Shear Transfer Mechanism of CFRP Grids in Concrete Sandwich Panels

G. Sopal 1, S. Rizkalla 2 and L. Sennour3

1, 2 Department of Civil, Construction and Environmental Engineering, North Carolina State University, Raleigh, North Carolina, USA.
3 President CEG-International, The Consulting Engineers Group, Texas, USA.

Abstract

Fiber Reinforced Polymer, FRP material has been accepted as an alternative construction material for several civil engineering applications. This paper presents the use of FRP material for the precast industry and more specifically Concrete Sandwich Panels typically used as bearing wall panels and building envelopes of many structures. The research program examines the use of a carbon fiber reinforced polymer (CFRP) material, configured as a grid and placed in composite action with rigid foam insulation, as the main shear transfer mechanism for precast concrete sandwich panels. The motivation for the use of these materials is in their ability to provide composite action between the two concrete wythes, allowing for greater structural capacity, higher thermal efficiency, and a longer service life. This study investigates the effect of several parameters believed to affect the shear flow capacity of the CGRID/foam insulation material mechanism, including the type of rigid insulating foam, the spacing between rows of CFRP grids, and the thickness of the foam insulation. A comprehensive experimental program was conducted to determine the characteristics of the shear transfer mechanism of the grid/insulation. Test results are used to develop an equation to estimate the shear flow strength using the CFRP grid/foam as affected by these parameters. A non-linear 3-D finite element program was used to model and predict the behavior of the test specimens and to study the behavior under several other parameters is presented. A solid element with different crushing and cracking characteristics are selected to model the concrete and the rigid foam materials. Contact elements are used by means of Coulomb Friction theory to model the shear transfer mechanism at the interface between the different layers. Rupture and buckling behavior of CGRID was simulated by non-linear spring elements. The ultimate strength and the degree of composite action were found to depend on the combined action of the bond between CGRID/Rigid foam and concrete.

Keywords

CFRP, Concrete Sandwich panels, Load bearing walls, FEM.

Introduction

Precast prestressed concrete insulated sandwich wall panels have been used over the past 50 years. With the advancement of the materials used for construction, the production of these panels has improved and became more efficient. Sandwich panels can provide the dual function of resisting gravity and wind or seismic loads as well as insulating a structure. The panel could resist these loads through three possible structural mechanisms, namely, composite, partially composite, and non-composite action. Typical Precast/prestressed concrete sandwich walls are constructed of two discrete layers of concrete, called wythes, separated by a layer of rigid foam insulation. To enhance the strength of the panel, a shear transfer mechanism is introduced by connecting the concrete wythes which allows the two independent layers of concrete to act together in composite action to resist the applied loads. The shear transfer mechanism were previously accomplished by casting solid concrete zones and ribs, or by placing steel trusses between the two wythes of concrete. These methods are capable of producing the desired composite action when designed properly; however, these systems have a negative consequence of thermally bridging the two concrete wythes, thus decreasing the thermal efficiency of the walls [1]. Recently, some of the precast industry started utilising Carbon Fiber Reinforced Polymer (CFRP) material to provide the connection between the inner and
outer concrete wythes. CFRP have high fatigue characteristics, excellent resistance to corrosion, and are electromagnetically neutral [2]. However, the most appealing characteristic of CFRP, in regards to concrete sandwich wall panels, is its low thermal conductivity that allows the panels to provide improved thermal properties in comparison to steel ties. The primary objective of the research study is to investigate and characterize the shear transfer mechanism provided by a combination of CFRP connectors (CGRID) and different rigid foam insulation by testing small segments of typical sandwich wall panels as shown in Figure 1.

The panels constructed using CGRID maintained the required composite action while minimizing the thermal bridging between two concrete wythes. The ultimate strength and the degree of composite action were found to depend on the combined action of the bond between CGRID/Rigid foam and concrete [3]. The different parameters that were selected for this study, and believed to influence the panels shear flow capacity measured over the total length of CGRID, included: the type and thickness of the rigid foam, and the spacing between the individual rows of grid. All the test specimens were configured to have three concrete wythes, with 2 inch (50 mm) thick outer wythes and a 4 inch (100 mm) thick centre wythe separated by two foam layers. Each specimen consisted of four vertical lines of CGRID as shear transfer mechanism between the centre wythe and outer concrete wythes through foam. Each specimen was tested in a direct shear which is mainly described as “push-out” fashion, with the bottom surfaces of the two outer concrete wythes supported vertically, leaving a 2 inch (50 mm) gap under the middle concrete wythe to allow for vertical deflection. Load was applied vertically to the top surface of the middle concrete wythe to test panels in double shear configuration to minimize the effect of moment due to eccentric location of the applied shear, as shown in Figure 2.
EXPERIMENTAL PROGRAM

Five samples for 20 different panel configurations totalling hundred push out panel specimens were tested to examine various parameters relevant to the behavior and strength of the CGRID/rigid foam shear transfer mechanism. All panels built in this research program were 6 feet (1.83 m) tall, while the width of panels were ranging from 2 feet (0.61 m) to 8 feet (2.44 m) to accommodate the required spacing of vertical lines of CGRID. Typical shop drawings for the specimens are shown in Figure 3 grid spacing and different insulation thickness.

Figure 3: Typical shop drawing (a) Elevation (b) Top View

Material configuration

Typically, three wythes of the test specimens were constructed using 6000 psi (41.4 MPa) self consolidating concrete (SCC) type of concrete. Concrete cylinders of 4 inch diameter x 8 inch (100 mm diameter x 200 mm) were produced in facility at the time of each panel casting, and were tested in accordance with ASTM C39. Patented CGRID® was custom engineered in rolled forms of an orthogonal grid. The roll of the CGRID was then cut so that individual elements within the grid were inclined at 45-degrees with respect to the panel surface to facilitate shear transfer between concrete wythes as shown in Figure 4. To determine the ultimate tensile strength and tensile modulus of elasticity, tests were conducted in accordance with ASTM D3039 on individual strands of CGRID cut from a roll of sampled material. Prior to testing, aluminum tabs were bonded to both ends of the CGRID test strand to enable gripping the strand in a universal testing machine. The average strand tensile strength for CGRID, typically used is 830 lbs (3.7 kN).

Figure 4: Typical CGRID reinforcement as shear connectors
The amount of thermal insulation or R value (U value) depends on the type and thickness of rigid foam insulation used within the panel. This research program has considered three type of rigid foams namely, Expanded Polystyrene (EPS), Extruded Polystyrene (XPS) and Polyisocyanurate (POLY-ISO). Previous test results [4] have indicated low bond strength for XPS foam due to the smooth coating of the surface. So to enhance the bond between the concrete and the insulation, an effort has been made to roughen the surface of the XPS foam using sand blasting and mechanical roughening using plastic rollers. The fundamental perception behind surface treating XPS foam is to improve bond strength between foam-concrete interfaces which will enhance the shear transfer mechanism of the concrete sandwich panels.

Test setup

All test specimens were constructed at Metromont precast concrete plant in Charlotte, North Carolina. All insulation boards were cut into three sections according to the spacing of vertical lines of the CGRID. The precut CGRID was then glued to the outer two sections of foam using foam board adhesive in such a way to ensure a 0.75 inch (19 mm) embedment depth of the CGRID into the concrete wythes. All panels were fabricated horizontally. Constructed panels were shipped to Constructed Facilities Laboratory at NC State University and were tested in a push-through fashion where the bottom surfaces of the outer two concrete wythes were supported vertically, leaving a gap under the bottom surface of the middle concrete wythe as shown in Figure 5-(A). Load was applied to the top surface of the center concrete wythe through 4 inch (100 mm) square HSS steel tubes using 60-ton hydraulic jacks, forcing it downward with respect to the outer wythes. The applied load was measured along with relative vertical deflection between the concrete wythes at eight locations and relative horizontal motion between the outer wythes was also measured at two locations as shown in Figure 5-(B).

![Figure 5](image)

Figure 5:(A) Typical Test Setup (B) Locations of Linear Pots #1-10 for All Tests

TEST RESULTS

One hundred specimens were tested in direct shear until failure to study various parameters believed to affect the shear flow capacity. The specimens included 20 categories and five specimens were duplicated for each category to provide sufficient statistical data. Load vs Displacement response for an individual specimen typically consisted of eight data curves measured from vertical sensors. These curves are converted into shear flow vs displacement response using the following equation

\[
q = \frac{F}{L}
\]

Where, \( q \) = shear flow capacity [lb/in, kN/mm], \( F \) = the max force at the interface at the critical section at the ultimate-load level [lb, kN], \( L \) = the total length of CFRP grid connecting concrete wythes along the height of the panel [in, mm]. Test result for each specimen is then denoted by a single curve obtained over the average relative vertical deflections measured from eight instruments.
Total of five curves are obtained for tested specimens in a group. Graphs used for comparison in this paper show the vertical deflections averaged over five specimens in each group. Further, test results are summarized in various sections to compare the behavior and discuss the effects of selected parameters.

**Effect of foam thickness**

This section discusses the effect of rigid foam thickness on shear flow strength of the panels for different foam types. Only one specific size of panel is considered to compare several thicknesses for each foam type. Summary of all the test results is provided at the end of this section. Test results as shown in Figure 6 indicate that increasing the thicknesses of the EPS as well as XPS-SB insulations tends to decrease the shear flow strength of the panel. Test results indicate that the effect of thickness of the Rolled XPS insulation seems to have minimal effect on shear flow strength of the panel. These panels exhibited sliding at the bonded interface in the testing process, suggesting weaker concrete bond than the majority of the other types of foam-concrete interfaces.

**Effect of CGRID spacing**

The effect of the spacing between the vertical CGRID lines is further examined in this section. In general for panels constructed with EPS and XPS-SB foam, test results indicate increasing the grid spacing increases the overall shear flow strength of the panel due to increased bonded area. However, it tend to decrease the overall shear stress due to the increase of interface surface area in comparison to the increase of the measured load capacity. Test results for the panels with XPS-R foam indicated that spacing between CGRID seems to have minimal effect on shear flow strength. This phenomenon was not similar to EPS and XPS-SB due to low bond strength development between foam and concrete interface for XPS-R foam. Test results for the panels with POLY-ISO foam indicated a minimal impact of CGRID spacing along the panel width. Decreased shear flow was observed for wider CGRID spacing due to large debonded interface area between POLY-ISO and concrete surface.

Figure 6: Effect of Thickness (A) EPS foam (B) XPS-SB foam

Figure 7: Effect of CGRID spacing (A) EPS foam (B) XPS-SB foam
These panels exhibited sliding at the bonded interface early in the testing process, suggesting larger area of debonded surface of the POLY-ISO to concrete than the majority of the other panels tested. It was determined that these panels likely contained manufacturing defects i.e. larger area of debonded surface. Test results of the panels with four different foam types, with different spacing between CGRID, are shown in Figure 7. Test results of the 100 specimens tested are summarized in graphical form in Figure 8.

![Shear flow strengths for 100 specimens](image)

**Figure 8: Shear flow strengths for 100 specimens**

**Failure Modes**

Typical failure modes observed during testing of concrete wall panels are shown in Figure 9-(A). Inspection of the specimens after testing revealed that EPS/XPS-SB foam failed with shear cracking indicating a stronger bond, while shear sliding was observed at XPS-R/POLY-ISO concrete interface indicating weaker bond.

![Failure Modes](image)

**Figure 9: (A) Typical failure modes (B) XPS-SB-concrete interface indicating strong bond (C) XPS-R-concrete interface indicating weak bond**
After testing, several panels were cut along a line 2 in (50 mm) away from the vertical strip of CGRID and opened to observe the amount of foam attached to concrete. Visual inspection of opened panels revealed that EPS/XPS-SB concrete interface resulted in a rough surface indicating a stronger bond as shown in Figure 9-(B). However, POLY-ISO/XPS-R foams depicted weak bond and this observation was evidenced by the clean concrete surfaces when the concrete wythes were separated from the foam cores as shown in Figure 9-(C). Complete foam layer was then mechanically removed along the cut to expose the CGRID over the height of the panel. It was observed that all panels exhibited rupturing of the CGRID in tension and buckling of the CGRID in compression.

**Design Equation**

The objective of the experimental program was to characterize the CGRID/foam shear mechanism for precast prestressed concrete sandwich wall panels. Based on the quantity of CGRID placed to connect the concrete wythes and the nature of bond between foam-concrete interfaces, a designer can rely on full composite, non-composite, or partially composite action. To achieve full composite action, it is necessary to provide adequate amount of CGRID connectors and specify a foam type that is capable of transferring the full shear force induced by the applied loading.

A design equation is proposed to assist designers in calculating the shear flow capacity of CGRID/foam used as a shear transfer mechanism for any combination of the parameters considered in this research. The overall nominal shear flow capacity of the CGRID/foam combination tested in this research study is calculated using Equation 2. Previous test results [4] have reported that the shear flow capacity of panels with CGRID alone is nearly 100 lbs/in (17.5 N/mm). This testing configuration helped to evaluate the shear flow capacity of the CGRID with no contribution from the bond between the rigid foam to the concrete. Hence, this obtained value is considered as a baseline for this design equation approach. This equation modifies the baseline shear flow capacity of the panels based on established factors for type of foam, thickness of foam, and spacing between vertical lines of CGRID.

The overall average shear flow capacity of the carbon grid/rigid insulation shear mechanism is calculated using the equation as

\[
q_{\text{average shear flow}} = q_{\text{baseline}} \times f_{\text{type}} \times f_{\text{thickness}} \times f_{\text{spacing}}
\]

Where, \( q_{\text{average shear flow}} \) = Predicted shear flow capacity of CGRID/foam [lbs/in, N/mm], \( q_{\text{baseline}} = 100 \) lbs/in (17.5 N/mm) [based on shear flow strength of CGRID alone], \( f_{\text{type}} \) = Factor for type of foam [EPS/XPS-SB/XPS-R/POLY-ISO], \( f_{\text{thickness}} \) = Factor for insulation thickness [2/4/6 inches], \( f_{\text{spacing}} \) = Factor for CGRID spacing [12/24/48 inches].

Based on test results of a total of 100 panels tested in this program and combined with 8 panels tested previously [4], a spreadsheet program is used to establish the factors for all the various tested parameters as shown in Figure 10-(A).
Originally all the factors were set to a value of 1.00, with $q_{baseline}$ equal to 100 lbs/in (17.5 N/mm). The initial analysis resulted in a shear flow capacity of 100 lb/in (17.5 N/mm) for all panels. The absolute error of the predicted average shear flow value, in comparison to the measured values was determined for each panel. This absolute error was squared and summed, for all panels containing four different type of foams. A multi-variable solver tool was used to minimize the summed error by adjusting the factors first for each type of foam. After the minimization routine was complete, all the factors were rounded to two decimal places for these values as shown in Figure 10-(B).

FINITE ELEMENT ANALYSIS

The non-linear 3-D finite element program is used to estimate the strength of the CGRID/Rigid foam system as affected by various parameters believed to influence the shear flow strength of this system. The parameters that were used in experimental program are selected for finite element modeling. The parameters included: the type of rigid foam, the thickness of rigid foam, and the spacing between the individual vertical lines of CGRID. The analysis was performed using a general purpose finite element analysis program commercially known as ANSYS utilizing non-linear geometry and non-linear material properties.

Concrete – Element and Constitutive Relationships

The three concrete wythes were modeled using eight-noded elements (known as SOLID65 in ANSYS program). Multi-linear isotropic plasticity was used to approximate the non-linear constitutive relationship for concrete in ANSYS program. In the analysis the descending branch of the stress-strain curve was not included and, the stress remained nearly constant with increasing strain, after reaching a peak stress. To help accelerate convergence of the calculations, option of stress relaxation at cracks was selected (changing input settings within ANSYS) when cracking was imminent.

Foam – Element and Constitutive Relationships

The two layers of rigid foam were modeled using the same eight-noded elements used for concrete. To model the behavior of rigid foam material in shear, the stress-strain parameters were input in ANSYS using multi-linear isotropic material model based on values obtained by an earlier experimental program [4,5]. The load-displacement curves, obtained from tested panels constructed with only EPS and XPS-SB, are converted into shear stress-strain curves. To model foam failure in shear a Von Mises’s theory was considered, where shear stress-strain values were converted in to tensile stress-strain curves. To verify the input material properties, specimens were loaded with similar boundary conditions. Each specimen was loaded in double shear to minimize the eccentric location of the applied shear, in a push-through fashion where the bottom surfaces of the outer two concrete wythes were fixed vertically, leaving a gap under the bottom surface of the middle concrete wythe. Results from ANSYS were post-processed to obtained load-displacement curves and are compared with test results in Figure 11.

Figure 11: Validation of FE model (A) EPS foam (B) XPS-SB foam
CGRID connector – Element and Constitutive Relationships

Rational prediction of shear flow strengths of concrete sandwich panels using FE analysis depends on accurately modeling the strength and stiffness of the CGRID connectors. Material properties of individual strand of CGRID connectors tested in tension indicate linear elastic behavior before rupturing of single strand of CGRID at ultimate load. The overall response of CGRID has not been straightforward when used as connectors between concrete wythes, as compared to the response from single strand in tension test, which is partially due to complex nature of CGRID geometry. Previous research [6] has indicated that to insure rupture of fibers, CGRID should be embedded ¾ inch (19 mm) deep in each layer of concrete wythe. To maintain that embedment depth, three different configurations of CGRID were used in this research program using 2 inch (50 mm), 4 inch (100 mm) and 6 inch (150 mm) foam thicknesses. The joint formed between two individual strands of CGRIDs are fixed in such a way that it only allows transfer of axial forces. It was observed that all the panels exhibited rupturing of the CGRID tension chords and buckling of the CGRID compression chords. Although, mostly CGRID chords were ruptured either near strand joints or near CGRID-concrete connections. This phenomenon was observed due to the rigid connections between concrete wythe and CGRID connectors as represented in Figure 12-(A). As the fibers are subjected to tension and compression, they are also clamped against the concrete, which results in shearing of individual strands at lower strengths as compared to observed ultimate strengths in tension tests. Hence, it was difficult to assume a linear elastic behavior of CGRID. To capture this complex behavior a panel tension test and a panel compression test were performed to evaluate CGRID response in compression as shown in Figure 12-(B).

Figure 12: (A) Typical CGRID failure (B) Panel Tension and Compression test

The individual strands of CGRID connecting three concrete wythes are modeled with a non-linear spring elements (commonly known as COMBIN39 in ANSYS program), without considering the intermediate joints. The element is
defined by two nodal points and a generalized force-deflection curve. The complex behavior of CGRID, considering clamping and premature failure in push-out test, is modeled through the input parameters of force-deflection curve. This force-deflection curve representing compression and tension behavior was obtained through two special specimens that were tested in direct compression and tension as shown in Figure 12-(B).

Foam-concrete interface

In general, test results have indicated a significant contribution of rigid foam towards shear flow strength of concrete sandwich panels through bond. However, this contribution is large only with strong bond strength between foam-concrete interfaces. A good construction practice is required to achieve good bond characteristics at all the foam-concrete interfaces. These test specimens were built in horizontal fashion, piling up layers of concrete-foam-concrete on top of each other. Due to this way of construction, there is a strong possibility of formation of air pockets at the interface which results in weaker bond. These defects significantly affect the shear flow strength of wall panels. To implement these effects in the model, contact elements are used to simulate bond strength between foam and concrete interfaces. Four interface between the foam and the concrete were modeled using 3-D contact pairs consisting of four-node contact elements (CONTA173) and four-node target elements (TARGE170). The purpose of these contact pairs is to account for shear sliding and separation that occur along the interface of solid elements. The shear strength of the interface is represented using Mohr-Coulomb friction model.

Comparison with Experimental results

Due to the highly non-linear nature of the local and global behavior, various numerical procedures were required to improve stability of the model. Wall panels with large foam thickness, can undergo very large displacements. The magnitude of these displacements has a significant impact on the overall behavior, especially as it relates to shear sliding. For this reason, the effects of non-linear geometry, i.e. large strain and large displacements were included in the analysis.

![Figure 13: Panel with 12 inch grid spacing (Size 24 inch x 72 inch) (A) EPS Foam (B) XPS-SB foam](image)

The results of the analysis are compared with the results of the experimental program to determine the effectiveness of the full-scale model in simulating the behavior are shown in Figure 13. Predicted peak shear flow strength using this FE model for all the panels with EPS and XPS-SB foam are summarized and compared with measured values in Figure 14-(A) and Figure 14-(B), respectively. The analysis showed reasonable agreement with the measured values for initial phase of load-deflection curves. However, the accuracy of the ultimate strength prediction for the finite element model shows considerable amount of variation. This difference is attributable to the uncertainties involved in construction process of these wall panels. For panels with EPS foam, the accuracy in predicting ultimate shear flow strength values using finite element model ranged from 2% to 8%. While the accuracy of predicting ultimate shear flow strength values for XPS-SB foam ranged from 2% to 39%. The large variation of accuracy in predicting shear flow strengths for XPS-SB foam is due to variable nature of the bond properties of foam-concrete interfaces. The bond strength is a function of type of surface that is prepared through sand blasting process. There are no specific criteria to control amount and nature of sand blasting. Comparisons of the predicted strength to the measured values indicate capability of finite element program in predicting the strength assuming the perfect bond.
of the foam to the concrete surface. Throughout this research program, it was observed that there are higher chances of formation of air pockets in panels built with XPS-SB foam as compared to panels with EPS foams. Hence, FE results for panels with different CGRID spacings and thicknesses with EPS foam showed higher accuracy in predicting shear flow strength values as compared to panels with XPS-SB foam due to large variation in presence of air pockets resulting in variable bond strength of foam-concrete interfaces.

**CONCLUSION**

All the wall panels were built with three concrete wythes connected with four 6 feet long vertical strips of CGRID along with two layers of rigid foams. Various parameters believed to affect the shear flow strength for this CGRID/foam system were examined by testing hundred panels. The parameters included: the type of rigid foam, the thickness of rigid foam, and the spacing between the individual vertical lines of CGRID. Panels produced with EPS and XPS-SB rigid foam developed higher shear strengths in comparison to panels insulated with XPS-R and POLY-ISO foam. For panels with EPS and XPS-SB foam, increasing the spacing between vertical lines of CGRID indicated increase in overall shear flow strengths due to increased bonded area. However, it showed decreased...
overall shear stresses due to the increase of interface surface area in comparison to the increase of the measured load capacity. Test results for the panels with XPS-R and POLY-ISO foam indicated that spacing between CGRID seems to have minimal effect on shear flow strength. This phenomenon was not similar to panels with EPS and XPS-SB due to low bond strength development between foam and concrete interface. Shear cracking, shear sliding and mix mode (cracking + sliding) were three different modes of failure observed throughout testing. A spreadsheet program was used to establish the factors for design equations and has exhibited reasonable prediction of the shear flow strengths for given CGRID/foam systems. The large variation of accuracy in predicting shear flow strengths for XPS-SB foam is due to variable nature of the bond strengths of foam-concrete interfaces as there are no specific quality control criteria for sand blasting. FE results for panels with different CGRID spacings and thicknesses with EPS foam showed higher accuracy in predicting shear flow strength values as compared to panels with XPS-SB foam due large variation in presence of air pockets resulting from variable bond conditions at foam-concrete interfaces.

REFERENCES


