ABSTRACT

SOPAL, GAUTAM JAYANT. Use Of CFRP Grid As Shear Transfer Mechanism For Precast Concrete Sandwich Wall Panels. (Under the direction of Sami H. Rizkalla).

Fiber Reinforced Polymer (FRP) material has been accepted as an alternative construction material for several civil engineering applications. This thesis 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 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. The research program investigated the effect of several parameters believed to affect the shear flow strength of the CFRP grid (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 design equations to estimate the shear flow strength and shear modulus for CGRID/rigid foam system as affected by these parameters.

A non-linear 3-D finite element program was used to model 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.
Use Of CFRP Grid As Shear Transfer Mechanism For Precast Concrete Sandwich Wall Panels

by
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DEDICATION

I dedicate this thesis to my loving and devoted wife Triveni Sopal. Thank you for your unwavering love, inspiration, patience, and countless sacrifices that made this accomplishment possible. I would also like to dedicate this thesis to my parents, Jayant and Prabha Sopal, thank you for your love, support, and strength raising me into the person I am today. I would also like to mention my brother Dr. Kaushik Shahir whose constant encouragement boosted my confidence which helped me to achieve my goals.

Thank you
Gautam Jayant Sopal was born and brought up in India, in a burgeoning industrial town in Maharashtra state bustling with activity in its transformation from rural to a semi-urban economic system. He achieved undergraduate degree in Civil Engineering in 2005 at Shivaji University with distinction remarks. His interest and passion in Structural Engineering field motivated him to pursue higher education. With this good reason, he completed Master of Science in Structural Engineering at Oregon State University in December 2008. With all education and experience, he knew an-in-depth knowledge of the field is necessary to develop more practical and robust techniques and so he enrolled in the Civil Engineering Graduate program at North Carolina State University. He further intends to pursue a career in structural engineering.
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1 INTRODUCTION

1.1 Background

Concrete wall panels could be casted at the construction site in a horizontal position and after proper curing; they are tilted up and installed in the proper location. Majority of wall panels are casted into a factory setting to improve their quality control and efficiency. Precast concrete sandwich walls are widely used, as the exterior building envelopes for warehouses and industrial buildings. Typical Precast/prestressed concrete sandwich walls are constructed of two discrete layers of concrete, called wythes, separated by a layer of rigid foam insulation. With the addition of numerous exterior finishes, their use has expanded to different types of structures including schools, residential and hospitals buildings (PCI Committee on Precast Sandwich Wall Panels, 2011). An illustration of a typical architectural sandwich panel with a thin brick veneer is shown in Figure 1-1.
In this thesis, precast prestressed concrete sandwich wall panels will be referred to as “sandwich panels” or “panels.” Sandwich panels can provide the dual function of resisting gravity and wind loads as well as insulating a structure. The panels are also designed to carry lifting and transportation loads. The panel could resist these loads through three possible structural mechanisms, namely, composite, partially composite, and non-composite action. The early generations of sandwich panels were built to behave in non-composite mechanism, where two concrete wythes resist the loads individually and steel ties were used to connect

Figure 1-1: Example of an Architectural Sandwich Panel
(AltusGroup, LLC website)
the two concrete wythes to ensure integrity of the panel. To enhance the strength of 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 load. This mechanism works similarly as the concrete deck of steel girders in bridges which are connected by Nelson studs.

The shear transfer could be accomplished by casting solid concrete zones and ribs, or by placing steel trusses between the two wythes of concrete. Although it has been shown that these methods are capable of producing the desired composite action when designed properly however, this system have a negative consequence of thermally bridging the two concrete wythes, thus decreasing the thermal efficiency of the panels (Lee & Pessiki, 2004). Recently, some of the precast plants use of fiber reinforced polymer (FRP) material to provide the connection between the inner and outer concrete wythes. FRP composites have many desirable qualities that make them an attractive alternative for the construction of prestressed precast concrete sandwich wall panels. When compared to steel, FRP composites have a high ratio of strength to mass density (10-15 times greater). In addition, CFRP have high fatigue characteristics, excellent resistance to corrosion, and are electromagnetically neutral (Erki & Rizkalla, 1993).

However, the most appealing characteristic of FRP and particularly CFRP, in regards to concrete sandwich wall panels, is its low thermal conductivity that allows the panels provide improved thermal properties in comparison to steel ties. The CFRP grid ties the two wythes of concrete together with minimal formation of thermal bridges in comparison to
concrete block-outs or steel ties. Based on the design of the CFRP grid used to connect the concrete wythes and the nature of bond between foam-concrete interfaces, a designer can rely on almost full composite, non-composite, or partially composite action. The ability of the shear connectors to transfer the shear forces through the insulated core, from one concrete wythe to the other, determines the amount of composite action that is achieved, as shown in Figure 1-2.

![Figure 1-2: Strain Profiles for Various Degrees of Composite Action](image)

Figure 1-2: Strain Profiles for Various Degrees of Composite Action

Non-composite panels rely on each concrete wythe to act independently to resist the applied loads. Therefore, the strain distribution is related to the individual stiffness of each concrete wythe. The non-composite wythes will each carry a percentage of the applied moment and act independently from each other, as shown in Figure 1-2(a). Partially composite panels have shear connectors that provide some shear resistance, as shown in Figure 1-2(b); therefore, the bending stiffness and strength are between those of the fully composite and
fully non-composite panels. The strain distribution of a fully composite panel is linear through the thickness of the uncracked concrete panel, as shown in Figure 1-2(c).

Structural behavior of these panels depends on the strength and stiffness of the CFRP connectors, CGRID, in addition with bond between foam-concrete interfaces while the thermal resistance of insulation layer governs the R-value of the panel. Hence, the amount of shear transferred, hereafter referred as “shear flow strength”, across the insulation for a specific CGRID/foam combination is challenging to predict, and therefore, the degree of composite action is difficult to determine. CGRID connectors have been successfully used by Altus Group to produce precast prestressed concrete sandwich panels that are both structurally and thermally efficient (Gleich, 2007). However, difficulty in determining the level of composite action leads to trouble in predicting the structural behavior of the panel, including moment capacity and deflections.

This thesis presents the research program conducted at the Constructed Facilities Laboratory at North Carolina State University to investigate the behavior of insulated concrete sandwich panels containing combinations of CGRID connectors and different insulation type. This research will help designers to determine the degree of composite action attained from different panel size and configurations.
1.2 Research Objectives

The primary objective of the research program is to study and characterize the shear transfer mechanism provided by a combination of CGRID connectors and different rigid foam insulation in prestressed precast concrete sandwich wall panels. Small segments of typical sandwich wall panels, as shown in Figure 1-3, are used for the experimental program to determine the shear flow strength of the CGRID/foam combination.

![Diagram of sandwich wall panel]

**Figure 1-3 : Small segment of typical wall panel used for testing program**

The different parameters that were selected for study, and believed to influence the panels shear flow strength, included: the type and thickness of rigid foam, and the spacing
between the individual rows of grid. Details of the selected specimens and the testing procedure are discussed in detail in Chapter 3. Typical test panels consist of three concrete wythes, as opposed to usual two concrete wythes panels, to act in double shear configuration to minimize the eccentric location of the applied shear, as shown in Figure 1-4.

![Figure 1-4: Typical specimen tested in Double Shear](image)

Test results are used to develop an equation to estimate the shear flow strength using the CFRP grid/rigid foam as affected by these parameters. A non-linear 3-D Finite Element Analysis was developed to model the behavior of the test specimens and to study the
behavior under several other affecting parameters such as insulation type, insulation thickness and CGRID spacing. 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. Details of the FE model are described in Chapter 5. The FE model was calibrated with experimental results to determine the degree of composite action achieved.

1.3 Scope

In order to achieve the objectives described, research study included the following phases:

a. Comprehensive literature review to investigate the history and nature of precast sandwich wall panels. Industry and innovative methods for design were also explored.

b. Test 100 specimens including various parameters believed to be affecting shear flow strength, in direct shear until failure. Test results and failure modes were examined to categorize the shear transfer mechanism formed by combining CGRID and different insulation types.

c. Use the experimental results to develop a design equation for various panel configurations as affected by the various parameters, including type of foam, thickness of the foam, and spacing between the rows of grids.

d. Develop a 3-D FE model to identify shear transfer mechanism and study the parameters affecting the level of composite action achieved for various combinations of CGRID and insulation types.
2 LITERATURE REVIEW

Precast prestressed concrete insulated sandwich wall panels have been used over the past 50 years. One of the earliest reported uses of concrete sandwich wall panels for building construction was in 1906. With the advancement of the materials and methods of construction over decades, the production of these panels has been improved and become more efficient. Typical sandwich wall panel consist two layers of concrete separated by foam core. The two concrete wythes are typically connected by different type of shear connectors. The materials for production have evolved over the years and higher quality control is achieved in construction of these panels as they are casted in a factory (PCI Committee on Precast Sandwich Wall Panels, 2011). Shear transfer mechanisms have evolved from solid concrete zones to steel truss mechanism. A major criterion in the recent advancements of precast concrete sandwich panel technology has led the building owners to attain Leadership in Energy & Environmental Design (LEED) certification. LEED maintains requirements and guidelines for thermal performance of building envelopes, focusing the precast industry’s attention toward a more thermally efficient panel system.

Innovative materials, such as carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP), are being explored to accomplish these goals. Various shear transfer mechanisms have been investigated quantifying their structural contribution along with their thermal performance. Several design philosophies have been developed for various
panel behaviors and shear transfer mechanisms. Several attempts have been undergone to accurately model the behavior using finite element method to describe the behavior.

2.1. History

Earliest known tilt-up building around dates back to 1893 at Camp Logan, IL when mobile cranes were not available, a tipping table was designed specifically to cast and erect the walls as shown in Figure 2-1.

![Early Example of Tilt-up Construction known as “Aiken Method”](image)

Figure 2-1: Early Example of Tilt-up Construction known as “Aiken Method”
At the beginning of century, designers and contractors in United States manifested an idea of concrete sandwich panels by constructing a “sandwich” tilt-up wall. The wall was constructed with a two inch layer of sand placed between two layers of concrete, often termed as “wythes” and tied together with reinforcement. The sand was eventually washed out as the wall was lifted into place, creating a hollow core sandwich panel. Early generations of concrete sandwich wall panels used different materials to separate the two wythes of concrete such as sand, woodchips, lightweight vermiculite concrete, cellular glass, foam and expanded shale (Collins, 1954).

It was well known earlier that shear ties were used to connect the outer concrete wythes together through the insulation material. Although, study suggested that a wood fiber filler material could possibly be used without shear connectors (Collins, 1954), most designers chose to include minimum shear ties for all tilt-up construction panels. Examples of shear ties used up to this time period are shown in Figure 2-2.

![Figure 2-2 : Examples of Shear Ties used earlier](image)
The potential of the precast concrete system was utilized in single family home construction as far back as 1938. A single family home was built in the suburbs of Washington, D.C. to demonstrate the concept of precast panels with two inch thick mosaic precast concrete panels as exterior walls. These precast panels were not sandwich panels and provided only the façade of the structure; a wood frame was used to support the panels and to supply the main structure for the home. This construction illustrated the potential savings in labor while aiding in the ease of construction/installation (Early, 1935). Further utilizing this technique, a 1000-family housing development named Forrestal Village was erected in 1951-1952 at Great Lakes, Illinois. It was the first large scale residential construction project in North America to employ precast concrete sandwich wall panels (Lorman & Wiehle, 1953). Shear connectors in the form of 6” long steel J-pins were used during construction, similar to the pin shown in Figure 2-2(D). These pins were punched through the foam insulation layer into the bottom concrete wythe and the top layer cast on the “J” portion protruding upward. Use of shear connectors became ideal and different variations were used like 4” wide strips of welded wire mesh and also metal shear connectors like the one shown in Figure 2-2(A&B).

Early versions of a sandwich wall panels were innovated through fire-proof home construction competition in the New York metropolitan area by the Portland Cement Association. As part of the initiative, Inter Industries, Inc. produced a house made up of concrete sandwich wall panels in which insulation was provided by inserting mineral wool in waterproof bags between vertical wall members.
Another type of early precast concrete system was developed by Quentin Twachtman in 1935. Wall units using this system were 9 ft. 6 in. x 15 ft. and were cast in one operation similar to the process used today. A 6 inch x 6 inch wire mesh was cast into a one inch layer of concrete on wooden formwork. Crimped metal lath was placed at 16 inches on center, forming ribs. An insulating layer was placed, followed by another layer of mesh and finally another one inch of concrete was cast. Vertical reinforcement was placed in the ribs. This made the wall section 8 inches thick. The large wall units were taken to the building site by truck and erected in place (Zipprodt, 1935) as shown in Figure 2-3. Though the materials used in constructing wall panels have improved substantially, the basic method of producing the panels remains very similar to this early version.

By this time ideal sandwich core materials were established. These middle layers were to be materials with low density, relatively high compressive strength, high shear strength, good bonding characteristics, high insulative qualities, and low cost. Available materials at the time were divided into four categories—cellular glass materials and plastic foam, compressed and treated wood fibers in cement, foam, and lightweight concrete—where it was concluded that for the precast industry materials such as cellular glass or compressed wood fibers should be used for the precision-made type of sandwich wall panel. Whereas the lightweight concrete mixes were suggested for the cast-in-place large tilt-up sandwich wall panel in order to achieve economic feasibility.
Figure 2-3: Construction of early Sandwich panels by Twachtman (ACI Journal, 1935)
The development of sandwich panel construction and design through the recent decades started in the 1960s with solid concrete zones used as core shear transfer mechanism to create full composite action. However, the thermal efficiency of these panels was reduced due to thermal bridging caused by the concrete ribs connecting the two wythes through the insulation core. To produce a more thermally efficient panel and maintain the full composite action, metal trusses began replacing the solid concrete ribs. Although these steel trusses provided an improvement over solid concrete shear zones, its conductivity still hampered the thermal efficiencies of these panels (Gleich, 2007).

It was stated that monolithically-cast concrete ribs, concrete shear connectors, or mechanical shear ties should connect the two concrete layers in a sandwich wall panel that consists of two layers of concrete separated by a nonstructural insulation core. The nonstructural insulation core should not transfer shearing stress and only the concrete sections should carry the compressive and bending stresses. Joining the concrete wythes with sufficient shear connectors allows them to act together, as one structural unit in composite action. Non-metallic ties were used in the late 1980s to produce thermally efficient non-composite panels; however, structural efficiency was sacrificed. To this point, structural and thermal efficiency were inversely related; therefore, increasing one desired property was at the expense of the other. Sandwich wall panel technology advanced gradually over this time period. The past decade has seen the concept take a major leap forward with the introduction of carbon fiber reinforce polymer shear reinforcement grids.
2.2 FRP Shear Connectors

There have been increasing demands to increase and improve the thermal insulation of buildings as well as efforts to reduce energy consumption along with decrease in carbon dioxide emission. Several efforts have been made to increase the thermal efficiency of prestressed precast concrete sandwich wall panels, while maintaining structural efficiency. Previously, metal shear connectors performed better than concrete solid zones, while the thermal efficiency of the panel was still a major concern. Recently, FRP or fiber reinforced polymer reinforced structural elements became available and are capable of providing structures that are thermally efficient as well as lighter, easier to assemble, more durable, and not susceptible to the deterioration from reinforcing steel corrosion. A novel method was investigated in an experimental program in which FRP bent bar trusses were used to transfer shear forces. The proposed system used in this study is shown in a panel section in Figure 2-4. Full scale testing of precast concrete sandwich panels using this shear transfer mechanism revealed that this system was capable of providing 84% composite action compared to 88% for steel truss connectors (Salmon, Einea, Tadros, & Culp, 1997). To prevent concrete ribs from forming around the FRP bent bar system, thus forming thermal bridges, a small block of insulation was placed around the bar prior to construction as shown in Figure 2-4. Another innovative technique containing GFRP shells, as shown in Figure 2-5 for shear transfer mechanism, was investigated. Test results indicated that 97-99% composite action could be attained in precast concrete sandwich wall panels using GFRP shells (Pantelides, 2008). It was found that the panels failed in a ductile manner, suggesting that the
GFRP shells provided sufficient shear transfer mechanism between the inner and outer concrete wythes.

Figure 2-4: FRP Bent Bar Shear Connector

The thermal capabilities of panels containing the FRP bent bar system was investigated and reported later. It was found that the energy efficiency building envelopes constructed with sandwich panels, using FRP bent bar truss as shear connectors, were 1.8 times more energy efficient than panels with solid concrete shear zones and 1.2 times more efficient than panels constructed with steel shear connectors (Chen, Salmon, Hancock, &
Detloff, 1994). These research programs have indicated that FRP shear connectors can provide the dual purpose of improving the thermal capabilities of a building envelope, while at the same time, providing the desired structural integrity and efficiency.

Recently, AltusGroup (National partnership of several leading precast manufacturers) introduced a carbon fiber reinforced polymer shear connector, often referred as “CGRID” which is cut at a 45 degree angle of an orthogonal grid, and placed in a truss orientation as shown in Figure 2-6. The panels constructed using CGRID connectors maintained the same composite action while minimizing the thermal bridging. The R-values of the concrete sandwich wall panels can be as high as 32, and typically range from 11 to 16, illustrating the
potential long term savings in the heating, ventilation, and air conditioning system of buildings incorporating this type of building technology (Gleich, 2007).

Frankl et al (2008) completed an experimental program to determine the behavior of precast, prestressed concrete sandwich wall panels reinforced with this CFRP shear grid. It was discovered that the desired composite action could be achieved using either EPS or XPS rigid foam insulation in combination with CFRP grid. However, panels constructed using EPS insulation, provided a better shear transfer mechanism and achieved higher percent composite action than XPS insulation due to better bond between EPS foam and concrete. This required higher amount of CGRID connectors for combination with XPS compared with

Figure 2-6 : CFRP Grid used as Shear Transfer Mechanism
EPS insulation. Detail of the panel cross-section and elevation, using this CGRID, are shown in Figure 2-7.

![Cross Section Views of Panels with CGRID](image)

**Figure 2-7 : Cross Section Views of Panels with CGRID**

The objective of the research by Frankl, was to determine the appropriate CGRID quantity and configuration to achieve optimal structural performance of the sandwich panel for lateral loads (Frankl, Lucier, et al, 2011). The ability to accurately predict the behavior of shear transfer mechanism for a certain CGRID/insulation combination is essential in predicting the structural behavior of a precast concrete sandwich wall panel. The behavior of any shear transfer mechanism must be well quantified in order to predict the ultimate response of a sandwich panel subjected to lateral loading. A series of push tests to investigate the shear strength of thirteen commercially produced shear ties was performed to assess their blast resistance (Naito, Hoemann, Bewick, & Hammons, 2009). The shear connectors tested
included those made of carbon steel, stainless steel, galvanized carbon steel, carbon fiber
reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP), and basalt fiber
reinforced polymer (BFRP). Further, results from experimental program conducted by Frankl
(Frankl, Lucier, et al, 2011) were analyzed by Hassan (Hassan & Rizkalla, 2010) to establish
the shear flow capacities of the carbon fiber grid when used with either EPS or XPS
insulation (Hassan & Rizkalla, 2010). The shear flow capacity of the CGRID/foil combination $q$ can be expressed using the following equation

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

(2.1)

where

$q =$ shear flow capacity [lb/in]

$F =$ the max force at the interface at the critical section at the ultimate-load level [lb]

$L =$ the length of CFRP grid along the width of the panel up to the critical section [in]

The nominal shear flow capacity of the CFRP grid/XPS combination was found to be
190 lb/in, while the CFRP grid/EPS combination produced 400 lb/in. Higher values of shear
flow strength from EPS insulation was attributed to the superior bond that EPS rigid foam
insulation forms at the concrete interface when compared with that of XPS. During post
testing inspection of the panels, XPS foam was easily removed by hand as it was completely
separated from the concrete wythes. In another experimental program, using CGRID as a
shear transfer mechanism, shear flow strengths were measured on scaled down specimens (Kim, Messenger, & Harmon, 2010). The program investigated the effect of several parameters such as grid embedment length, insulation thickness and type, shear grid density, and the effect of repeated loading, on the shear flow strength of the composite connector. Results indicated that the shear transfer strength depends on both the shear grid density (spacing), and the insulation type and thickness.
2.3 Degree of Composite Action

The nature of the connection between two concrete wythes determines the degree of composite action which can be achieved by the panel. Composite action is achieved when the shear forces that are developed at the face of one wythe are transferred to the other wythe through the shear connectors. This allows both wythes to work together to resist the applied forces as a single section. Until recently, the knowledge base on the performance and behavior of sandwich panels was centered primarily on the observations of panels in service and limited testing up to failure. There have been several studies recently on sandwich wall panels examining several different parameters believed to affect overall performance of panel. This experimental work has been carried out in an effort to better characterize the composite action of sandwich panels and develop more accurate predictions of their behavior (PCI Committee on Precast Sandwich Wall Panels, 2011).

In general, there are three types of sandwich wall panels: composite panels, partially composite panels, and non-composite panels. The non-composite panels behave and are designed such that each of the two concrete wythes resist the applied loads independently. Non-composite panels have a thick inner structural concrete wythe and thin outer non-structural wythe, are typically used as architectural cladding. Examples of architectural loadbearing panels are shown in Figure 2-8 (Freedman, 1999). These panels are used instead of composite panels due to the amount of steel and concrete shear connections is kept to a minimum, reducing thermal bridging, and results in a panel with superior thermal capabilities.
Figure 2-8: Various Types of Architectural Load bearing Wall Panels

- (a) Flat, hollow-core, or insulated panel.
- (b) Vertical window or mullion panel.
- (c) Horizontal window or mullion panel.
- (d) Ribbed panel.
- (e) Double-tee panel.
- (f) Spandrel (same as "a").
Non-structural concrete wythe must be transferred its self-weight to the loading wythe through the insulation core. Steel pins and ties, or solid concrete zones, have typically been used in past to connect the two concrete wythes, transfer this dead weight, and maintain structural integrity in these non-composite wall panels. Recently, to effectively minimize the thermal bridging effect and improve the effective thermal properties of these panels, fiber reinforced polymer (FRP) pins have been incorporated to transfer forces between the concrete wythes. FRP materials have a thermal conductivity much lower than that of steel and concrete, therefore, their use effectively eliminates the thermal bridge and improves the panel’s thermal performance while maintaining structural integrity. Typical non-composite connectors, including FRP connectors, are shown in Figure 2-9 (PCI Committee on Precast Sandwich Wall Panels, 2011). Thinner, more efficient wall panels can be produced by designing with some degree of composite action between the concrete wythes. This can be accomplished by connecting the concrete wythes with one-way shear connectors, including wire trusses. Examples of one-way shear connectors are shown in Figure 2-10.
Figure 2-9: Examples of Non-composite Connectors (PCI Journal, Spring 2011)

Figure 2-10: One-way Shear Connectors
Study suggested that steel trusses are capable of creating nearly full composite action assuming that the proper design approach is used (Nijhawan, 1998). This paper highlights the need for an accurate method to evaluate the shear flow characteristics of any shear transfer mechanism used in prestressed precast concrete sandwich wall panels. The percent composite action achieved for a particular panel configuration cannot be determined unless the load carrying capacity and stiffness of the shear connectors is well defined. Partially composite panels typically act as a composite or semi-composite panel during handling and erection, but then as non-composite panels under the effect of wind pressure. It has been shown that early on, the bond developed between the concrete wythes and certain types of insulation can provide enough shear transfer for composite action during handling. Although composite action has many advantages, it does present the disadvantage of possible bowing which must be accounted for in design. Bowing of sandwich wall panels is a complicated issue, difficult to predict, and highly dependent on many factors. In some cases, the secondary moment effects caused by this bowing can ultimately control the design of load bearing panels. Composite action between the wythes causes the panel to act as a single unit in resisting bending forces, as shown in Figure 2-11. This composite behavior has a drawback in that the differential strain between the wythes, caused by temperature or humidity gradients, may cause bowing (Losch, 2003). Non-composite panels typically do not experience this thermal bowing because as each wythe will deform independently.
In one of the research program panels were subjected first to axial loading (Benayoune, Samad, Abang Ali, & Trikha, 2007), while the second tested the panels under eccentric axial loading (Benayoune, Samad, Trikha, Ali, & Ashrabov, 2006). Panels loaded in axial compression behaved in a near fully composite manner, demonstrating the adequacy of the steel truss shear connectors. While, shear forces were induced by the bending stresses from the eccentric location of the load. The induced shear forces were transferred through the insulating layer by the steel truss mechanism, which created full composite action, and resulted in tension failure of unloaded concrete wythe. In another research program, flexural behavior of one-way and two-way sandwich panel slabs, using steel truss shear connectors,
were investigated and compared with finite element analysis (Benayoune, Abdul Samad, Trikha, Abang Ali, & Ellinna, 2008). Results indicated that the truss girders were able to transfer a significant amount of shear and create a high degree of composite action, as shown in Figure 2-12.

Figure 2-12 : Load Deflection at Mid-Span
2.4 FEM modelling

The behavior of concrete sandwich panel is highly dependent on the degree of composite action achieved. It is important that the actual behavior of the sandwich panels match the predicted behavior and design assumptions, as well as detailing the panel and connections to allow for anticipated movement for successful designs to be achieved. Several attempts have been undergone to model the behavior of sandwich panels using finite element method. Previously, a study was conducted on precast concrete sandwich panels with a hybrid shear connectors made of FRP and prestressed steel strands (Salmon, Einea, Tadros, Culp, 1994). A finite element modeling was developed using ANSYS where the slab was modeled using plane stress elements to model the concrete and insulation layers with an assumption of full bond between the layers. Beams elements were used to model the steel strands and truss elements to model the FRP connectors as shown in Figure 2-13. Cracks were modeled using a combination of interface and control elements.
In a different study (Benayoune, 2008) the concrete wythes were modeled as 3D shell elements and 3D bar elements were used to model the shear connectors and steel reinforcement. The contribution of the foam was ignored and was not included in the model. A study (Lee, Pessiki, 2008) investigated the structural behavior of a three wythe structural system under flexure only. Flexural behavior of three wythe panels showed that staggered solid concrete zones exhibits behavior similar to that of a fully composite panel. Along with high flexural capacity, these systems exhibit a ductile flexural behavior for proportionally reinforced panels. Panel ductility is attributed to the formation of a uniformly distributed crack system along the height of the panel and yielding of the longitudinal reinforcement. It was also observed that release of the prestressing force induced cracks in the concrete wythes.
parallel to the prestressing strands. A Finite Element Modeling (FEM) analysis was conducted to investigate the prestressing forces during release. A comparison of experimental results and FEM results showed that modeling the concrete and the foam insulation with solid block elements provided close results to the measured values. FEM analysis was then utilized to conduct a parametric study. FEM results revealed that increasing the concrete area near the end regions of the panel reduces the number of cracks induced during prestressing.

Another research (Benayoune, 2008) stated a two way system exists when the height to width aspect ratio is less than one. A one way system exists when the height to width aspect ratio is greater than 2.67. Consequently, intermediate aspect ratios yields intermediate behavior. This study showed FEM accurately represents one way systems using 2-D isoperimetric plane stress elements. The FEM is a 2-D system representing the behavior of the wall panel per foot width. Similar results for a two way system can be obtained by using 3-D thin shell elements. A two way system has to be analyzed using a 3-D model to capture behavior along the width and height of the panel. Results were confirmed by comparing the FEM deflection and strain behavior with experimental results. It was found that FEM models can exhibit increased stiffness in comparison to experimental tests.

In another study (Kabir, 2005), the FE model consisted of two types of non-linear element - 8 noded solid elements for the concrete portion and a beam element for the welded wire space frame, including bent bar connectors and wythe steel reinforcement. In an effort to estimate service load deflections and bending stresses for non-loadbearing semi-composite sandwich panels, a research program was undertaken to develop a closed form elastic
continuum approach for discrete steel truss connectors (Bush Jr., Wu, 1998). The solution was then compared with finite element models (FEM) and experimental data obtained from work previously described (Bush Jr., Stine, 1994). The FEM and closed form solutions used nominal values for the elastic modulus of concrete and shear modulus of the insulation, as these values were not available from the experimental work. The discrepancy in experimental values and predicted values was far larger for forces in the diagonal truss elements. The models overestimated the forces in the truss element by as much as six to eight fold compared to those obtained from strain gauge data during testing. The analytical and experimental work completed need to better characterize shear transfer mechanism used in sandwich wall panels, in order to better predict panel performance and behavior.
2.5 Design Approaches

Structural demand from applied gravity and wind loading induce flexural, shear, tension, and compression stresses in the precast concrete sandwich panels. Resisting these demands in the most efficient way requires some degree of composite action be achieved between the two separate concrete wythes of the sandwich panel. This can be accomplished by providing sufficient shear reinforcement to transfer the forces from the inner to the outer concrete wythe, through the insulation core. Shear connectors and/or solid concrete zones are used to transfer the applied forces and resist the load as a composite cross section. Three different methods can be used to determine the magnitude of the shear force generated by the applied load and are described in the following sections. The quantity of shear reinforcement required to develop composite action can then be determined based on the shear force and the shear capacity of the connector. To ensure sufficient composite action between the inner and outer concrete wythes is achieved, the quantity of shear grid required for a certain cross-section of the panel can be computed as follows:

\[ N_{required} \geq \frac{\gamma \cdot q_{required}}{\varphi \cdot q_{grid\text{-}capacity}} \] (2.2)
where

\[ N_{\text{required}} = \text{Number of rows of grid required at a certain cross-section} \]

\[ q_{\text{required}} = \text{Maximum applied shear flow [kip/in or lb/in]} \]

\[ q_{\text{grid-capacity}} = \text{Shear flow strength of grid [kip/in or lb/in]} \]

\[ \gamma = \text{Load factor [i.e. 1.6]} \]

\[ \varphi = \text{Material resistance factor [i.e. 0.85]} \]

The following sections present the three design methods typically used to determine the maximum shear flow required, \( q_{\text{required}} \), to create full composite action for precast concrete sandwich wall panels.

i. **Principles of Mechanics**

The first method, based on the elastic response of the member, uses the principles of mechanics. The maximum shear force is determined from the design load combination and the shear flow required is calculated at the concrete/rigid foam interface using the following equation:

\[
q_{\text{required}} = \frac{V_{\text{max}} \cdot Q_t}{I_{\text{total}}} \tag{2.3}
\]
Figure 2-14: Shear Evaluation Method 1

where

\[ q_{\text{required}} = \text{Shear flow required to create composite action [lb/in]} \]

\[ V_{\text{max}} = \text{Maximum shear force due to the applied loading [lb]} \]

\[ Q_t = \text{First moment of area above the concrete/foam interface [in}^3\text{]} \]

\[ I_{\text{total}} = \text{Total moment of inertia of the panel [in}^4\text{]} \]

ii. ACI Simplified Method

In the second method, recommended by ACI 318, shear stress (\( \tau \)) is computed based on the maximum shear force acting on the panel. The shear stress acting at the interface is calculated based on the full effective cross section \( bd \). Therefore, the shear flow can be calculated as follow:

\[ q_{\text{required}} = \frac{V_{\text{max}}}{d} \]  \hspace{1cm} (2.4)
where

\[ q_{\text{required}} = \text{Shear flow required to create composite action [lb/in]} \]

\[ V_{\text{max}} = \text{Maximum shear force due to the applied loading [lb]} \]

\[ d = \text{Distance between resultant tension and compression forces [in]} \]

\[ \tau = \frac{V}{bd} \]

**Figure 2-15 : Shear Evaluation Method 2**

### iii. PCI Method

The third method, recommended by PCI, requires design of the composite action based on the full capacity of the panel; therefore, the shear stress is calculated at the maximum moment region from the compression and tension forces acting on the cross-section. (PCI Committee on Precast Sandwich Wall Panels, 2011) The maximum horizontal shear force is determined based on the lesser of the compression and tension capacity of the section at mid-span. To simplify the calculation, the assumption is made that the entire exterior wythe is acting in compression. The required shear flow capacity, \( q_{\text{required}} \), can be computed as follows:
\[ V_{\text{required}} = \min (T_{\text{max}}, C_{\text{max}}) \text{ [kips]} \]  
\[ T_{\text{max}} = A_{ps} f_{ps} + A_s f_y \]  
\[ C_{\text{max}} = 0.85 * f'_c * b * t_c \]  
\[ q_{\text{required}} = \frac{V_{\text{required}}}{dL} \]

where

\( V_{\text{required}} = \) Shear force required to create composite action [kips]

\( A_{ps} = \) Area of prestressing steel in tension wythe, [in\(^2\)]

\( A_s = \) Area of non-prestressed steel in tension wythe, [in\(^2\)]

\( f_{ps} = \) Stress in prestressing steel at ultimate flexural strength, [ksi]

\( f_y = \) Yield stress in non-prestressed steel [ksi]

\( f'_c = \) Concrete compressive strength, [ksi]

\( b = \) Width of wall panel, [in.]

\( t_c = \) Thickness of compression wythe, [in.]

\( q_{\text{required}} = \) Shear flow required to create composite action [lb/in]

\( dL = \) Length of panel from \( M_{\text{max}} \) to the nearest support [in]
3 EXPERIMENTAL PROGRAM

The experimental program was designed to study the effect of several parameters believed to affect the behavior of CGRID and the rigid foam insulation as a shear transfer mechanism for concrete sandwich panels. The experimental program consists of 100 panels with the following parameters:

1) Type of Rigid Foam insulation:
   I. EPS (Expanded polystyrene)
   II. XPS-SB (Extruded polystyrene with sandblasted surface)
   III. XPS-R (Extruded polystyrene with rolled surface)
   IV. POLY-ISO (Polyisocyanurate)

2) Thickness of Rigid Foam insulation:
   I. Three thicknesses of EPS foam that were tested: 2 inch, 4 inch & 6 inch
   II. Two thicknesses of XPS-SB & XPS-R foam that were tested: 2 inch & 4 inch
   III. One thicknesses of POLY-ISO foam was tested: 4 inch

3) Spacing between the vertical rows of CGRID:
   I. 12 inch
   II. 24 inch
   III. 48 inch

   All the test specimens were configured to have three concrete wythes, with 2 inch thick outer wythes and a 4 inch thick center wythe separated by two foam layers. Each
specimen consisted of four vertical lines of CGRID as shear transfer mechanism between center wythe and outer wythes through foam as shown in Figure 3-1.

Figure 3-1 : Typical test specimen
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 gap under the middle concrete wythe to allow for vertical deflection. Load was applied vertically to the top surface of the middle concrete wythe, directly testing the shear transfer between the center wythe and the two outer wythes through the proposed CGRID/Rigid foam shear transfer mechanism.
3.1 Test Matrix

A total of 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. Table 3-1 presents the designation of the hundred panels with typical vertical CGRID, that were tested to examine the effects of the type of rigid foam insulation, the thickness of the insulation, and the spacing between vertical rows of CGRID. Note that each of the 20 configurations given in the table has five samples. All panels built in this research program were six feet tall, while the width of panels were ranging from 2 feet to 8 feet to accommodate the required spacing of vertical lines of CGRID. Typical shop drawings for the specimens presented in Table 3-1 are shown in Figure 3.3 to Figure 3.6 demonstrating different grid spacing and insulation thickness. Typical test designation used to describe each panel is simplified in Figure 3-2:

```
XX.XXX.X.XX
```

**Figure 3-2 : Panel Designation**
Table 3-1: Test Matrix for Design Equation Specimens

<table>
<thead>
<tr>
<th>Insulation Thickness</th>
<th>Insulation Type</th>
<th>Sample Size</th>
<th>Grid Spacing</th>
<th>Sample Name</th>
<th>Quantity</th>
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<tr>
<td>2&quot;</td>
<td>EPS</td>
<td>96&quot; x 72&quot;</td>
<td>48&quot;</td>
<td>96.EPS.2.48</td>
<td>5</td>
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<tr>
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<td></td>
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<td>24.EPS.4.12</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>24&quot;</td>
<td>48.EPS.4.24</td>
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</tr>
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<td></td>
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<td>48&quot;</td>
<td>96.EPS.4.48</td>
<td>5</td>
</tr>
<tr>
<td>4&quot;</td>
<td>XPS (Sand Blasted)</td>
<td>24&quot; x 72&quot;</td>
<td>12&quot;</td>
<td>24.XPS.SB.2.12</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48&quot; x 72&quot;</td>
<td>24&quot;</td>
<td>48.XPS.SB.2.24</td>
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<td></td>
<td>96&quot; x 72&quot;</td>
<td>48&quot;</td>
<td>96.XPS.SB.2.48</td>
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</tr>
<tr>
<td>6&quot;</td>
<td>XPS (Rolled)</td>
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<td>48.XPS.R.2.24</td>
<td>5</td>
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<td></td>
<td></td>
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<td>5</td>
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<td>48&quot; x 72&quot;</td>
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<td>48.POLY.4.24</td>
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</table>
Figure 3-3: Typical shop drawing for 24" x 72" specimen
Figure 3-4: Typical shop drawing for 48" x 72" specimen
Figure 3-5: Typical shop drawing for 96" x 72" specimen
Figure 3-6: Typical shop drawing for section view for 2", 4" & 6" insulation
3.2 Material Properties

3.2.1. Concrete Strengths

All test specimens were constructed by Metromont Precast Plant in Charlotte, North Carolina. Concrete cylinders were produced in facility at the time of each panel casting, and were stored and transported with the panels. Tests were conducted on 4”x8” concrete cylinders in accordance with ASTM C39, confined with neoprene caps and were loaded in a universal compression testing machine. The reported values in Table 3-2 shows concrete strengths for a given group of panels averaged over four tests.
### Table 3-2: Concrete Compressive Strength at the Time of Panel Testing

<table>
<thead>
<tr>
<th>Insulation Thickness</th>
<th>Insulation Type</th>
<th>Sample Size</th>
<th>Grid Spacing</th>
<th>Sample Name</th>
<th>Concrete Strength (psi)</th>
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<td>EPS (1# Density)</td>
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<td>4&quot;</td>
<td>XPS (Sand Blasted)</td>
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#### 3.2.2. Carbon Fiber Reinforced Polymer Grid (CGRID)

Patented C-GRID® are light weight, high strength and non-corrosive composite reinforcements. They are custom engineered for the internal reinforcement in these sandwich wall panels. This reinforcement comes in form of rolls as shown in Figure 3-7.
Figure 3-7: Typical CGRID reinforcement
The roll of CGRID is then cut so that individual elements within the grid are inclined at 45-degrees with respect to the panel surface to facilitate shear transfer between concrete wythes as shown in Figure 3-7. Tests were conducted 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, as shown for typical tension specimens in Figure 3-8.

Figure 3-8: Typical C-GRID® Tension Specimens
Tension tests were conducted in accordance with ASTM D3039 to determine the ultimate tensile strength, ultimate tensile strain, and tensile modulus of elasticity. The nominal dimensions of each tension specimen were 12 inch x 1 inch. All tension tests were conducted in an electro-mechanical universal testing machine with pneumatic wedge grips. The specimen dimensions, applied load, cross-head displacement, and tensile strain were measured for each test. An external clip-on electronic extensometer was used to measure axial strain. All specimens were tested to failure at a constant displacement rate of 0.05 inches per minute. A typical tension test setup is shown in Figure 3-9.
All tension test results are summarized in Figure 3-10. The average strand tensile strength for CGRID, typical in use by AltusGroup, is about 700 lbs. The material properties specified on company website are shown in Table 3-3.

![Figure 3-10: Tension Tests results](image)
3.2.3. Rigid Foam insulation

The amount of thermal savings is dependent on the type of rigid foam insulation used within the panel. Previous research program conducted at NC State University, commonly used two types of rigid foam EPS and XPS, as an insulation material in sandwich panels (Bunn, 2011) is shown in Figure 3-11. EPS foam consists of 0.07 inch to 0.12 inch polystyrene beads that are expanded and fused together to form a solid insulation block (Horvath 1994). XPS foam is produced from a solid mass of molten material resulting in a dense consistency in comparison to EPS foam (PCA 2008). EPS foam densities range from 0.6 pcf to 2.5 pcf in comparison to XPS foam which exhibits densities up to 3 pcf (Horvath 1994, PCA 2008, ASTM C578 2007). Consequently, EPS foam can retain an R-value up to 4.35 per inch thickness in comparison to XPS foam with an R-value up to 5 per inch thickness (PCA 2008).

Figure 3-11: Typical EPS and XPS rigid foams
This research program has considered additional type of rigid foam, namely Polyisocyanurate (POLY-ISO) including previous two types. Poly-Iso is a closed-cell, rigid foam board insulation and because of its high R-value ranging from 6 to 6.5 per inch thickness, it is the product of choice for energy-aware homebuilders and consumers. The material properties for the three types of rigid foam are given in Table 3-4.

Table 3-3: Material Properties for Rigid Foam Insulation (Bunn, 2011)

<table>
<thead>
<tr>
<th>Rigid Foam Insulation</th>
<th>Expanded Polystyrene (EPS)</th>
<th>Extruded Polystyrene (XPS)</th>
<th>Polyisocyanurate (POLY-ISO)</th>
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<tr>
<td>Density</td>
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<td>2.1 pcf</td>
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<tr>
<td>Compressive Strength (10% Deformation)</td>
<td>10-14 psi</td>
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<td>16-20 psi</td>
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<td>Modulus of Elasticity</td>
<td>180-220 psi</td>
<td>675 psi</td>
<td>200-250 psi</td>
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</table>

Previous test results (Bunn, 2011) have indicated low bond strength for XPS foam. To enhance the shear transfer mechanism of the panels, an effort has made to roughen the surface of the XPS foam using sand blasting and rolling technique. For this research program though the foam material remains same, since the surface for XPS foam is different, it is treated as separate foam type; XPS Sand Blasted (XPS-SB) and XPS Rolled (XPS-R). The
fundamental perception behind surface treating XPS foam is to improve bond strength between foam-concrete interface which will enhance the shear transfer mechanism of the concrete sandwich panels. A special kind of plastic rollers shown in Figure 3-12 were used to manufacture XPS rolled surface foam pieces. Difference between XPS-R and XPS-SB is shown in Figure 3-13.

Figure 3-12: Typical technique to produce Rolled XPS
Figure 3-13: Typical XPS R and XPS SB surfaces
3.3 **Panel Fabrication**

All test specimens were constructed at Metromont Precast Plant in Charlotte, North Carolina. All foam layers 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 embedment depth of the CGRID into the concrete wythes as shown in Figure 3-14. All panels were fabricated in horizontal positions.

![Figure 3-14: Precut foam and CGRID for fabrication](image)
The fabrication process for all panels was the same and is described below with detailed figures. Minor differences in the procedure are noted where appropriate.

1. Wood forms were constructed on the casting platform in proper configuration and size.
2. A Layer of W2.5xW2.5 Welded Wire Fabric (WWF) was then placed in the bottom with 1 inch cover as reinforcement for first concrete wythe.
3. Concrete was poured in the wooden forms 2 inch high and vibrated as shown in Figure 3-16.

Figure 3-15: Illustration of step 1,2 & 3
4. Pre-fabricated CGRID/rigid foam combinations were placed in the wooden forms on top of 2 inch thick layer of concrete wythe.

5. Lifting insert was installed into the middle-top of the center wythe.

6. Another layer of W2.5xW2.5 WWF was placed in center as reinforcement for the middle concrete wythe.

7. A 4 inch thick layer of concrete was then poured on top of first foam layer which act as middle wythe as shown in Figure 3-16.

Figure 3-16: Illustration of step 4, 5, 6 & 7
8. Pre-fabricated CGRID/rigid foam combinations were placed in the wooden forms on top of middle concrete wythe. (Same note as step 4)

9. Final layer of W2.5xW2.5 WWF was placed in center of the top concrete wythe.

10. Top 2 inch wythe of concrete was casted, vibrated, and the concrete surface was troweled as shown in Figure 3-16. Concrete cylinders were made to determine concrete strength at the time of testing.

11. Once the panel were cured, they were removed from wooden forms using lifting hooks and loaded on the truck to ship.

Figure 3-17: Illustration of steps 8 to 11
3.4 Test Setup

All the test specimens were configured with three concrete wythes and two layers of rigid foam. Each specimen was tested in double shear to minimize the eccentric location of the applied shear. Tests were conducted 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. The typical push test set-up used for testing all specimens is shown in Figure 3-18.

![Figure 3-18: Typical Test Setup](image)
A rendered 3D drawing of typical test setup is shown in Figure 3-19. The three-wythe panels were supported vertically at the bottom edge of the two outer concrete wythes by 2” x 2” steel bar stock. Load was applied to the top surface of the center concrete wythe using 60-ton hydraulic jacks and lengths of 4” square HSS steel tubes, 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. Relative horizontal motion between the outer wythes was also measured at two locations.
3.5 Instrumentation

Two types of instruments shown in Figure 3-20 were used to monitor the behavior under the effect of the applied load:

1. Load cell (150 kip)

2. Linear potentiometers, commonly referred as pots and shown in Figure 3-20.

All instruments were wired to an electronic data acquisition system. Data was recorded continuously at a sample rate of 1 Hz during loading.

Figure 3-20: Typical Linear pots for measuring displacements

Ten linear potentiometers were used to measure the relative vertical and horizontal displacement between the concrete wythes at selected locations. Measurements were taken by fixing a support block to the center wythe and extending a bar to both outer wythes. Two
linear potentiometers were attached to the bar, one on each end. The opposite ends of these potentiometers rested on blocks fixed to the outer wythes. Relative vertical displacements between the inner and outer concrete wythes were monitored on the left side of each panel at 3” below the top, 3” above the bottom, and at the mid-height, as shown in Figure 3-21. The relative vertical displacement was also measured at the mid-height on the right side of each panel, as shown in Figure 3-21. Left and right sides were determined while looking at the smooth concrete wythe that was cast down on the casting bed. Two linear potentiometers were also added on the left side of the specimens, one 9 inches below the top, and the other 9 inches above the bottom, as shown in Figure 3-21. These additional pots were included to measure the relative lateral deflection between the outer wythes.
Figure 3-21: Locations of Linear Pots #1-10 for All Tests
One hundred specimens were tested in direct shear until failure to study various parameters believed to affect the shear flow strength. The specimens included 20 categories and five specimens were duplicated for each category to provide sufficient statistical data. Test results for the parameters presented in Figure 4-1, are briefly discussed in this chapter. Detailed test results for each of the hundred push-out panels tested in the experimental program are given in appendices. In this chapter, test results are summarized in various sections to compare the behavior and discuss the effects of selected parameters. Conclusions relevant to each study are presented within the sections.
A typical test result for an individual specimen indicating data from all eight vertical sensors is shown in Figure 4-2. Test result for that individual specimen is then denoted by a single curve obtained over the average relative vertical deflections measured from eight instruments. Total five curves are obtained for tested specimens in a group. Graphs used in given sections of this chapter show the vertical deflections averaged over five specimens in each group. Graphs showing the vertical deflections measured from all individual
instruments for five specimens in each group are documented in appendix. Sixth graph on lower right corner represent the average relative vertical deflections measured from all instruments for each of five specimens in a group. Based on the detailed test results presented in the appendix, the effect of the various parameter was evaluated and presented in the following sections.

Figure 4-2 Typical test result for individual specimen
4.1 Effect of Foam Thickness

This section presents effects of rigid foam thickness on shear flow strength of the panels for different foam type. Results for the panels with several thicknesses of EPS, XPS-SB and XPS-R insulations are shown in Figure 4-2 through Figure 4-4 respectively. Only one specific size of panel is considered to compare several thicknesses for each foam types. Summary of entire test results is provided at the end of this section. Test results 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.
Figure 4-3: Effect of Thickness For EPS

Figure 4-4: Effect of Thickness for XPS SB
Figure 4-5: Effect of Thickness for XPS R
4.2 Effect of Grid Spacing

The effect of the spacing between the vertical CGRID lines is further examined in this section. Test results of the panels with four different foam types, with different spacing between CGRID, are shown in Figure 4-5 through Figure 4-8. In general for EPS and XPS-SB, 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.

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. 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. After failure, each of these panels were taken out and opened to observe the amount of foam attached with concrete which is discussed in the later part of this section. By observation of the behavior while testing and visual inspection of opened panels, it was determined that these panels likely contained manufacturing defects i.e. larger area of debonded surface which are discussed extensively later in this thesis.
Figure 4-6: Effect of Grid Spacing for EPS

Figure 4-7: Effect of Grid Spacing for XPS-SB
Figure 4-8: Effect of Grid Spacing for XPS-R

Figure 4-9: Effect of Grid Spacing for POLY_ISO
4.3 Effect of type of foam

This section presents the effect of four types of rigid foam insulation typically used in this research program for construction of concrete sandwich wall panels. To compare the results of all four type of foams, 4 inch insulation thickness is considered, as POLY-ISO foam type used in this research program is available only in that thickness size. Results are presented in Figure 4-9 through Figure 4-11 for the 2’, 4’, and 8’ wide panels respectively. The spacing referred to in the figures is the spacing between two vertical rows of CGRID.

![4" - Effect of Insulation Type](image)

**Figure 4-10: Effect of foam type for 12 inch CGRID spacing**
Figure 4-11: Effect of foam type for 24 inch CGRID spacing

Figure 4-12: Effect of foam type for 48 inch CGRID spacing
4.4 Failure modes

Typical failure modes observed during testing of concrete wall panels are shown in Figure 4-13. After testing, several panels were cut along a line 2” away from vertical strip of CGRID, as shown in Figure 4-13 (marked as red line). The foam layer was then mechanically removed along the cut to expose the CGRID over the height of the panel as shown in Figure 4-14. It was observed that all panels exhibited rupturing of the CGRID in tension and buckling of the CGRID in compression, as shown in Figure 4-15 and Figure 4-16. Several panels also showed signs of the CGRID pull out from the concrete. Some parts of EPS and XPS-SB foam remained well bonded to the concrete after they were pulled apart. Inspection of the panels also demonstrated that EPS/XPS-SB concrete interface resulted in a rough surface indicating a stronger bond as shown in Figure 4-17 and Figure 4-18, while XPS-R/POLY-ISO concrete interface indicated weaker bond. This observation was evidenced by the clean concrete surfaces when the concrete wythes were separated from the XPS-R cores after testing, as shown in Figure 4-19.
Figure 4-13 Typical failure modes

Shear Cracking

Shear Cracking + sliding

Shear Sliding
Figure 4-14: Cut line for panels to open for observations

Figure 4-15: Exposed CGRID for observations
Figure 4-16: Typical Rupture of CGRID in Tension

Figure 4-17: Typical Buckling of CGRID in Compression
Figure 4-18: Typical EPS-concrete interface indicating strong bond

Figure 4-19: Typical XPS-SB-concrete interface indicating strong bond
Figure 4-20: Typical XPS-R-concrete interface indicating weak bond
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 proposed design equation is presented in the following section which is intended to assist designers in calculating the shear flow strength of CGRID/foam used as a shear transfer mechanism for any combination of the parameters considered in this research. Finally, a design example will be presented to demonstrate the use of proposed design equation. A similar approach is used to establish the design equation incorporating various tested parameters to estimate average shear modulus.
5.1 Design Equation calculating shear flow strength

This section presents the proposed equation along with the method used to establish the values for the various factors tested and believed to affect the behavior of the shear transfer mechanism of concrete sandwich wall panels. The overall nominal shear flow capacity of the CGRID/foam combination tested in this research study is calculated using Equation 5-1.

Previous test results (Bunn, 2011) have reported that the shear flow capacity of panels with CGRID alone is 100 lbs/in. 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 below.

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

\( q_{\text{average shear flow}} \) = Predicted shear flow capacity of of CGRID/foam [lbs/in]

\( q_{\text{baseline}} \) = 100 lbs/in [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]
5.1.1. Calculation of factors

Based on test results of a total of 100 panels tested in this program and combined with 8 panels tested previously (Bunn, 2011), an excel program is used to establish the factors for all the various tested parameters. Originally all the factors were set to a value of 1.00, with \( q_{\text{baseline}} \) equal to 100 lbs/in. The initial analysis resulted in a shear flow capacity of 100 lb/in 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. The analysis lead to the factors for the different parameters are enlisted in Table 5-1. The predicted values based on proposed design equation are compared with measured values shown in Table 5-2.
Table 5-1: Factors for all tested parameters based on 108 panels

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<th>f_{Type}</th>
<th>Insulation Thickness (in.)</th>
<th>f_{thickness}</th>
<th>Grid Spacing (in.)</th>
<th>f_{Spacing}</th>
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\[ q_{avg.\ shear\ flow} = q_{base} \times f_{type} \times f_{thickness} \times f_{spacing} \]

\[ q_{base} = 100 \text{ lbs/in} \]
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<th>Specimen Size</th>
<th>Insulation Thickness</th>
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<td></td>
<td>48&quot;</td>
<td>102</td>
<td>104</td>
</tr>
</tbody>
</table>

*Based on two test specimen previously tested (Bunn, 2011)
5.1.2. Example to demonstrate the method

The research presented in this thesis proposes the use of CGRID/foam as a shear transfer mechanism and establishes an equation to determine the average shear flow capacity of the panel. The design example, shown in Figure 5-1, is presented in this section to illustrate the use of the proposed design equation and demonstrate the effect due to use of different type of foam. The panel under consideration is 12 ft. wide and 30 ft. tall and is simply supported at the bottom and at 2 ft. from the top. The panel consists of 3” inner and outer concrete wythes separated by a 4” layer of EPS insulation and is subjected to a factored wind load of 40 psf. The induced shear force and bending moment diagram are shown in Figure 5-1. The design procedure consists of the following steps.

1) Determine the section properties of the panel cross-section
2) Determine the maximum induced shear force
3) Determine the capacity of the proposed CFRP grid/rigid foam shear transfer mechanism based on the panel parameters
4) Determine the number and location of the required grid
Figure 5-1: Panel Configuration, Loading, Shear, and Moment Diagrams
1) **Panel Section Properties**

- **Cross section area**
  
  Outer and Inner Concrete Wythes:
  
  \[ A_o = A_i = b \times t_o = \left(12 \text{ ft} \times \frac{12 \text{ in}}{1 \text{ ft}}\right) \times 3 \text{ in} = 432 \text{ in}^2 \]

  Total Area:
  
  \[ A_{total} = A \times 2 = 432 \text{ in}^2 \times 2 = 864 \text{ in}^2 \]

- Area of the rigid foam insulation is not considered

- **Centroids**
  
  Outer Wythe:
  
  \[ y_o = \frac{t_o}{2} = \frac{3 \text{ in}}{2} = 1.5 \text{ in} \]

  Inner Wythe:
  
  \[ y_i = t_o + t_{ins} + \frac{t_i}{2} = 3 \text{ in} + 4 \text{ in} + \frac{3 \text{ in}}{2} = 8.5 \text{ in} \]

  Centroid of the Section:
  
  \[ y_{total} = \frac{(A_i \times y_i + A_o \times y_o)}{A_c} \]

  \[ y_{total} = \frac{(432 \text{ in}^2 \times 8.5 \text{ in} + 432 \text{ in}^2 \times 1.5 \text{ in})}{864 \text{ in}^2} = 5 \text{ in} \]

- **Moments of Inertia**
  
  Outer Wythe:
  
  \[ I_o = \frac{b \times t_o^3}{12} + A_o \left(y_{total} - y_o\right)^2 \]

  \[ I_o = \frac{144 \text{ in} \times (3 \text{ in})^3}{12} + 432 \text{ in}^2 \times (5 \text{ in} - 1.5 \text{ in})^2 \]

  \[ I_o = 5616 \text{ in}^4 \]

  Inner Wythe:
  
  \[ I_i = \frac{b \times t_i^3}{12} + A_i \left(y_{total} - y_i\right)^2 \]

  \[ I_i = \frac{144 \text{ in} \times (3 \text{ in})^3}{12} + 432 \text{ in}^2 \times (5 \text{ in} - 8.5 \text{ in})^2 \]

  \[ I_i = 5616 \text{ in}^4 \]
Total Section: $I = I_o + I_i = 2 \times 5616 \text{ in}^4 = 11232 \text{ in}^4$

- First Moment of Area (At the concrete/insulation interface)
  
  Outer Section: $Q_o = A_o (y_{total} - y_o) = 432 \text{ in}^2 (5 \text{ in} - 1.5 \text{ in})$
  
  $Q_o = 1512 \text{ in}^3$

  Inner Section: $Q_i = A_i (y_i - y_{total}) = 432 \text{ in}^2 (8.5 \text{ in} - 5 \text{ in})$

  $Q_i = 1512 \text{ in}^3$

2) Maximum Shear Forces

- $V_{1u} = \left( \frac{\gamma w b + h}{L} \right) \times \left( L - \frac{h}{2} \right)$
  
  $V_{1u} = \left( \frac{1.6 \times 25 \text{ psf} \times 12 \text{ ft} \times 30 \text{ ft}}{28 \text{ ft}} \right) \times \left( 28 \text{ ft} - \frac{30 \text{ ft}}{2} \right)$

  $V_{1u} = 6686 \text{ lb}$.

- $V_{2u} = \left( \frac{\gamma w b + h^2}{2 + L} \right) - (\gamma w b + a)$
  
  $V_{2u} = \left( \frac{1.6 \times 25 \text{ psf} \times 12 \text{ ft} \times (30 \text{ ft})^2}{2 + 28 \text{ ft}} \right) - (1.6 \times 25 \text{ psf} \times 12 \text{ ft} \times 2 \text{ ft})$

  $V_{2u} = 6754 \text{ lb}$. = Maximum factored shear force

- $V_{3u} = (\gamma w b + a)$
  
  $V_{3u} = (1.6 \times 25 \text{ psf} \times 12 \text{ ft} \times 2 \text{ ft})$

  $V_{3u} = 960 \text{ lb}$.
3) **Shear Flow Strength of the Proposed CFRP Grid/Rigid Foam**

To compare results for all foam types, it is decided to choose 4 inch foam thickness and 24 inch CGRID spacing. Based on the selected parameters, the corresponding predicted shear flow capacities are summarized in Table 5-3.

**Table 5-3 : Shear Design Example Panel Parameters**

<table>
<thead>
<tr>
<th>Insulation Type</th>
<th>Predicted Shear flow capacity, (lbs/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>280</td>
</tr>
<tr>
<td>XPS-SB</td>
<td>445</td>
</tr>
<tr>
<td>XPS-R</td>
<td>140</td>
</tr>
<tr>
<td>POLY-ISO</td>
<td>223</td>
</tr>
</tbody>
</table>

4) **Number of Required CFRP Grid**

The first principles of mechanics method was used to establish the required shear flow to create full composite action as is common design practice and calculate number of lines of CGRIDS for each type of foam proposed to be used in this example is given in Table 5-4.

\[
q_{\text{required}} = \frac{V_{\text{max}} \cdot Q_i}{I_{\text{total}}} \tag{2.9}
\]

\[
q_{\text{required}} = \frac{6754 \text{ lb} \cdot 1512 \text{ in}^3}{11232 \text{ in}^4}
\]
\[ q_{\text{required}} = 909 \, \frac{lb}{in} \]

Table 5-4: Shear Design Example Panel Parameters

<table>
<thead>
<tr>
<th>Insulation Type</th>
<th>Number of CGRID lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>4</td>
</tr>
<tr>
<td>XPS-SB</td>
<td>2</td>
</tr>
<tr>
<td>XPS-R</td>
<td>7</td>
</tr>
<tr>
<td>POLY-ISO</td>
<td>4</td>
</tr>
</tbody>
</table>
5.2 Design Equation calculating shear modulus

This section presents the proposed design equation established to estimate shear modulus based on previously discussed approach. The calculation of shear modulus, $G$, is based on deformation measurements of the push test specimens and is determined using slope of line between load levels $0.1*V_{\text{max}}$ to $0.3*V_{\text{max}}$ as shown Figure 5-2.

![Figure 5-2: Typical load vs Displacement curve for Push tests](image)

The equation used to calculate the shear modulus, $G$ for all tested specimen is as follows,
\[ G = \frac{0.3 \cdot V_{max} - 0.1 \cdot V_{max}}{\Delta_{0.3 \cdot V_{max}} - \Delta_{0.1 \cdot V_{max}}} \cdot \frac{t}{2 \cdot W \cdot H} \]  

(2.10)

where

\( G \) = Shear Modulus [lbs/in²]

\( W \) = Width of specimen [in]

\( H \) = Height of specimen [in]

\( t \) = Thickness of rigid foam [in]

The calculated average shear modulus using above equation for all CGRID/Insulation specimens is summarized in Figure 5-3. A similar excel program is used to establish the factors for all the various tested parameters to estimate average shear modulus and is presented in Table 5-5. The shear modulus of the insulation alone, \( G_{\text{Baseline}} \), was set to 300 lb/in based on the measured values of panels tested with no CGRID. The equation modifies the baseline shear modulus (300 lb/in) based on factors for insulation type, thickness and grid spacing. Table 5-6 presents comparison of measured shear modulus based on push tests and estimated values based on design equations.

The comparison of experimental values and values obtained from proposed design equations indicates reasonable prediction of the overall shear flow strength and shear modulus of the CGRID/foam systems. The shear flow strengths and shear moduli obtained from the proposed equations are nominal values and should be reduced using proper strength reduction factors.
### Figure 5-3: Summary of calculated average shear modulus (lbs/in²)

| FOAM THK. (IN.) | 2 | 2 | 2 | 4 | 4 | 4 | 6 | 6 | 2 | 2 | 2 | 4 | 4 | 4 | 2 | 2 | 2 | 4 | 4 | 4 | 4 |
| GRID SPACING (IN.) | 12 | 24 | 48 | 12 | 24 | 48 | 12 | 24 | 48 | 12 | 24 | 48 | 12 | 24 | 48 | 12 | 24 | 48 |

- EPS
- XPS SB
- XPS R
- POLY ISO
Table 5-5: Factors for all tested parameters based on 108 panels

\[ G_{\text{avg. shear flow}} = G_{\text{base}} \times f_{\text{type}} \times f_{\text{thickness}} \times f_{\text{spacing}} \]

<table>
<thead>
<tr>
<th>f_{\text{Type}}</th>
<th>Insulation Thickness (in.)</th>
<th>f_{\text{thickness}}</th>
<th>Grid Spacing (in.)</th>
<th>f_{\text{Spacing}}</th>
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Table 5-6: Comparison of measured and estimated average shear modulus

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<th>Specimen Size</th>
<th>Insulation Thickness</th>
<th>Grid Spacing</th>
<th>Experimental Shear Modulus, lbs/in²</th>
<th>Estimated Shear Modulus, lbs/in²</th>
</tr>
</thead>
<tbody>
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</tbody>
</table>

*Based on two test specimen previously tested (Bunn, 2011)
This chapter presents finite element modeling of the shear transfer mechanism proposed for concrete sandwich wall panels using CGRID/Rigid foam systems. 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 modelling. 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. A typical FE mesh used to model typical push-out test specimen is shown in Figure 6-1.
6.1 Selected Elements and Material Constitutive Relationships

The following section presents various elements utilized to model the different material used in typical push-out test specimen simulating the behavior of sandwich wall panels.

6.1.1. Concrete

The three concrete wythes were modeled using eight-noded elements (known as SOLID65 in ANSYS program) which have three degrees of freedom at each node: translations in the nodal x, y, and z directions. The geometry, node locations, and the coordinate system for this element are shown in Figure 6-2. As concrete is highly non-linear, the most important aspect
of this element was a close approximation of material properties. Typical stress-strain constitutive relationship for concrete material is shown in Figure 6-3.

Figure 6-2: Typical Solid65 element representing concrete

Figure 6-3: Constitutive relation for concrete
Multi-linear isotropic plasticity was used to approximate the non-linear constitutive relationship for concrete in ANSYS program as given in Figure 6-4. In the analysis the descending branch of the stress-strain curve was not be 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. The relaxation did not represent a revised stress-strain relationship for post-cracking behavior. After convergence of the solution at the cracked state, the analysis assumed that the modulus normal to the crack face was set to zero. Both cracking and crushing failure modes are accounted through this material model, which is available with the reinforced concrete element SOLID65.

![Multi-linear constitutive model in ANSYS](image)

**Figure 6-4: Multi-linear constitutive model in ANSYS**
6.1.2. Rigid Foam Insulation

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 inputed in ANSYS using multi-linear isotropic material model based on values obtained by an earlier experimental program (Bunn, 2011 & Soriano, 2012). The two panels with configurations given in Table 6-1 were used to examine the shear flow contribution from the rigid foam insulation alone without any CGRID. The four tested specimens (two identical specimens tested for each configuration shown) are defined in this thesis as “no grid panels,” and typical cross-section of these panels is shown in Figure 6-5. The load-displacement relationship, which is the average of two tests specimens, using EPS and Sand-blsated XPS (XPS-SB) are shown in Figure 6-6 and Figure 6-7 respectively.

<table>
<thead>
<tr>
<th>Foam Type</th>
<th>Panel Size (inch x inch)</th>
<th>Foam Thickness (inch)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPS</td>
<td>48 x 72</td>
<td>2</td>
<td>Bunn, 2011</td>
</tr>
<tr>
<td>XPS-SB</td>
<td>24 x 36</td>
<td>2</td>
<td>Soriano, 2012</td>
</tr>
</tbody>
</table>
Figure 6-5: No Grid Specimen Section View with 2” foam

Figure 6-6: Load Deflection for Panel with 2” EPS without CGRID
Note that the results for XPS-SB compared to EPS are lower due to the use of small size of specimen. The measured shear force from these results were converted to shear stress-strain relationship using following equation:

\[
\tau = \frac{P}{b \times L} \quad (5.1)
\]

\[
\gamma = \frac{\Delta}{t} \quad (5.2)
\]
Where,

\[ \tau = \text{Shear stress [lbs/in}^2] \]
\[ \gamma = \text{Shear Strain [in/in]} \]
\[ P = \text{Load from Push-out tests [lbs]} \]
\[ \Delta = \text{Displacement from Push-out tests [in]} \]
\[ b = \text{Width of the panel [in]} \]
\[ L = \text{Height of the panel [in]} \]
\[ t = \text{Thickness of rigid foam [in]} \]

The calculated stress-strain relationship curves are shown in Figure 6-8. It clearly indicates XPS-SB foam is stronger and provides higher stiffness in carrying shear as compared to EPS. The experimental shear moduli calculated based on these curves were 0.27 ksi and 0.62 ksi for EPS and XPS-SB respectively. XPS-SB being stiff in nature exhibited brittle failure while EPS foam exhibited relatively ductile failure with more prominent shear cracks.
In pure shear, material failure of foam occurred due to sliding of particles (movement of dislocations) could be simulated as shown in Figure 6-9 and eventually the particles separated after large displacements. Thus, the stress or energy required for this distortion is much less than that required for separating the particle planes. Hence, for foam material the maximum shear stress causes a large distortion which is similar to yielding phenomenon.
According to the Von Mises’s theory, a solid will yield when the distortion strain energy density reaches a critical value for that material. In the case of uniaxial stress state, strain energy density is equal to the area under the stress–strain curve. At the instance of yielding in a uniaxial tensile test, the state of stress in terms of principal stresses is given by $\sigma_1 = \sigma_y$ (yield stress) and $\sigma_2 = \sigma_3 = 0$; where $\sigma_1$, $\sigma_2$ and $\sigma_3$ are stresses in three principal directions. In this research, the shear stresses are the only stresses, therefore the principal stresses can be $\sigma_1 = -\sigma_2 = \tau$ and $\sigma_3 = 0$. A graphical form of the pure shear stress state is represented as a straight line through the origin at $-45^\circ$ in on the $\sigma_1-\sigma_2$ plane.
Figure 6-10: Failure envelope of the distortion energy theory

The line intersects the Von Mises failure envelope at two points, A and B. The magnitude of stress and corresponding strain at these points can be found as:

\[ \sigma = \sqrt{3} \cdot \tau \quad (5.3) \]

\[ \varepsilon = \frac{\sqrt{3} \cdot \tau}{2G \cdot (1 + \nu)} + \frac{1}{\sqrt{3}} \left( \gamma - \frac{\tau}{G} \right) \quad (5.4) \]

Where,

\( \tau \) = Shear stress [lbs/in\(^2\)]

\( \gamma \) = Shear Strain [in/in]

\( \sigma \) = Tensile stress according to Von Mises criteria [lbs/in\(^2\)]

\( \varepsilon \) = Tensile Strain [in/in]
\[ G = \text{Shear Modulus [lbs/in}^2\text{]} \]

\[ v = \text{Poisson’s ratio} \]

To model rigid foam material in push-out specimen, shear stress-strain values were converted in to tensile stress-strain curves (using equation 5.3 & 5.4) and are shown in Figure 6-11. Two models representing no CGRID specimens with EPS and XPS-SB foam are shown in Figure 6-12. 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 6-13 and Figure 6-14. Comparisons with the experimental results indicated that the overall behaviors of the rigid foam materials are well predicted inputting tensile stress-strain curve through multi-linear isotropic material model in ANSYS.
Figure 6-11: ANSYS input as Tensile stress strain constitutive relation

Figure 6-12: FE model (a) With EPS (b) With XPS-SB
Figure 6-13: Validation of FE model for EPS foam

Figure 6-14: Validation of FE model for XPS-SB foam
6.1.3. CGRID connector

Structural behavior of concrete sandwich panels depends on the strength and stiffness of the CGRID connectors. Material properties of individual strand of CGRID connectors tested in tension are reported in Chapter 3. Test results 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 (Gleich, 2007) has indicated that to assure rupture of fibers, CGRID should be embedded ¾ inch 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”, 4” and 6” foam thicknesses as shown in Figure 6-15, respectively. The joint formed between two individual strands of CGRIDS are fixed in such a way that it only allows transfer of axial forces as shown in Figure 6-16. 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 nature rigid connections between concrete wythe and CGRID connectors as represented in Figure 6-17 and fixity of strand connections in Figure 6-16. 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 was designed and is explained in detail in this section.

Figure 6-15: CGRID configuration used in this research program
Figure 6-16: Typical strand connections

Figure 6-17: Typical CGRID failure
In this research program, the individual strands of CGRID used to connect three concrete wythes are modeled with a non-linear spring elements (commonly known as COMBIN39 in ANSYS program) of lengths ‘L’ as shown in Figure 6-18, without considering the intermediate joints. COMBIN39 is a unidirectional element with nonlinear and large displacement capability. The element is defined by two nodal points and a generalized force-deflection curve, separately for uniaxial compression and tension.

Figure 6-18: Sketch representing CGRID in FE model
The longitudinal option for COMBIN39 element is activated (option provided within ANSYS program), creates a uniaxial tension-compression element with two or three translational degrees of freedom at each node and no bending is considered. The force-deflection values were inputted such that initial part of curve implicated compression phase followed by tension phase. As per software requirements, care was taken to maintain a positive slope of the force-deflection curve at the end.

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 6-19, respectively. The first type of specimen was designed to capture the buckling behavior of CGRID in compression. The second type of specimen was designed to capture failure mode of individual strands of CGRID in tension, in which two layers of concrete were pushed apart from each other using two hydraulic jacks.
Nine specimens were built using three different foam thicknesses (2/4/6 inches). The CGRID was precut such that each test specimen contained twelve individual strands and was further glued to foam as given in Figure 6-15. To ensure zero contribution of bond at foam-concrete interface throughout test, foam material was wrapped with plastic. Detail test matrix for nine specimens is given in Table 6-2.

Table 6-2 : Test matrix to evaluate CGRID constitutive relationships

<table>
<thead>
<tr>
<th>Foam Thickness (inch)</th>
<th>Test</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Compression</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Tension</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Compression</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Tension</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>Compression</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Tension</td>
<td>2</td>
</tr>
</tbody>
</table>
6.1.3.1. Direct Compression test

To study the behavior of CGRID material in compression, three specimens with 2/4/6 inch thick foams were tested under MTS machine as shown in Figure 6-20. Test was performed under displacement control settings with constant load rate of 0.05 inch/min. Load and displacement were recorded through data acquisition system connected to MTS. Test results shown in Figure 6-21 indicated the response of CGRID in compression was similar for three thicknesses of foam. Test data values were further used to generate an average force-displacement curve for individual CGRID strand. This force-displacement curve data was used as an input in ANSYS program to reflect the compression behavior of non-linear spring element.
Figure 6-20 Test setup for direct compression

Figure 6-21 Test results for direct compression test
6.1.3.2. Direct Tension test

ANSYS input value for CGRID material represented by non-linear spring in tension was evaluated by testing six specimens. Each test specimen consisted of two layers of concrete which were pushed apart from each other by two hydraulic jacks. A load cell was mounted under one hydraulic jack and displacements were measured using linear potentiometers at four locations. A typical experimental setup for direct tension test is shown in Figure 6-22. All the individual CGRID strands were in tension and failed due to rupture. Typical failure picture for tension test specimen is shown in Figure 6-23. A horizontal movement of top concrete wythe was observed after rupture of the CGRID strands. Test results shown in Figure 6-24 indicated the response of CGRID in tension was similar for specimens with three thicknesses of foam. Test results were used to calibrate load-deflection curve for single strand. Input values for load-deflection curves in compression and tension calibrated with special tests are shown in Figure 6-25. Using this material property, a debonded specimen (no foam contribution) was simulated and compared with experimental results to validate the approach and is shown in Figure 6-26. Comparison of ANSYS output and experimental results show good agreement and validity of model.
Figure 6-22: Typical setup for direct tension test

Figure 6-23: Typical failure mode for pilot test
Figure 6-24 Test results for direct tension test

Figure 6-25: Ansys input for COMBIN39 element
6.1.4. Foam-Concrete Interfaces

In general, test results have indicated a significant contribution of rigid foam towards shear flow strength of concrete sandwich panels. 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, pilling up layers of concrete-foam-concrete on top of each other as depicted in Figure 6-27.
Due to this way of construction, there is a strong possibility of formation of air pockets at the interface marked by red line in Figure 6-27 which results in weaker bond. Some test specimens were opened for observation show clear evidence of these air pockets as shown in Figure 6-28. Also, in some observed specimens, the foam material expanded due to heat of hydration released from concrete. This heat was trapped and was unable to release out from the forms separating foam and concrete, especially for large contact surface of large specimens, as shown in Figure 6-29.
Figure 6-28: Formation of air pockets due to poor construction

Figure 6-29: Separation of foam-concrete layers due to heat
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 as shown in Figure 6-30. A penalty stiffness algorithm was used in compression to restrict penetration of the concrete into the foam. The foam was allowed to separate from the concrete in tension according to a constant opening stiffness that was significantly less than the penalty stiffness in compression. The shear strength of the interface is represented as Mohr-Coulomb friction model in Figure 6-31.
Figure 6-30: Contact pair representing foam-concrete interface

Figure 6-31: Mohr-Coulomb Model for contact pair at foam-concrete interface
\[ \tau_{max} = \mu \cdot P + b \]  \hspace{1cm} (5.5)

Where,

\[ \tau_{max} = \text{Max Shear stress [lbs/in}^2\text{]} \]

\[ \mu = \text{Coefficient of friction} \]

\[ P = \text{Normal pressure [lbs/in}^2\text{]} \]

\[ b = \text{Cohesion [lbs/in}^2\text{]} \]

There is no presence of normal pressure, hence the maximum shear strength entirely depend on the cohesion between foam and concrete. To validate the friction model, a simulation was performed on small test model as shown in Figure 6-32. The cohesion value was selected as 9 psi, as soon as the shear between foam and concrete exceeded the cohesion value, the surface of foam started to slide relative to concrete surface without any friction. The amount of defects in terms of surface area was unknown at the time of test. Although by inducing very low cohesion values to the interface areas, the analytical results can be compared with experimental results to estimate the area of debonded parts in wall panels.
Figure 6-32: (a) Small test model (b) Shear Sliding relative to outer concrete layers

(c) Contact status before and after sliding
6.2 Boundary Conditions and loadings

Correct simulation of the boundary conditions is essential for modeling the walls panels. The bottom of the outer wythes were restrained against vertical and horizontal movements. Rotation was allowed in all direction to simulate rigid body rotation of outer wythes and avoid any moments at the support. Load was applied uniformly over the top of center concrete wythe. Due to the nature of the test, a displacement-controlled approach was much suitable in which the displacement was increased in small increments up to a desired level and after that analysis was terminated.

6.3 Numerical procedures

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. Displacement-based and force-based convergence criteria were used in the analysis. The convergence criteria were based on the $L^2$ norm (square root of the sum of the squares) of the applied forces and displacements respectively. The convergence tolerance used was $1.0E-3$ times the reference value, which the program automatically calculates from the total applied loading and displacements. The full Newton-Raphson solution procedure was used in which the stiffness matrix is updated every iteration.
Unsymmetrical matrices were enabled in order to allow for the full coupling of the sliding and normal stiffnesses, which is important for frictional contact analysis.

### 6.4 Comparison with Experimental results

The results of the analysis are compared with the results of the experimental program to determine the effectiveness of the model in simulating the behavior. All the material models described in previous sections are summarized in Table 6-2 below.

<table>
<thead>
<tr>
<th>Material</th>
<th>Element type</th>
<th>Description</th>
<th>Input model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>SOLID65</td>
<td>3-D eight-node</td>
<td>Multilinear isotropic</td>
</tr>
<tr>
<td>Foam</td>
<td>SOLID65</td>
<td>3-D eight-node</td>
<td>Multilinear isotropic</td>
</tr>
<tr>
<td>CGRID</td>
<td>COMBIN39</td>
<td>Non-linear spring</td>
<td>Force-deflection curve</td>
</tr>
<tr>
<td>Foam-concrete</td>
<td>Contact pair</td>
<td>3-D four-node</td>
<td>Mohr’s-Coulomb Friction</td>
</tr>
</tbody>
</table>

Post-processing from simulations gather load and displacement values which is further converted and presented in terms of shear flow vs displacement to compare with the measured values. Analysis was performed assuming perfectly bonded conditions at foam-concrete interface.
6.4.1. Thickness of Rigid foam

This section presents effect of the thickness of the rigid foam. Predicted behaviors for the panels with several thicknesses of EPS and XPS-SB foams are compared with corresponding measured results in Figure 6-33 through Figure 6-35 and Figure 6-37 through Figure 6-38, respectively. Panel with size 24 inch x 72 inch is chosen to compare the results. Comparison of analytical results using various thicknesses for EPS and XPS-SB are shown in Figure 6-36 and Figure 6-39, respectively.
Figure 6-33: Panel with 12” grid spacing and 2” EPS (24”x72”)

Figure 6-34: Panel with 12” grid spacing and 4” EPS (24”x72”)
Figure 6-35: Panel with 12” grid spacing and 6” EPS (24”x72”)

Figure 6-36: FE Prediction for various thickness of EPS (24”x72”)
Figure 6-37: Panel with 12” grid spacing and 2” XPS-SB (24”x72”)

Figure 6-38: Panel with 12” grid spacing and 4” XPS-SB (24”x72”)

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Figure 6-39: FE Prediction for various thickness of XPS-SB (24”x72”)

Shear Flow (lbs/in) vs. Displacement (in)
6.4.2. Effect of spacing between the CGRIDS

The effect of the spacing between vertical line of CGRID is examined in the following section. Predicted behaviors for the panels with several CGRID spacings containing EPS and XPS-SB foams are compared along with corresponding measured results in Figure 6-40 through Figure 6-42 and Figure 6-44 through Figure 6-46, respectively. Panel with 2 inch foam thickness is chosen to compare the results. Comparison of analytical results for various grid spacing with EPS and XPS-SB are shown in Figure 6-43 and Figure 6-47 respectively.

Figure 6-40: Panel with 12” grid spacing and 2” EPS (24”x72”)

![Graph showing shear flow vs. displacement for a panel with 12” grid spacing and 2” EPS (24”x72”).]
Figure 6-41: Panel with 24” grid spacing and 2” EPS (48”x72”)

Figure 6-42: Panel with 48” grid spacing and 2” EPS (96”x72”)

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Figure 6-43: FE Prediction for various CGRID spacing of 2” EPS

Figure 6-44: Panel with 12” grid spacing and 2” XPS-SB (24”x72”)
Figure 6-45: Panel with 24” grid spacing and 2” XPS-SB (48”x72”)

Figure 6-46: Panel with 48” grid spacing and 2” XPS-SB (96”x72”)
Figure 6-47: FE Prediction for various CGRID spacing of 2” XPS-SB
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. Analytical results for all the panels with EPS and XPS-SB foam are summarized in Figure 6-48 and Figure 6-49, respectively.

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 large variation in presence of air pockets resulting variable bond strength of foam-concrete interfaces.
Figure 6-48: Summary of Analytical results for panels with EPS foam

<table>
<thead>
<tr>
<th>Foam Thickness (inch)</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>2</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid Spacing (inch)</td>
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<td>24</td>
<td>48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Measured Strengths**

**FE prediction**
Figure 6-49: Summary of Analytical results for panels with XPS-SB foam
7 SUMMARY AND CONCLUSIONS

The research reported in this thesis summarizes test results and analysis of a comprehensive research program undertaken to study a proposed CGRID/foam system as shear transfer mechanism used in precast concrete sandwich wall panels. 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 one 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. Test results were used to develop design equations to estimate the shear flow strength and shear modulus for CGRID/rigid foam system as affected by these parameters. A non-linear 3-D finite element analysis was performed using a commercial software utilizing non-linear geometry and non-linear material properties. Research findings based on the test results and analysis can be summarized as follows.

1. 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 when compared with the same quantity of CGRID spacing.

2. 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.
3. 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.

4. Test results also indicated that increasing the thicknesses of the EPS as well as XPS-SB insulations showed decrease in the shear flow strength of the panel.

5. Shear cracking, shear sliding and mix mode (cracking + sliding) were three different modes of failure observed throughout testing.

6. A spreadsheet program used to establish the factors for design equations exhibited reasonable prediction of the shear flow strengths and shear moduli for given CGRID/foam systems.

7. 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.

8. 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.
8 REFERENCES


APPENDIX
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Figure 9-2 Failure photos - EPS 2” Insulation & 48” Spacing
Figure 9-3 EPS 4" Insulation & 12" Spacing
Figure 9-4 Failure photos - EPS 4” Insulation & 12” Spacing
Figure 9-5 EPS 4” Insulation & 24” Spacing
Figure 9-6 Failure photos - EPS 4” Insulation & 24” Spacing
Figure 9-7 EPS 4” Insulation & 48” Spacing
Figure 9-8 Failure photos - EPS 4” Insulation & 48” Spacing
Figure 9-9 EPS 6” Insulation & 48” Spacing
Figure 9-10 Failure photos - EPS 6” Insulation & 48” Spacing
Figure 9-11 XPS SB 2” Insulation & 12” Spacing
Figure 9-12 Failure photos – XPS SB 2” Insulation & 12” Spacing
Figure 9-13 XPS SB 2” Insulation & 24” Spacing
Figure 9-14 Failure photos – XPS SB 2” Insulation & 24” Spacing
Figure 9-15 XPS SB 2” Insulation & 48” Spacing
Figure 9-16 Failure photos – XPS SB 2” Insulation & 48” Spacing
Figure 9-17 XPS SB 4” Insulation & 12” Spacing
Figure 9-19 XPS SB 4” Insulation & 24” Spacing
Figure 9-20 Failure photos – XPS SB 4” Insulation & 24” Spacing
Figure 9-21 XPS SB 4" Insulation & 48" Spacing
Figure 9-22 Failure photos – XPS SB 4” Insulation & 48” Spacing
Figure 9-23 XPS R 2” Insulation & 12” Spacing
Figure 9-24 Failure photos – XPS R 2” Insulation & 12” Spacing
Figure 9-25 XPS R 2” Insulation & 24” Spacing
Figure 9-26 Failure photos – XPS R 2” Insulation & 24” Spacing
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Figure 9-33 XPS R 4” Insulation & 48”
Figure 9-34 Failure photos – XPS R 4” Insulation & 48” Spacing
Figure 9-35 POLYISO 4” Insulation & 12” Spacing
Figure 9-36 Failure photos – POLY ISO 4” Insulation & 12” Spacing
Figure 9-37 POLYISO 4” Insulation & 24” Spacing
Figure 9-38 Failure photos – POLY ISO 4” Insulation & 24” Spacing
Figure 9-39 POLYSIO 4” Insulation & 48” Spacing
Figure 9-40 Failure photos – POLY ISO 4” Insulation & 24” Spacing