

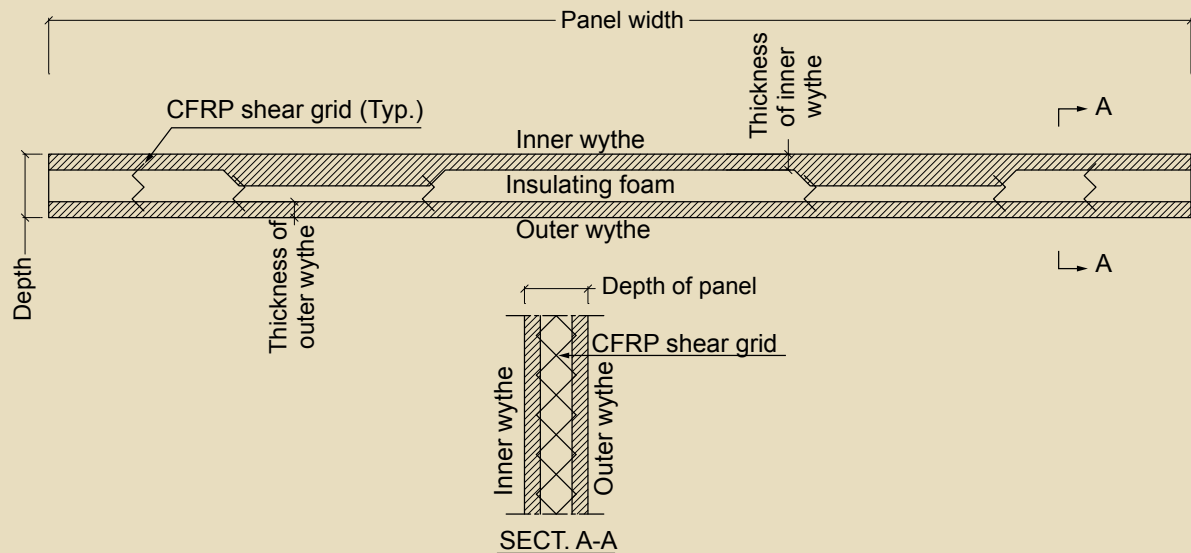
Analysis and design guidelines of precast, prestressed concrete, composite load-bearing sandwich wall panels reinforced with CFRP grid

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The use of precast concrete sandwich wall panels (SWPs) has increased gradually over the past four decades with the growing call for energy-efficient structures. The use of precast concrete SWPs allows for a high level of quality control and quick enclosure of a structure. The first prefabricated panels were noncomposite and consisted of a structural wythe and a nonstructural wythe separated by a layer of insulation.^{1,2} A composite load-bearing SWP is typically fabricated using two thin reinforced or prestressed concrete wythes connected using shear connectors and insulating material. The thickness of the concrete layers varies depending on the structural requirements of the building. The most common load requirements include wind and seismic loads. Conventional shear connectors can include longitudinal steel-wire trusses, continuous bent bars, expanded perforated plates, or solid concrete zones.

Editor's quick points

- Three different precast concrete sandwich wall panels, reinforced with carbon-fiber-reinforced-polymer shear grid and constructed using two different types of foam, expanded polystyrene (EPS) and extruded polystyrene (XPS), were selected from the literature to validate the proposed approach.
- Results of the analysis indicated that the proposed approach is consistent with the actual behavior of the panels because the predicted strains compared well with the measured values at all load levels for the different panels.
- The approach is beneficial to determine the degree of the composite interaction at different load levels for different panels at any given curvature. A simplified design chart is provided to calculate the nominal moment capacity of EPS or XPS wall panels as a function of the maximum shear force developed at the interface.



Cross-section details



Test setup

Figure 1. The graphic shows the cross-sectional details for a precast concrete sandwich panel reinforced with carbon-fiber-reinforced-polymer (CFRP) shear grid, and the photo shows the test setup for a CFRP precast concrete sandwich panel from Frankl's 2008 master's thesis. Note: SECT = section; typ. = typical.

One of the earliest studies on precast concrete SWPs was conducted by Pfeifer and Hanson.³ The study included 50 reinforced SWPs with a variety of wythe connectors. The panels were tested in flexure under uniform loading. Test results showed that welded truss-shaped steel connectors were more effective in transferring shear than steel connectors without diagonal members. The study also demonstrated the beneficial effect of using concrete ribs to connect the wythes. Hamburger et al. assessed the poor performance of welded-steel-plate connectors in precast concrete shear-wall panels following the Whittier Narrows earthquake in 1987.⁴ Tests by Bush and Stine showed that a high degree of composite stiffness and flexural capacity

could be achieved with truss connectors oriented longitudinally in precast concrete SWPs.⁵ It was also shown that the friction bond between insulation and concrete provided a reasonable contribution to the overall shear transfer. Hofheins et al. conducted cyclic load tests to quantify the performance and assess the ductile capabilities of loose welded-steel-plate connectors.⁶ Test results showed that the connector exhibits low strength with little ductile capability. The behavior of precast concrete SWPs under axial load was investigated by Benayoune et al.⁷ The inner and outer wythes were tied together using truss-shaped steel connectors. The panels were found to behave in a fully composite manner almost up to failure as only a small

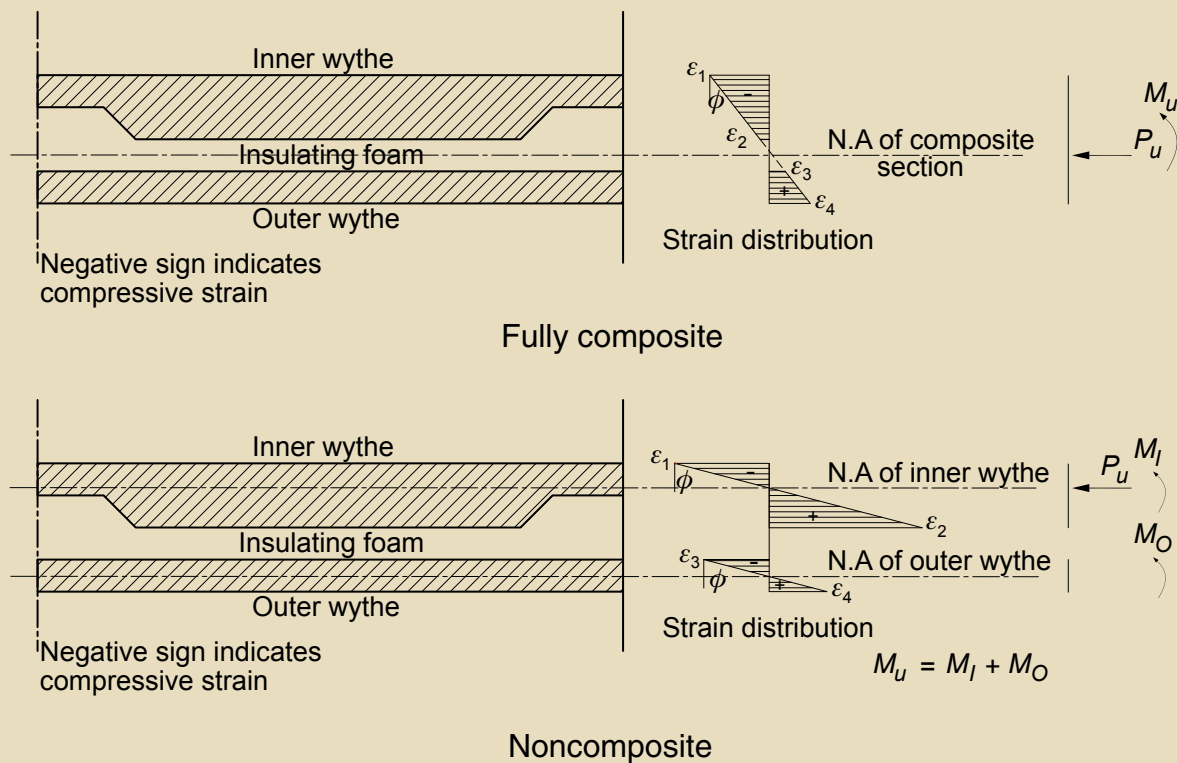


Figure 2. The strain distribution is shown for fully composite and noncomposite precast concrete sandwich panels. Note: M_i = moment in the inner wythe; M_o = moment in the outer wythe; M_u = factored moment; NA = neutral axis; P_u = factored force; ε = strain in concrete; ϕ = curvature.

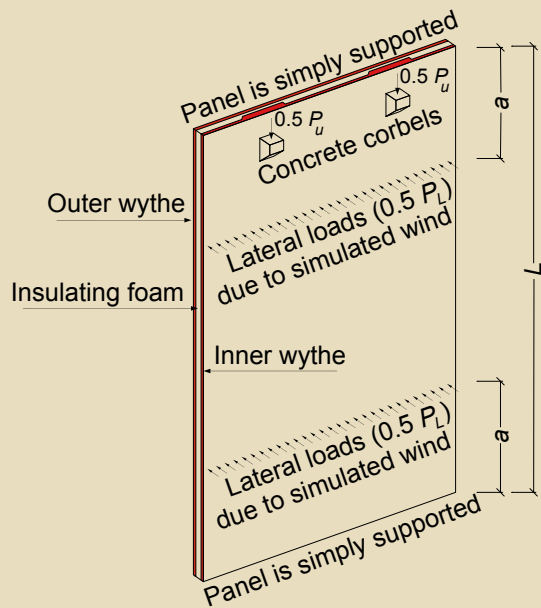
discontinuity of strain was observed across the insulation layer. The structural performance of these panels was satisfactory. Nevertheless, the use of solid concrete zones and/or steel reinforcement created thermal bridges between the wythes and led to a thermally deficient structural wall system.

A great interest in using load-bearing, thermally efficient SWPs recently emerged with the introduction of new materials, such as fiber-reinforced-polymer (FRP) shear reinforcement grids or bent bars, which significantly enhance both the structural and thermal performance of the panels. Salmon et al. introduced the use of FRP bent bars as connectors in precast concrete SWPs.⁸ The use of FRP as the connector material increases the thermal efficiency of the SWPs compared with SWPs that have steel or concrete connectors. The ultimate strength of the SWPs was comparable to the strength expected of fully composite SWPs.

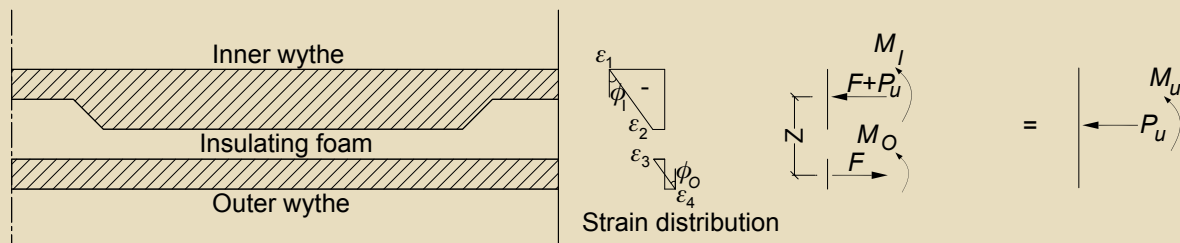
Pantelides et al. tested nine precast concrete wall assemblies with CFRP connectors.⁹ Variations in shear area and surface preparation were investigated. Test results showed that failure of the CFRP composite connection was non-ductile, similar to that of the steel connection but at three times the lateral load resisted by the steel connection. The development length of the CFRP composite was found to be highly dependent on the geometry and stiffness of the

connection. Pessiki and Mlynarczyk conducted lateral-load tests on four full-scale precast concrete SWPs using different shear transfer mechanisms.¹⁰ Test results showed that solid concrete regions provided most of the composite action. Steel ties and bond between the insulation material and concrete contributed relatively little to the composite behavior.

Recently, insulated wall panels were fabricated using carbon FRP (CFRP) grid. Each panel comprised two pre-stressed concrete wythes separated by rigid foam insulation boards and connected by carbon-fiber shear trusses, as shown in Fig. 1.¹¹ Three types of rigid foam insulation boards can be used: expanded polystyrene (EPS), extruded polystyrene (XPS), and polyisocyanurate (ISO). The properties and the microstructure of each type of foam are reported elsewhere.¹¹ Frankl investigated the behavior of six full-scale, precast concrete SWPs reinforced with CFRP shear grid.¹² The panels were constructed using EPS and XPS foam materials. Figure 1 shows the test setup used in the experimental program. The panels were subjected to an axial load to simulate gravity loads and two line lateral loads to simulate the wind effect. Test results showed that the EPS foam-core panels exhibited enhanced behavior with respect to strength, stiffness, and percentage of composite action compared with XPS foam-core panels. Nevertheless, the study did not quantify the shear-flow



Applied vertical and lateral forces



Strain distribution

Figure 3. These figures show the applied vertical and lateral forces and strain distribution in precast concrete sandwich panels with partially composite interaction. Note: F = applied force at the interface; L = total length of the CFRP grid along the width of the panel up to the critical section; M_i = moment in the inner wythe; M_o = moment in the outer wythe; M_u = factored moment; P_L = total applied lateral load; P_u = factored force; Z = distance between the centroids of the inner and outer wythes; ϵ = strain in concrete; ϕ = curvature.

capacity of the CFRP shear grid or the effect of the different foam materials.

This paper presents design guidelines for precast concrete SWPs reinforced with CFRP shear to achieve full composite interaction. The analytical approach provides a general methodology to determine the behavior of fully and partially composite wall panels at any given curvature. The approach is calibrated with the test results reported by Frankl.¹² A sensitivity analysis was conducted using test results to estimate the shear-flow capacity of the insulating materials as well as the CFRP connectors. The influence of the degree of the composite interaction on the induced curvature and slip-strain behavior is also enumerated.

Partial interaction theory for precast concrete SWPs

The assessment approach developed in this paper is based on the partial interaction theory that was originally developed by Newmark et al. for composite steel beams with incomplete interaction.¹³ The approach has been modified to account for the nonlinear behavior of the concrete and the wall-panel configuration. The approach is primarily based on iteration procedures that can be easily programmed, as will be presented in the following sections.

Theory and assumptions

Precast concrete SWPs are typically subjected to axial gravity loads acting on corbels extending from the inner wythe and lateral wind or seismic loads. For any given bending moment M_u and an axial force P_u , the correspond-

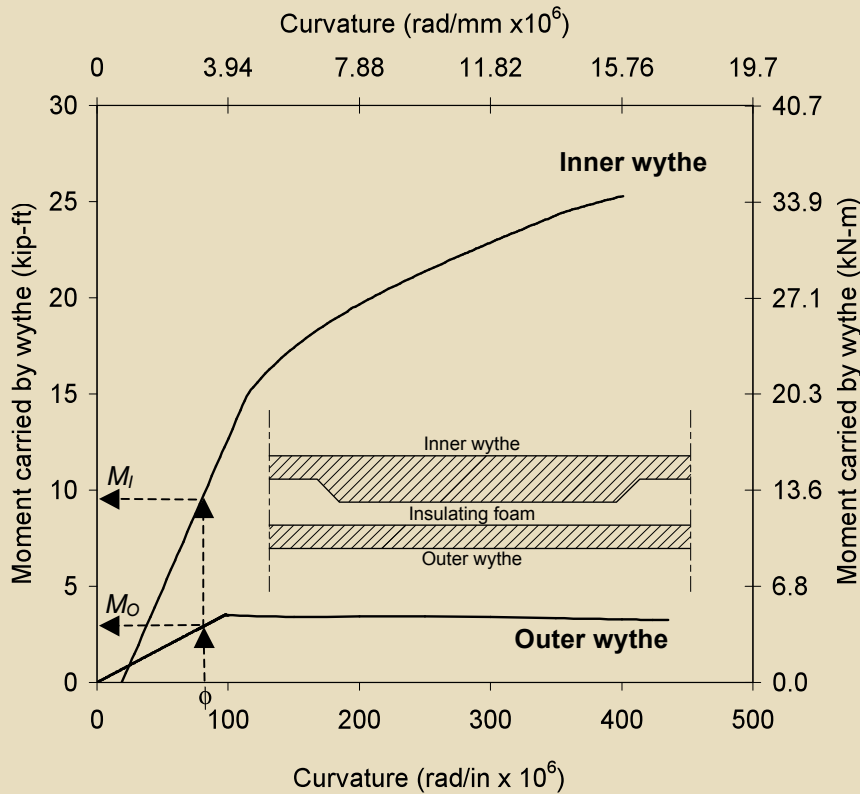


Figure 4. Typical moment-curvature relationships are shown for the inner and outer wythes at a certain value of the interfacial force F . Note: M_i = moment in the inner wythe; M_o = moment in the outer wythe; ϕ = curvature.

ing strains at the inner and outer wythes can be estimated assuming a fully composite interaction using strain compatibility and equilibrium of the wall-panel section, as shown in **Fig. 2**. Typically, a situation of full interaction arises when there is no slip at the interface and therefore there is a continuous strain distribution over the entire section with only one neutral axis at the centroid of the composite section. Conversely, the noncomposite interaction occurs when there is no shear connection and the two concrete wythes act independently. In this case, there are two neutral axes at the centroid of the inner and outer wythes, as shown in **Fig. 2**. The presence of the shear forces at the interface of the wythes and the insulating materials provides the mechanism for partial interaction.

Under the action of the applied loads for the simply supported precast concrete SWPs shown in **Fig. 3**, the outer fibers tend to lengthen, whereas the inner fibers tend to shorten. The shear connectors, which comprise CFRP shear grid and insulating foam, counteract these tendencies by exerting forces that produce compression in the inner wythe and tension in the outer wythe, as shown in **Fig. 3**. These forces typically act at the interface and can be replaced by a couple and a force acting at the centroid of the inner and outer wythe, as shown in **Fig. 3**.

The analysis presented in this paper is based on the following assumptions:

- The shear connectors between the concrete wythes are assumed to be continuous along the length of the wall panel.
- The distribution of strains along the depth of the inner and outer wythes is linear.
- Both inner and outer wythes are assumed to displace equal amounts at all points along their lengths. Therefore, the curvature of the inner and outer wythes is equal at all loading stages as expressed in Eq. (1). Such an assumption is reasonable based on the experimental results reported by Frankl.¹²

$$\phi_i = \phi_o \quad (1)$$

where

ϕ_i = curvature of the inner wythe

ϕ_o = curvature of the outer wythe

The total applied moment M_u is resisted by three components as given by Eq. (2).

$$M_u = M_i + M_o + FZ \quad (2)$$

where

M_i = moment in the inner wythe

M_o = moment in the outer wythe

F = applied force at the interface

Z = distance between the centroids of the inner and outer wythes

The last term in Eq. (2) represents the composite interaction between the inner and outer concrete wythes.

Full composite interaction

At any applied lateral and axial load levels, the maximum force required at the interface to develop the full composite interaction F_c can be estimated by plotting the moment-curvature relationship of the inner and outer wythes independently for an assumed value of the force F_c . The sum of internal forces of the inner wythes at every single point on the moment-curvature relationship can be expressed by

$$\sum C - \sum T = P_u + F_c$$

$\sum C$ = sum of all compressive forces acting on the section

$\sum T$ = sum of all tensile forces acting on the section

The sum of internal forces of the outer wythes at every single point on the moment-curvature relationship can be expressed by

$$\sum T - \sum C = F_c$$

Where, for a given curvature of the fully composite section under the action of the applied moment and axial load, the moments carried by the inner and outer wythes can be estimated as shown in Fig. 4. The analysis can be repeated for different values of the force F_c until Eq. (2) is satisfied. The internal forces as well as the strains at the top and bottom layers of the inner and outer wythes can be extracted from the moment-curvature analysis at the final selected value of the force F_c that satisfies the equilibrium.

Partial composite interaction

For any value of an interaction force F less than F_c , partial composite interaction takes place. The degree of composite interaction k can be expressed as

$$k(\%) = \frac{F}{F_c}(100)$$

At any value of the interaction force F , the unknowns are M_i , M_o , ϕ_i , and ϕ_o . These unknowns can easily be determined using the moment-curvature relationship of the inner and outer wythes and satisfying both Eq. (1) and (2) as shown in Fig. 4.

The analysis can be repeated at different levels of composite interaction by varying the force F at the interface, reestablishing the moment-curvature relationships for the inner and outer wythes, and finding the curvature that satisfies equilibrium.

Comparison with experimental results

Validation of the analytical approach

To validate the proposed approach for precast concrete SWPs, three different panels were selected from the literature.¹² The panels were reinforced with CFRP shear grid and constructed using two different types of foam, EPS and XPS. Figure 5 shows the dimensions and arrangement of the CFRP shear grid used in these panels. The panels were subjected to an axial load of 37.8 kip (168 kN) to simulate gravity loads typically encountered for these types of panels in the field and reversed cyclic lateral loading to simulate the wind effect of a 50-year service life of the structure. The strains at the top and bottom surfaces of the inner and outer wythes and lateral displacement were measured at midspan. More details about the experimental program, failure loads, and ultimate load-carrying capacity are reported elsewhere.¹²

The panels were analyzed at different lateral-load levels. At every load increment, the following procedures were carried out:

1. The moment was calculated at midspan of the panel based on the applied axial and lateral loads.
2. The curvature of the fully composite section was evaluated based on strain compatibility and equilibrium of the composite section.
3. The maximum force required at the interface F_c to develop the full composite action was estimated using the procedures outlined in the previous section of this paper.
4. Different degrees of composite interaction were considered by reducing the interaction force at the interface and calculating the corresponding curvature and strains at the top and bottom surfaces of the inner and outer wythes from the moment-curvature analysis.

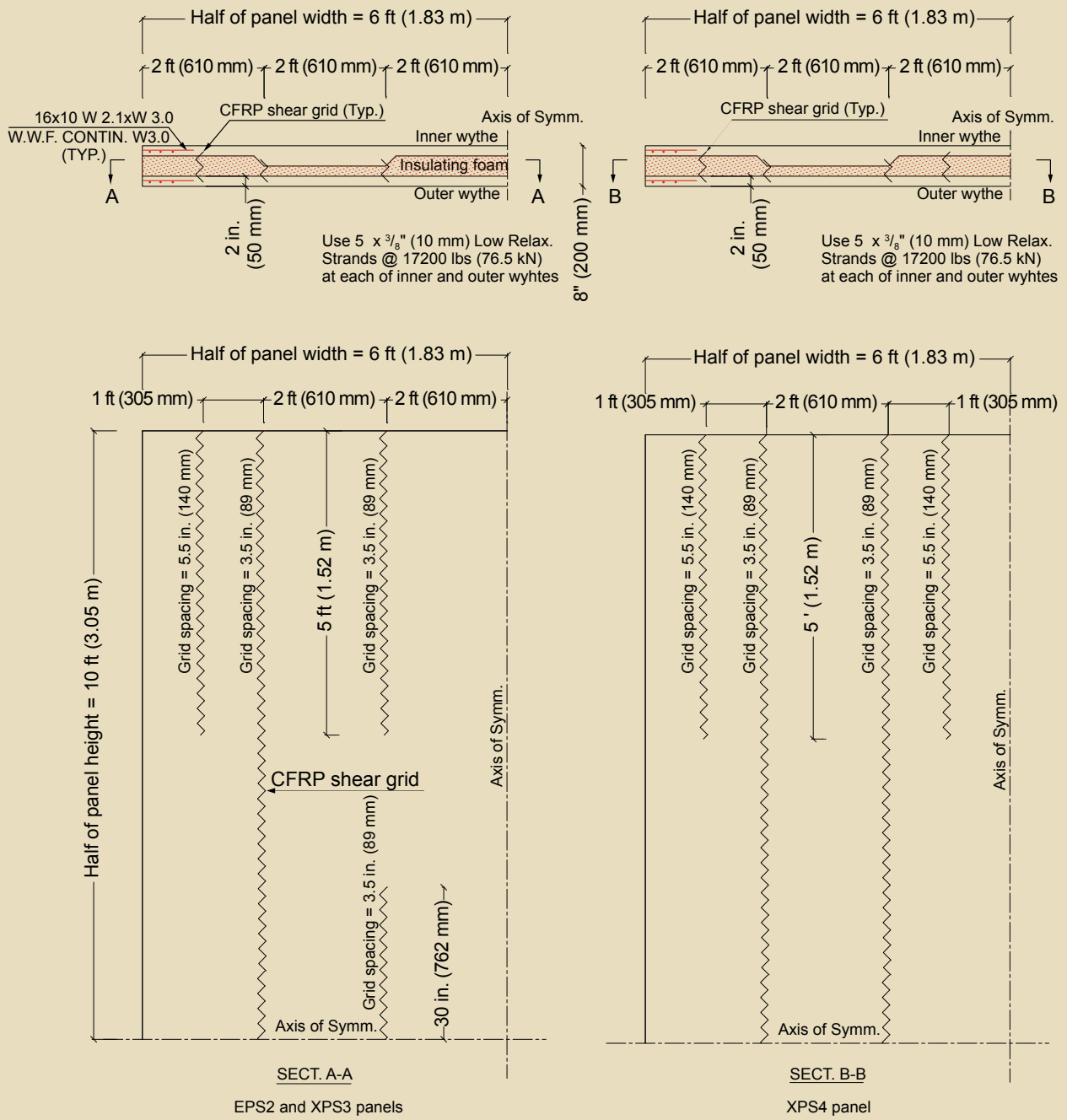
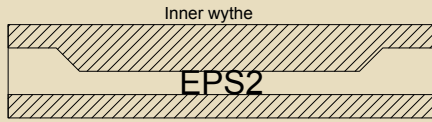


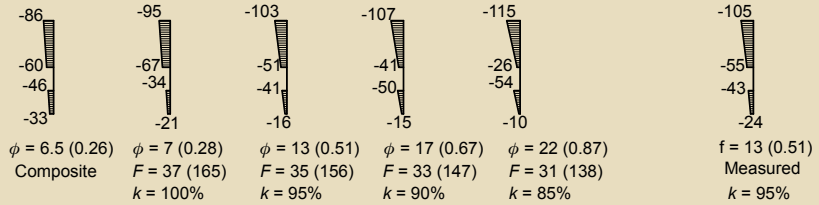
Fig. 5. Dimensions and layout of CFRP-grid used in the PCSP in the current study

Figure 5. This gives the dimensions and layout of the carbon-fiber-reinforced-polymer (CFRP) grid used in the precast concrete sandwich panel (PCSP) in the current study. Note: EPS = expanded polystyrene; Relax. = relaxation; SECT = section; symm. = symmetry; typ. = typical; WWF = welded-wire fabric (reinforcement); XPS = extruded polystyrene. ' = ft; " = in.

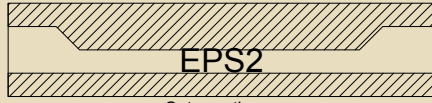
- The measured curvature was determined from the experimental results.
- The predicted strains at the same curvature were compared with the measured values, and the degree of composite interaction was evaluated at that load level.



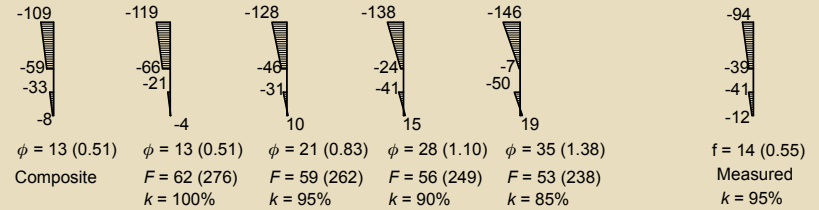
$\phi = 10^{-6} / \text{in.} (10^{-6} / \text{mm})$
 $F = \text{kips (kN)}$
 Strains are in micro in./in. or micro mm/mm



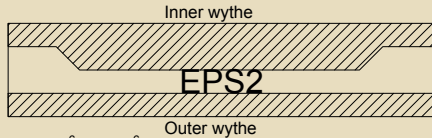
Lateral load of 0 kip



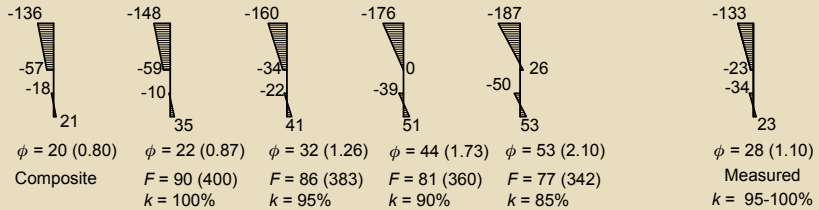
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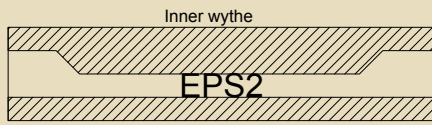
Lateral load of 5 kip



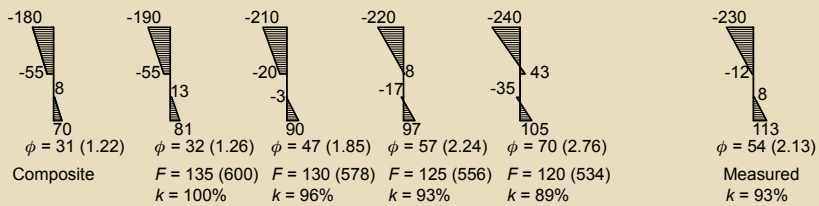
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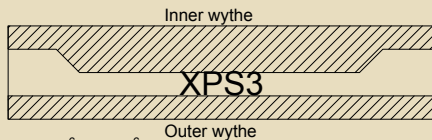
Lateral load of 11 kip



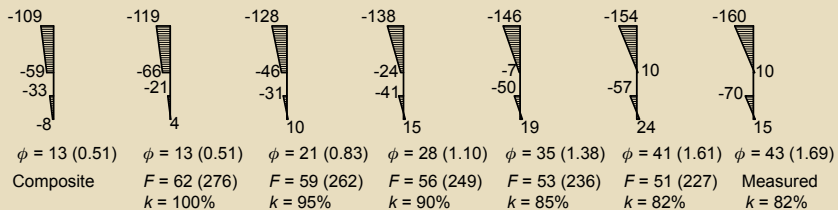
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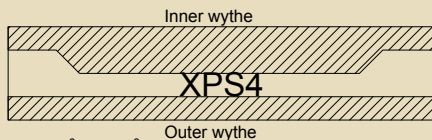
Lateral load of 20 kip



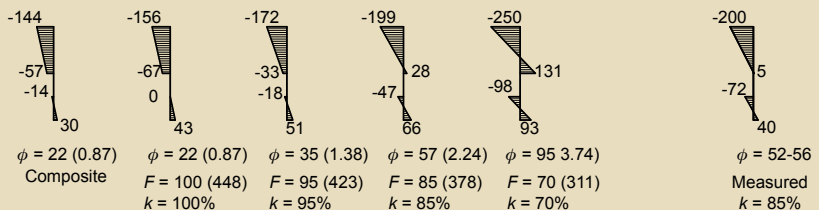
$\phi = 10^{-6} / \text{in.} (10^{-6} / \text{mm})$
 $F = \text{kips (kN)}$
 Strains are in micro in./in. or micro mm/mm



Lateral load of 5 kip



$\phi = 10^{-6} / \text{in.} (10^{-6} / \text{mm})$
 $F = \text{kips (kN)}$
 Strains are in micro in./in. or micro mm/mm



Lateral load of 12.6 kip

Figure 6. These diagrams show the strain distribution under an axial load of 37.8 kip for various lateral loads and panels. Note: EPS = expanded polystyrene; F = applied force at the interface; k = composite interaction; XPS = extruded polystyrene; ϕ = curvature. 1 in. = 25.4 mm; 1 kip = 4.448 kN.

Figure 6 shows the predicted strain distribution for the three panels used in the current study at different load levels. Results of the analysis indicated that the proposed approach is consistent with the actual behavior of the panels because the predicted strains compared well with the measured values at all load levels for the different panels.

The approach is beneficial to determining the degree of the composite interaction at different load levels for different panels at any given curvature. Results of the analyses showed that the percentage of composite interaction for both EPS and XPS foam-core panels was about 95% to 100% under the applied axial load only (lateral load = 0). As the lateral load increases, the percentage of composite interaction decreases. At ultimate load level, the percentage of composite interaction for EPS foam-core panels was about 93%, whereas for XPS foam-core panels, the percentage of composite interaction was about 82% to 85%, depending on the reinforcement ratio of the CFRP shear grid.

Such a behavior was also observed experimentally, but it was not quantified.¹² It should be noted that the configuration and layout of the CFRP shear grid were identical for panels EPS2 and XPS3. In the XPS4 panel, the amount of the CFRP grid was increased 33%, as shown in Fig. 5.

Shear-flow capacity of CFRP shear grid and foam insulations

In this section, the proposed approach is extended to determine the shear-flow capacity of the CFRP shear grid and EPS and XPS foam materials based on test results. The panels were reanalyzed at the critical section (the section of maximum bending moment) at the ultimate-load level. Steps 1 through 4 in the previous section were carried out, and the maximum force at the interface F required to develop the specified percentage of composite interaction at ultimate was evaluated for different panels. Results of the analysis are summarized in Fig. 7. The combined shear-flow capacity of the CFRP shear grid in addition to the foam q can be expressed by

$$q = \frac{F}{L}$$

where

L = the total length of the CFRP grid along the width of the panel up to the critical section

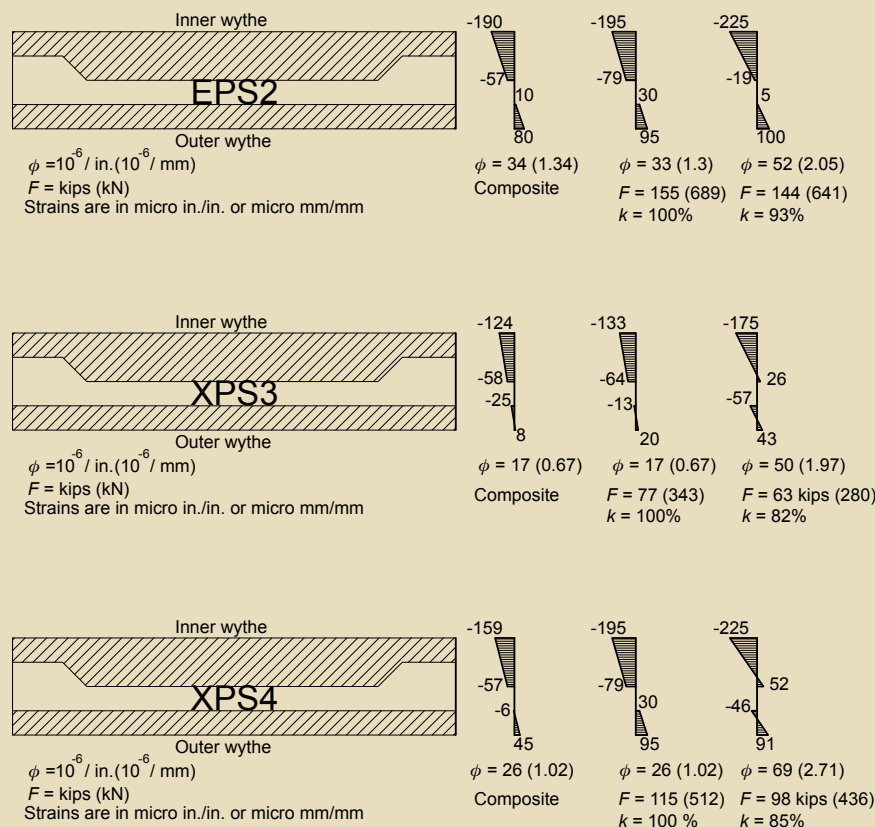


Fig. 7. Strain distribution at ultimate for EPS2, XPS3 and XPS4 panels at critical section

Figure 7. Strain distribution is shown at ultimate load for EPS2, XPS3, and XPS4 at critical sections. Note: EPS = expanded polystyrene; F = applied force at the interface; k = composite interaction; XPS = extruded polystyrene; ϕ = curvature. 1 in. = 25.4 mm; 1 kip = 4.448 kN.

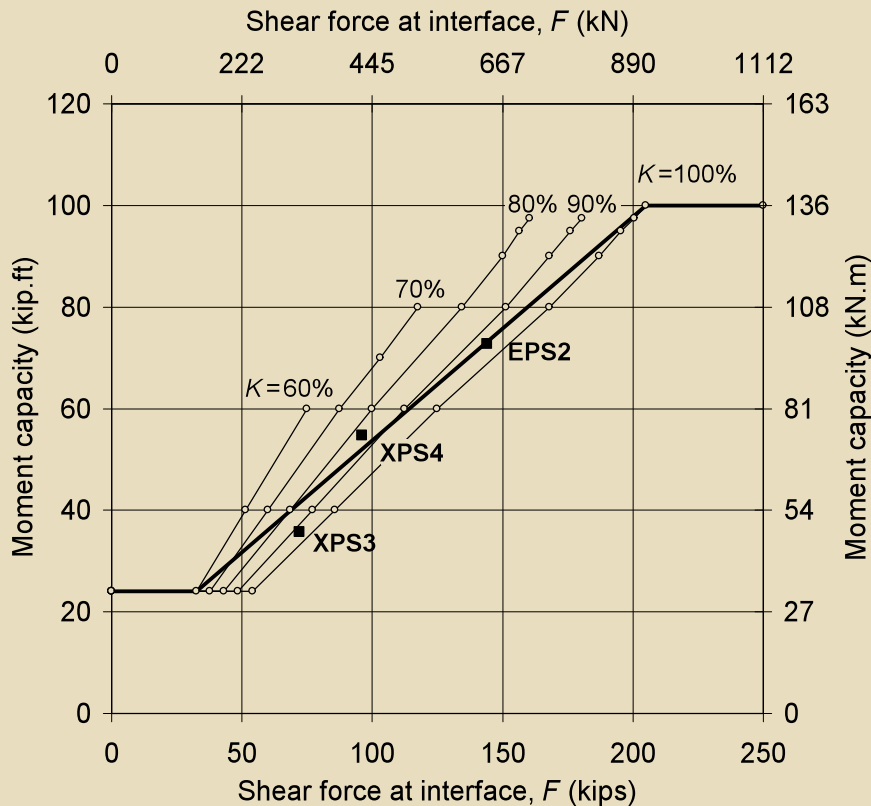


Figure 8. This design chart is proposed for calculating the nominal moment capacity of precast concrete sandwich panels reinforced with carbon-fiber-reinforced polymer grid. Note: EPS = expanded polystyrene; K = composite interaction; XPS = extruded polystyrene.

It should be noted that L is equal to 360 in. (9.1 m) in EPS2 and XPS3 panels and 480 in. (12.2 m) in the XPS4 panel.

Tests by Frankl revealed a very weak bond between the XPS foam and the concrete. Inspection of the panels after testing showed that the XPS foam was completely separated from the concrete and could be pulled up easily by hand.¹² Therefore, the shear-flow capacity of the XPS foam-core panels can be assumed to represent the capacity of the CFRP grid alone. Results of the analysis showed that the maximum force developed at 82% and 85% of composite interaction for panels XPS3 and XPS4 was 63 kip (280 kN) and 98 kip (436 kN), respectively. Consequently, the nominal shear-flow capacity of the CFRP grid for XPS3 and XPS4 is $63/360 = 0.18$ kip/in. (32 kN/m) and $98/480 = 0.20$ kip/in. (35 kN/m), respectively, with an average value of 0.19 kip/in. (34 kN/m).

For the EPS foam-core panel, the maximum shear force developed at the interface at 93% of composite interaction is 144 kip (641 kN), which reveals a combined nominal shear-flow capacity of the CFRP grid and EPS foam of $144/360 = 0.40$ kip/in. (70 kN/m). It should be noted that these estimated shear-flow capacities for EPS and XPS foam-core panels are nominal values and should not be used in design without a suitable strength-reduction factor.

It is also interesting to note that the durability of the EPS foam has not been investigated experimentally. Therefore, the proposed shear-flow capacity for the EPS foam-core panels is preliminary until further test data are available.

Simplified design chart for precast concrete SWPs reinforced with CFRP shear grid

The analytical approach proposed in this paper is too computationally intensive to be used in everyday design of wall panels with EPS or XPS foam materials. Therefore, a simplified procedure is required to calculate the moment capacity of these panels at different degrees of composite interaction. **Figure 8** shows a proposed design chart to calculate the nominal moment capacity of EPS or XPS wall panels as a function of the maximum shear force developed at the interface. The chart can be varied by varying the cross-sectional dimensions and/or the reinforcement configuration or layout of the inner and outer wythes. The chart was developed by varying the applied moment and finding the corresponding shear force at the interface at different degrees of composite interaction. The degree of composite interaction was varied from 60% to 100%. Reducing the degree of composite interaction to below 60% increases the curvature of the panel significantly and

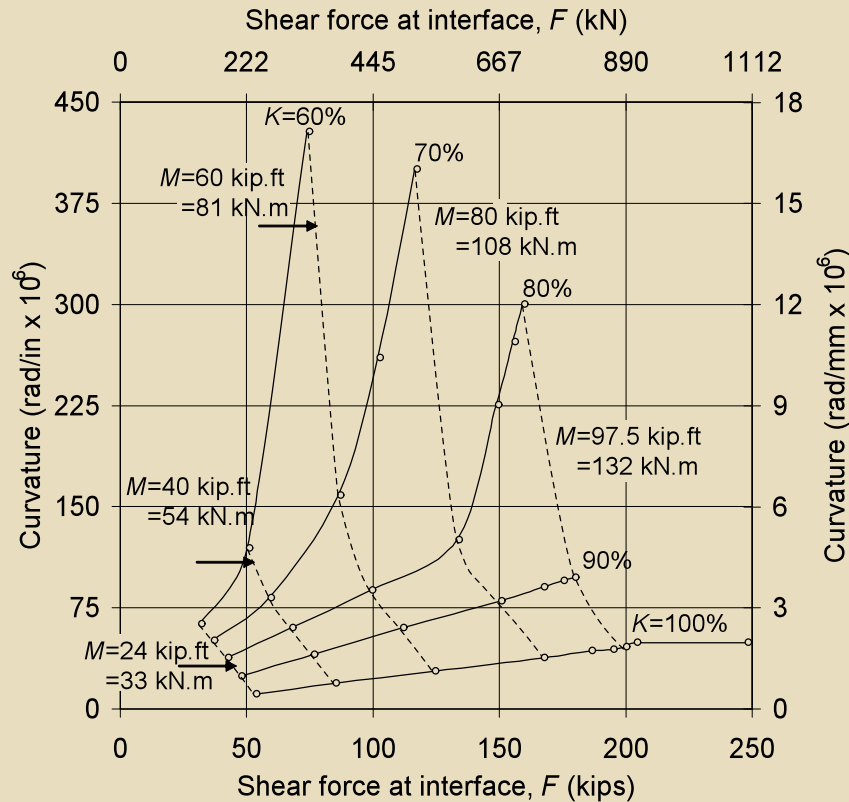


Figure 9. This graph shows the influence of the percentage of composite action on the induced curvature at ultimate load. Note: K = composite interaction; M = moment capacity.

induces severe cracking prior to failure. This behavior is not recommended in practical applications because the panels are typically designed to remain uncracked up to the ultimate-load level.

The chart demonstrates that for any required moment capacity, there is a range for the shear force at the interface that the designer can select from depending on the desired degree of composite interaction. However, the lower the degree of composite action, the higher the curvature and consequently the deflections, as shown in **Fig. 9**.

The minimum nominal moment corresponds to the fully noncomposite panel, which is the sum of the moment capacities of the inner and outer wythes. Conversely, the maximum nominal moment is the capacity of the fully composite section of the wall panel. The thick solid line shown in **Fig. 8** is proposed to simplify the calculation and to optimize the selection of the shear force needed at the interface for any required moment capacity. The required force F at the interface can be used with Eq. (3) to estimate the total length of the CFRP grid up to the critical section. The predicted capacities for the different wall panels used in the current study are also shown to illustrate the adequacy of the proposed simplified approach.

$$L = \frac{F}{q} \quad (3)$$

where

$q = 0.19$ kip/in. (34 kN/m) for XPS panels and 0.40 kip/in. (70 kN/m) for EPS panels

Comparison with finite-element analysis

In the current study, the behavior of both panels, EPS2 and XPS3, was predicted using the commercial finite-element software STRAND 7.¹⁴ Results from the moment-curvature analyses in the previous sections showed that the panels were uncracked up to the service-load level. Therefore, linear elastic analysis was performed to compare the predicted strains and displacements with the measured values.

The concrete and the foam materials were modeled using three-dimensional, eight-node brick elements. Each node had three translational degrees of freedom. The CFRP shear grid was modeled using two-dimensional truss elements. The support conditions were considered pinned

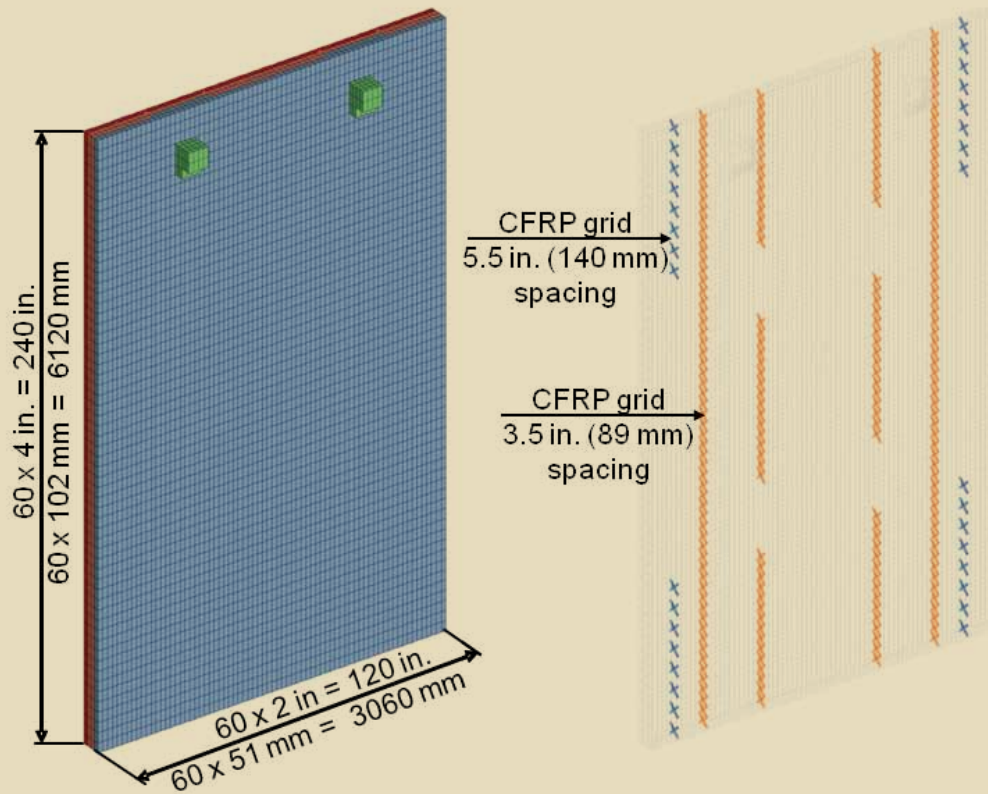


Figure 10. These mesh dimensions were used in the finite-element analysis. Note: CFRP = carbon-fiber-reinforced polymer.

at all nodal points at the bottom of the panel and at the top nodal points of the inner wythe at the locations of the corbel to mimic the actual test setup in the laboratory.¹² The foam was completely eliminated when modeling the XPS foam-core panel because of its weak bond with the concrete, as was observed in the experimental program. The finite-element mesh was selected so that elements would maintain acceptable aspect ratios while accurately representing geometry, loading conditions, and support conditions. **Figure 10** shows the finite-element mesh used in the current study. Properties of the materials used in the finite-element analysis are summarized in **Table 1**.

Figure 11 plots the predicted and measured lateral displacements for EPS2 and XPS3 wall panels under the applied lateral loads only up to the service-load level. The XPS3 panel failed prematurely under a lateral load of 5 kip (22 kN), which is 50% of the design service load. The measured displacements are plotted for the first load cycle to eliminate any stiffness degradation with increased load cycles. The predicted displacements using hand calculation (Eq. [4]) and considering only bending deformations due to two concentrated line loads placed symmetrically on the wall panel are also shown for comparison.

$$\Delta = \frac{0.5P_L a}{24E_c I_c} (3L_p^2 - 4a^2) \quad (4)$$

where

Δ = lateral displacement due to bending

P_L = total applied lateral load due to simulated-cladding wind load as shown in Fig. 3

a = distance from the supports to the applied load

E_c = modulus of elasticity of the concrete

I_c = gross moment of inertia of the composite section

L_p = span of the panel

For both panels, the predicted stiffness using finite-element analysis compared well with the measured value. The analysis indicates that the properties used to model the EPS foam material based on previous research findings are adequate and can be used to model EPS foam-core panels

Table 1. Material properties used in the finite-element analysis

Property	EPS2	XPS3
Concrete compressive strength, psi	7670	7670
Concrete modulus of elasticity, ksi	2500*	5000
Modulus of elasticity of EPS foam, psi	1550	Foam is not modeled
Poisson's ratio of foam	0.08	Foam is not modeled
Modulus of elasticity of CFRP shear grid, ksi	30,000	30,000

Source: Data from Frankl 2008; Berrie and Wilson 2003.

The low value of the concrete modulus of elasticity is attributed to the type of aggregate used by the precasting plant.

Note: CFRP = carbon-fiber-reinforced polymer; EPS = expanded polystyrene; XPS = extruded polystyrene. 1 psi = 6.895 kPa; 1 ksi = 6.895 MPa.

of different configurations and loading conditions.¹⁵ The discrepancy of the predicted stiffness using hand calculations compared with the measured values is attributed to the contribution of the shear deformation to the total displacement. Such a phenomenon was highly pronounced for the XPS foam-core panel because of its weak bond with the concrete compared with EPS foam-core panels. The predicted stiffness of EPS and XPS foam-core panels, ignoring shear deformations, was 13% and 150% higher than the measured values, respectively.

Figure 12 depicts a typical strain distribution for the EPS2 panel across its thickness under service-load level at midspan (axial load of 37.8 kip [168 kN] in addition to a lateral load due to simulated-cladding wind load of 11 kip [49 kN]). The measured strains, as well as those predicted from the rational analysis, are also shown for comparison. A small discontinuity of the strain was predicted across the insulation material in both the rational and finite-element analyses, which matched the observed behaviors. The predicted slip strain using the rational approach was 25% less than the measured value.

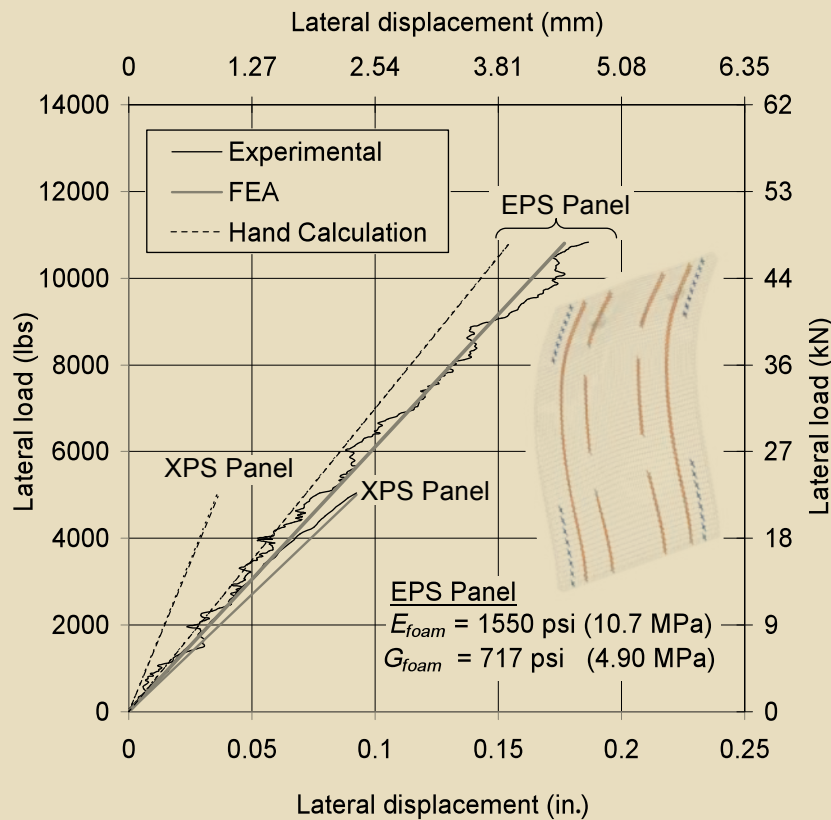


Figure 11. The predicted load displacement behavior is compared with the experimental results. Note: FEA = finite-element analysis; E_{foam} = modulus of elasticity of the foam; EPS = expanded polystyrene; G_{foam} = shear modulus of the foam; XPS = extruded polystyrene.

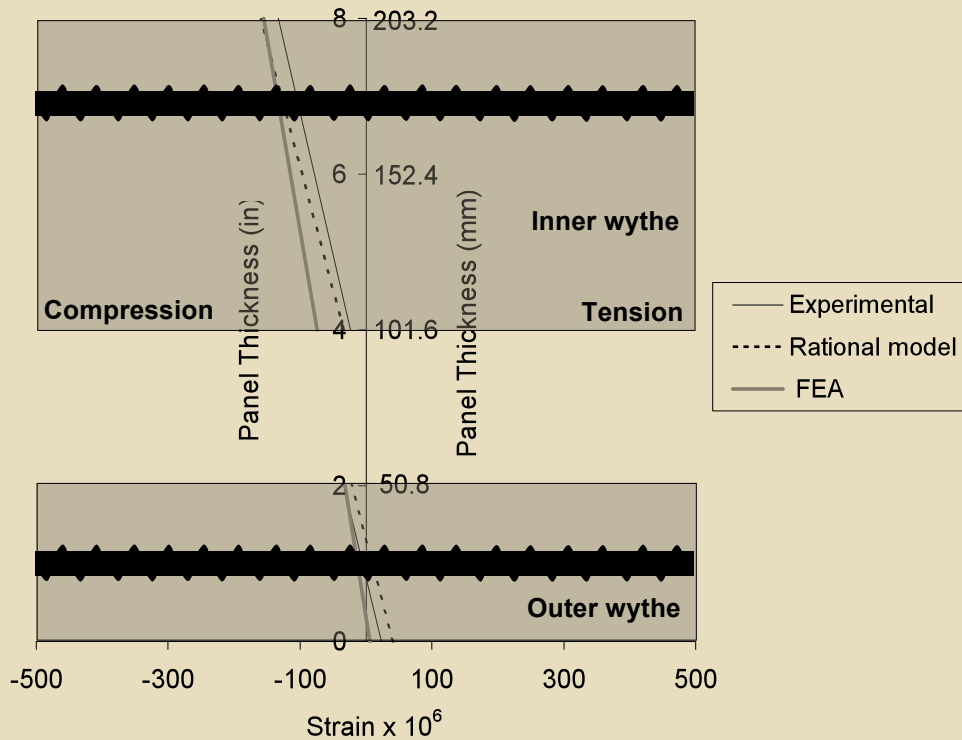


Figure 12. Strain distribution is shown along the EPS2 panel thickness at the service-load level. Note: FEA = finite-element analysis.

Conclusion

Based on the findings of the current study, the following conclusions can be drawn:

- An analytical approach for precast concrete SWPs has been developed based on the interaction theory originally developed for composite steel beams. The approach can be used to determine the percentage of composite interaction for precast concrete SWPs at different load levels at any given curvature of the panel. The approach has been validated with the experimental results, and the predicted strains compared well with the measured values. The approach is applicable to precast concrete SWPs of different configurations and can be applied to quantify the efficiency of various shear-transfer mechanisms.
- Both EPS and XPS foam-core panels do not exhibit plane section behavior at ultimate loads. The percentage of composite interaction at ultimate for EPS foam-core panels is superior to that of the XPS foam-core panels.
- XPS foam does not contribute considerably to the shear-transfer mechanism between the inner and outer wythes and can be completely ignored in the analysis of XPS foam-core panels.
- The combined shear-flow capacity of the EPS foam and CFRP shear grid used in the current study is estimated to be 0.40 kip/in. (70 kN/m). Results of the analysis showed that the average corresponding value for XPS foam-core panels is 0.19 kip/in. (34 kN/m).
- A simplified design chart is proposed to calculate the nominal moment capacity of EPS and XPS foam-core panels at different degrees of composite interaction. The chart is valid only for the panel configuration, geometry, materials, and reinforcement used in the current study. However, it can easily be produced for different panels. The chart demonstrates the effect of composite interaction on the induced curvature.
- Linear finite-element analysis can be used to determine the stiffness of precast concrete SWPs up to the service-load level with sufficient accuracy. The properties used to model the EPS foam material based on previous research findings are adequate and can be used to model EPS foam-core panels of different configurations and loading conditions.
- Shear deformations of precast concrete SWPs should be accounted for in design. The predicted stiffness of EPS and XPS foam-core panels ignoring shear deformations was 13% and 150% higher than the measured values, respectively.

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Notation

- a = distance from the supports to the applied load
- E_c = modulus of elasticity of the concrete
- F = applied force at the interface
- F_c = maximum force required at the interface to develop the full composite interaction
- I_c = gross moment of inertia of the composite section
- k = composite interaction
- L = total length of the CFRP grid along the width of the panel up to the critical section
- L_p = span of the panel
- M_I = moment in the inner wythe
- M_O = moment in the outer wythe
- M_u = factored moment
- P_L = total applied lateral load as shown in Fig. 3
- P_u = factored force
- Z = distance between the centroids of the inner and outer wythes
- Δ = lateral displacement due to bending
- $\sum C$ = sum of all compressive forces acting on the section
- $\sum T$ = sum of all tensile forces acting on the section
- ϕ = curvature
- ϕ_I = curvature of the inner wythe
- ϕ_O = curvature of the outer wythe

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Synopsis

This paper presents newly developed design guidelines for precast/prestressed concrete wall panels reinforced with carbon-fiber-reinforced-polymer (CFRP) shear grid to achieve the composite interaction. The analytical approach provides a general methodology to determine the behavior of fully and partially composite wall panels.

The effects of an imperfect connection between the two concrete wythes are considered by varying the total shear force transmitted through the shear connectors at the interface. The predicted strains along

the thickness of the panel at different load levels compared well with recent test results conducted at North Carolina State University in Raleigh. The shear-flow capacity of the insulating materials and the CFRP shear grid are determined using the proposed approach.

The influence of the degree of the composite interaction on the induced curvature and slip-strain behavior is presented. A simple design chart for estimating the flexural capacity of the wall panels with different shear-reinforcement ratios is proposed. The approach is also verified by using finite-element analysis up to the service-load level. The predicted displacement and strains compared well with the measured values reported by the experimental program.

Keywords

Carbon-fiber-reinforced polymer, CFRP, composite, noncomposite, panel, wall.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process.

Reader comments

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