure decreased abruptly after it reached the structure's ultimate strength. This was probably because several shear connectors failed due to the slippage induced by the shear forces, where the slippage between concrete and XPS in FICSPs at the ultimate pressure is clearly visible and the panel was initially broken at the middle.

It is clear from Figure 8 that the current ACI Code and design practices provide the upper and lower boundaries for the FE analyses and tests. These comparisons confirm that the modeling methodology applied in this study is indeed an efficient way to model the shear resistance of the various type of connectors used in sandwich panels.

8. Conclusions

An analytical study was conducted to evaluate the flexural behavior of FICSPs subjected to uniform pressure. The high-fidelity FE models were created to understand the failure mechanisms and characteristics of FICSPs for both composite and non-composite action. The laboratory and full-scale tests were used to increase the effectiveness of FE models and validate the modeling methodology. Based on the results of the research program, the following conclusions can be made:

1) Failure mechanisms of FICSPs were satisfactorily evaluated using the FE models incorporating with concrete damage plasticity model and the multi-point constraint (MPC) approach used to simulate shear connector resistance. The results from the FE models showed good agreements with those from the tests.

2) From this analysis it was apparent that shear connectors greatly affect the flexural behavior of sandwich panels subjected to uniform pressure.

3) The current ACI Code provides the upper and lower boundaries for the tests and FE analyses. The numerical examples presented in this study help understand the current design code and practices.

4) The pressure-displacement histories from the ACI Code and design practices, however, showed initial stiffness higher than those from the test and FE analyses. Therefore, the effect of the shear connectors for the cracking moment in ACI Code needs to be incorporated in the numerical analyses of FICSPs.

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