Experimental and Numerical Investigation of FRP Shear Mechanism for Concrete Sandwich Panels

K. Hodicky*†, G. Sopala, S. Rizkalla, T. Hulin†, H. Stang†

† Technical University of Denmark, Department of Civil Engineering, Section of Structural Engineering, Brøvej, Building 118, Kongens Lyngby, Denmark.

Tower Engineering Professionals, Inc., 3703 Junction Blvd, Raleigh, North Carolina, USA

b North Carolina State University, Department of Civil, Construction and Environmental Engineering, 2414 Campus Shore Drive, Raleigh, North Carolina, USA

*Corresponding author. Tel.: +4545251741, E-mail address: kamh@byg.dtu.dk

Abstract: This paper investigates the composite action of forty-six segments representing precast concrete sandwich panels (PCSP) using the Carbon Fiber Reinforcement Polymer (CFRP) grid/rigid foam as shear mechanism. Various parameters believed to affect the shear flow strength for this CFRP grid/foam system were examined. The parameters that were considered are the spacing between vertical lines of CFRP grids and the thickness of the rigid foam. The research includes comprehensive experimental program that was conducted to determine the characteristics of the shear transfer mechanism of the CFRP grid/rigid foam. Results of the experimental program indicated that increasing the spacing between vertical lines of CFRP grid increase the overall shear flow strengths due to the increase of the bonded contact area of the rigid foam and the concrete surface. However, it should be noted that the overall shear stresses were decreased due to the increase of interface surface area. Test results also indicated that increasing the rigid foam thickness decrease the overall shear flow strength. A non-linear 3-D FEM analysis was performed to model the behaviour of the test specimens and to study the behaviour of PCSP. Results of FEM analysis were found in good agreement with the experimental results. Design equation was developed to determine the shear flow strengths for given CFRP grid/foam systems. The parametric study was performed to predict shear flow strength of different fiber reinforced polymer materials, rigid foam thickness and spacing between vertical lines of the grid.
Keywords: Concrete sandwich panel, Non-linear analysis, Finite element analysis, Carbon-fiber-reinforced polymer, Shear test, Bond-slip behaviour.

1. Introduction:

Precast concrete sandwich panels (PCSP) are typically used as exterior walls for multi-unit residential, commercial, and warehouse buildings. A typical PCSP consists of two concrete wythes and one layer of insulation in between the two concrete wythes. Typically, connectors penetrate the insulation layer and join the two concrete wythes. The panels are designed to carry gravity loads from floors or roofs, as well as to resist lateral loads caused by wind. The rigid foam is provided to insulate the structure, therefore, PCSP are structurally and thermally efficient. Typical PCSP are fabricated with heights up to 13.7 m and with widths up to 4.0 m [1]. The concrete wythe thickness ranges from 50 to 150 mm, with overall panel thicknesses ranging from 125 to 300 mm [2]. The PCSP have several beneficial features such as high quality, proven durability, fast erection, and attractive architectural appearance [3].

The PCSP may be designed with various degrees of composite action: non-composite, partially composite or fully composite [4]. Providing a composite action can significantly increase the structural efficiency and reduce both initial and lifecycle costs of these types of panels [5]. The degree of composite action depends on the nature of the connection between two concrete wythes.

PCSP were first introduced during the 1960's as double tee sandwich panels [6]. Solid concrete zones were used between the double tees to develop full composite action. Double tee sandwich panels provided a robust structural wall, but sacrificed the potential thermal savings. In order to reduce concrete material, optimize the structural performance, and reduce overall costs, flat concrete slabs were soon used in place of double tees. More recently, steel ties connecting the two concrete wythes were introduced to replace solid concrete zones in an attempt to enhance the thermal performance of the PCSP. It was found that the use of steel ties improved the thermal efficiency in comparison to solid concrete zones [6]. Increasing the degree of composite action between two concrete wythes by using any type of these connectors increases the structural capacity of the PCSP, making it more structurally efficient. However, increasing the degree of composite
action may lead to significantly lower thermal efficiency of the panel due to the creation of thermal bridges [7].

Non-composite panels were introduced in the 1980's and aimed to address the thermal deficiencies created by the steel ties. Non-composite panels contained minimal shear connectors for handling loads only; however, a lack of shear transfer compromised the structural integrity of the system. Recent tests by Lee and Pessiki [8] showed that a panel with staggered solid concrete zones exhibited similar behaviour to a fully composite panel. The bond between the insulation and concrete wythes provides some shear transfer [9-12]; however, the bond diminishes over time and will not provide full strength over the service life of the panel [13].

Recently, the PCSP design concept has leaped forward by introducing Fiber Reinforced Polymer (FRP) shear reinforcement. FRPs have a relatively high strength and stiffness combined with a relatively low thermal conductivity, compared to steel [14]. Wade et al. [7] and Einea et al. [3] performed the first attempt to use Glass Fiber Reinforced Polymer (GFRP) connectors for insulated concrete sandwich walls. Salmon et al. [13] introduced GFRP bars formed in a truss orientation in place of metal wire trusses. The experimental investigation showed that the use of GFRP resulted in 84 % composite action compared to 88 % for steel truss connectors. Following the same concept, Morcous et al. [15], Lameiras et al. [16,17], Maximos et al. [18], Naito et al. [19] and Woltman et al. [20] studied different shapes of GFRC shear connectors to obtain the full composite action. These research programs have indicated that FRP shear connectors can provide a dual purpose of improving the thermal capabilities of a building envelope, while at the same time, providing the desired structural integrity and efficiency.

Most recently, Rizkalla et al. [4], Frankl et al.[21,22], Sopal [23], Bunn [24] and Hassan et al. [25] investigated the use of a Carbon Fiber Reinforced Polymer (CFRP) and Hodicky et al. [26] investigated the use of a Basalt Fiber Reinforced Polymer (BFRP) material configured as a grid. The grid was placed in composite action with rigid foam insulation to serve as the main shear transfer mechanism for PCSP. It was observed that the desired composite action can be achieved using either EPS or XPS rigid foam insulation in combination with CFRP grid. Since carbon and basalt fibers have a thermal conductivity approximately 14
percent that of steel, connecting concrete wythes with the grid allows a panel to develop composite structural action with minimum thermal bridges, therefore maintaining the insulating value of the panel.

Several authors have attempted to develop numerical models to simulate the behaviour of PCSP under axial, shear and flexural loading [25-33]. The behaviour of PCSP is rather complicated due its highly non-linear behaviour of the constituent materials and the interaction of the FRP grid and the rigid foam. Some researchers simplified their models by using linear material models and linear elastic analysis e.g. [3,25]. Most of the other researchers approached the problem using non-linear 2-D [29,31,32] or 3-D [17,23,26,33] models. However, 2D and 3D modelling approaches significantly simplify the behaviour of PCSP. Some researchers disregarded the insulation layer from their FEM analysis e.g. [13,31-33]. Additionally, some researchers ignored the relative slip between the concrete and reinforcement/shear connector [25-33], the effect of bond slip and dowel action, and the slip of steel reinforcement [31-33]. With these assumptions, the numerical analysis resulted in an overestimation of the PCSP behaviour in comparison to experimental data [13,23,29,31-33].

It was reported by several researchers [21-27] that the rigid foam has significant contribution to the shear transfer mechanism and it is essential to include its effect in the prediction of the behaviour of PCSP.

The paper presents an experimental and numerical investigation of small segments representing a typical PCSP, as shown in Fig. 1, using the CFRP grid/rigid foam as a shear mechanism to achieve the composite action of the panel. The research program investigated the effect of several parameters believed to affect the shear flow strength of the CFRP grid/rigid foam shear connection. The parameters that were considered are the spacing between vertical lines of CFRP grids and the thickness of the rigid foam. A comprehensive experimental program was conducted to determine the characteristics of the shear transfer mechanism of the CFRP grid/rigid foam. Test results were 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 FEM analysis was performed to model the behaviour of the test specimens and to study the behaviour of PCSP.
2. Experimental Investigation

A total of forty-six panel specimens were tested to examine various parameters relevant to the behaviour and strength of the CFRP grid/rigid foam shear transfer mechanism. All panels built in this research program were 1830 mm high, while the width of panels ranged from 610 mm to 2440 mm to accommodate the required spacing of vertical lines of CFRP grid. All specimens were configured with three concrete wythes, 50 mm outer wythes and a 100 mm center wythe, and two EPS insulation layers as shown in the cut-away rendering in Fig. 2.

2.1 Material Properties

The following sections provide brief description of the material properties of the three materials used to construct the panels.

2.1.1 Concrete

All test specimens were constructed using self-consolidating concrete (SCC). Concrete cylinders were produced at the time of casting and were stored and transported with the panels. Tests were conducted on 100 mm diameter x 200 mm concrete cylinders in accordance with ASTM C39 [34], confined with neoprene caps and loaded in a universal compression testing machine. Typical test results for the compressive concrete strength, \(f_{\text{cm}}\), tensile strength of concrete, \(f_t\) and concrete modulus of elasticity, \(E_C\) are given in Table 1.

2.1.2 Rigid Foam

Lightweight EPS insulation was used as the rigid foam insulation material due to its cost efficiency and availability. The polystyrene sheet was cut into pieces and inserted between the inner and the outer concrete wythes and between the CFRP grids. Small segment of EPS insulation were tested in compression. The
average mechanical properties of three specimens for the thicknesses 50 mm (EPS.2), 100 mm (EPS.4) and 150 mm (EPS.6) are summarized in Table 2 and graphically presented in Fig. 3, respectively.

Where $E_i$ and $f_{ci}$ is modulus of elasticity and compression strength of EPS rigid foam, respectively.

### 2.1.3 CFRP Grid

The textile reinforcement selected for this experimental study was composed of weaved carbon fibres. Patented CFRP grid was custom engineered in rolled forms of an orthogonal grid. The average spacing between individual strands was 40 mm. The roll of the CFRP grid was then cut at 45-degrees of an orthogonal grid to produce truss and facilitate shear transfer between the concrete wythes, as shown in Fig. 4.

To determine the ultimate tensile strength and tensile modulus of elasticity, tests were conducted in accordance with ASTM D3039 [35] on individual strands of CFRP grid cut from a roll of sample material. Prior to testing, aluminium tabs were bonded to both ends of the CFRP grid test strand to grip the strand in a universal testing machine. The average mechanical properties including tensile strength, $f_{t,CFRP}$; modulus of elasticity, $E_{CFRP}$ and the strain at failure for the CFRP grid are given in Table 3.

#### 2.2 Panel Configurations

Three different panel configurations were considered: panels without CFRP grid, panels with CFRP grid, and panels with CFRP grid and de-bonded EPS insulation. Configurations of the various panels considered in this program are described in detail in the following sub-sections.

##### 2.2.1 Panels Without CFRP Grid

The two panel configurations were tested without any CFRP grid to examine the shear flow contribution from the EPS insulation without CFRP grid. Details of the dimensions, foam thicknesses for the panels
without CFRP grid are given in Table 4. Two panels were tested for each configuration. Typical panel without CFRP grid is shown schematically in Fig. 5.

### 2.2.2 Panels With CFRP Grid

Table 5 provides details of the thirty panels tested with typical vertical grid. The effects of the type of rigid foam insulation, the thickness of the insulation, and the spacing between vertical rows of CFRP grid were examined. Typical specimen with CFRP grid is shown schematically in Fig. 6.

### 2.2.3 De-bonded Panels

Table 6 presents the panels that were tested to examine the effect of the bond between concrete and the EPS insulation on the shear strength and behaviour. The specimens are referred to in this paper as “de-bonded panels”. Two specimens of each type were tested for a total of four specimens. All specimens were fabricated in the same manner as the vertical grid panels, except the bond between concrete and insulation was intentionally broken. This was achieved by using two layers of thin plastic placed between each insulation surface and the fresh concrete, as shown in Fig. 7.

### 2.3 Fabrication of the Panels

All test specimens were constructed by local precast concrete producer. All EPS insulation layers were cut into three sections according to the spacing of vertical lines of the CFRP grid. The pre-cut CFRP grid in truss configuration was then glued to the outer two sections of EPS using insulation board adhesive to ensure a 20 mm embedment depth of the CFRP grid into the concrete wythes. All panels were fabricated in horizontal positions.

### 2.4 Test Setup
Each specimen was tested in a push-through configuration, with the bottom surfaces of the outer two concrete wythes supported vertically, leaving a 50 mm gap under the middle concrete wythe to allow for vertical deflection. The push-out test has been used by several researchers for similar purposes e.g. [19, 20, 24, 29]. Load was applied vertically to the top surface of the middle concrete wythe to test panels in a double shear configuration to minimize the effect of moment due to the eccentric location of the applied shear. The typical push test set-up used for testing all specimens is shown in Fig. 8. The three-wythe panels were supported vertically at the bottom edge of the two outer concrete wythes by 50 mm x 50 mm steel bar stock. Load was applied to the top surface of the center concrete wythe using 60-ton hydraulic jacks and lengths of 100 mm square HSS steel tubes, forcing the middle wythe downwards with respect to the two outer concrete wythes.

### 2.5 Test Instrumentation

The applied load was measured until failure. The relative vertical and horizontal deflection between the concrete wythes were measured by ten linear potentiometers at selected locations. All instruments were wired to an electronic data acquisition system. Data was recorded continuously at a sample rate of 1 Hz during loading. Measurements were taken by fixing a support block to the center concrete wythe and extending a bar to both outer concrete 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 concrete wythe. Relative vertical displacements between the inner and outer concrete wythes were monitored on the left side of each panel at 75 mm below the top, 75 mm above the bottom, and at the mid-height, as shown in Fig. 9. The relative vertical displacement was also measured at the mid-height on the right side of each panel. 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 225 mm below the top, and the other 225 mm above the bottom, as shown in Fig. 9. These additional potentiometers were included to measure the relative horizontal deflection between the outer concrete wythes.
3. Finite Element Analysis

A 3-D non-linear macro-scale FE model of sandwich panels was developed to further investigate its structural behaviour under shear stress. The model was developed using the finite element analysis software DIANA with pre- and post-processor FX+ [36]. The mesh size was adopted to provide satisfactory convergence. The non-linear solution was based on the Newton-Raphson procedure. The following sub-sections present various elements utilized to model the different materials used in typical push-out test specimen simulating the behaviour of PCSP.

3.1 Concrete - Element and Constitutive Relationships

The three concrete wythes were modelled using eight-node elements (HX24L). Multi-linear isotropic material input was used to approximate the non-linear constitutive relationship for concrete in compression. The multi-linear diagram fully describes the relationship between the compressive stress and the equivalent strain. Brittle tension softening model was included to define concrete behaviour in tension, see Fig. 10.

3.2 Rigid Foam - Element and Constitutive Relationships

The two layers of rigid foam were modelled using the same eight-node elements used for concrete (HX24L). To model the behaviour of rigid foam material in shear, the stress-strain parameters were input in DIANA using a multi-linear isotropic material model based on values obtained by the experimental programs [14,24].

3.3 CFRP Grid - Element and Constitutive Relationships
Material properties of individual strands of CFRP grid connectors tested in tension were reported in chapter 2.1.3. Test results indicated linear elastic behaviour before rupture of the single strands of CFRP grid. The overall response of CFRP grid has not been straightforward when used as connectors between concrete wythes, as compared to the response from single strand in tension test. This is partially due to complex nature of CFRP grid geometry. As the fibers are subjected to tension and compression, they are also clamped against the concrete, resulting in shearing of individual strands at lower strengths as compared to the observed ultimate strengths in tension tests. To capture this complex behaviour some of the panels were subjected to pure tension test compression test to evaluate CFRP grid response [24]. The individual strands of CFRP grid connecting three concrete wythes were modelled with a four-node, three-side isoparametric solid pyramid elements (TE12L), considering the intermediate joints. The complex behaviour of CFRP grid was modelled through the input parameters of stress-strain curves representing compression and tension behaviour as shown in Fig. 11. Three curves are for 50 mm, 100mm and 150mm thick rigid foam used for these panel specimens.

3.4 Rigid Foam/Concrete Interface

To implement the bond strength between foam and concrete interfaces in the model, contact elements were used. Four interfaces between the foam and the concrete were modelled using 3-D interface elements (Q24IF). The purpose of these contact pairs was to account for shear sliding and separation that could occur along the interface of solid elements. The shear strength of the interface was extracted from experimental results of panels without CFRP grid. The measured shear force from these results was translated to a shear stress-displacement relationship as given in Eq.1:

\[ \tau = \frac{P}{b \cdot h} \]  

(1)
where $\tau$ denotes shear stress, $P$ is load from push-out tests, $b$ and $h$ represent width and height of the panel, respectively. Shear stress-displacement relationship inputs used to model rigid foam/concrete interfaces are shown in Fig. 12.

### 3.5 CFRP Grid/Concrete Interface

The bond-slip relationship between the CFRP grid and concrete matrix was incorporated in the model to simulate the bond. This data is typically obtained by means of pull-out tests, which were not included in the scope of the experimental study. A bond-slip relationship for a similar combination of CFRP grid obtained from Ref. [37] was thus included in the model. CFRP grid/concrete interface was modelled using 3-D interface element ($T18IF$). Detail of the connection between CFRP grid and concrete is shown in Fig. 13, where $\tau_i$ denotes interface shear stresses. The bond-slip relationship is defined according to a multi-linear model in DIANA and is depicted in Fig. 14.

### 3.6 Loading and Boundary Conditions

The symmetry of the mounting and loading of the tested specimens allowed for only one-fourth of the panel to be considered in the FE model. The bottoms of the outer wythes were restrained against vertical and horizontal movements. Rotation was allowed in all direction to simulate rigid body rotation of the outer wythes and to avoid any moments at the support. Loading until failure was applied uniformly to the center concrete wythe by means of displacement control, such that an imposed displacement was applied at the location of loading. The displacement was increased in small increments up to a desired level, and then the analysis was terminated.

### 4. Results and Discussion
Test result for each specimen is given by a single curve based on the average relative vertical deflections measured from eight instruments. A total of two or five curves are obtained for tested specimens in a group. The results of the FE analysis were compared with the results of the experimental program to determine the effectiveness of the analysis to simulate the panel behaviour. Furthermore, test results are summarized in various sub-sections to compare the behaviour and discuss the effects of selected parameters.

4.1 Failure Modes

Typical failure modes observed during testing of concrete wall panels are shown in Fig. 15. Inspection of the specimens after testing revealed that foam failed with shear cracking and/or shear sliding. After testing, several panels were cut along a line 50 mm away from the vertical strip of CFRP grid. The foam layer was then mechanically removed along the cut to expose the CFRP grid over the height of the panel. It was observed that all panels exhibited rupturing of the CFRP grid in tension and buckling of the CFRP grid in compression, as shown in Fig. 16. Several panels also showed signs of CFRP grid pull out from the concrete. Some parts of EPS foam remained well bonded to the concrete after they were pulled apart.

4.2 Panels Without CFRP Grid

Results of the analysis using DIANA FE program were post-processed to obtain load-displacement curves and are compared with measured values for the panels with 50 mm EPS insulation in Fig. 17. The remaining comparisons can be found in author’s Ref. [38]. Comparisons with the experimental results indicated that the overall behaviour of the rigid foam materials is well predicted by inputting a multi-linear isotropic material model in combination with a shear stress-displacement relationship at the concrete/rigid foam interface.

4.3 De-bonded Panels
Comparisons of experimental and numerical results for de-bonded panels are shown in Fig. 18. The FE analysis showed reasonable agreement with the measured values for the initial phase of the load-deflection curves. However, the accuracy of the ultimate strength prediction for the FE model shows a considerable amount of variation. This difference is attributed to the fact that the FE model assumed no interaction between the concrete and rigid foam. Despite using two layers of thin plastic, some interaction between the concrete and thin plastic occurred during testing.

4.4 Panels With CFRP Grid

Figs. 19-21 depict comparisons of experimental and numerical load-displacement curves for the panels with 50 mm thick EPS insulation and CFRP grid spacing of 305 mm, 610 mm, 1220 mm, respectively. The remaining comparisons can be found in author’s Ref. [38]. Generally, FE analyses showed reasonable agreement with the measured values. The model predicts the initial phase of the load-deflection curves, as well as, the ultimate strength and post-failure behaviour well for the panels with CFRP grid spacing of 305 mm and 610 mm. In respect to the panel with CFRP grid spacing 1220 mm, the FE model reasonably predicts the initial phase of the load-deflection curves and the ultimate strength. However, interpretation of the post-failure behaviour of the panels showed discrepancies in comparison with experimental data (Fig. 21). These discrepancies could be attributed to problems during construction of the panels such as formation of air pockets at the concrete/rigid foam interface. Presence of air pockets result in a weaker bond at the highly non-linear regime.

Additionally, the effect of foam thickness and CFRP grid spacing was studied. Test results indicate that increasing the thicknesses of the EPS insulation tends to decrease the shear flow strength of the panel. Further, test results indicate increasing the CFRP grid spacing increases the overall shear flow strength of the panel due to increased bonded area. However, it tends to decrease the overall shear stress due to the increase of interface surface area in comparison to the increase of the measured load capacity.

5. Design Equation
To achieve full composite action, it is necessary to provide an adequate amount of CFRP grid connectors and specify a foam type that is capable of transferring the shear force induced by the applied loading. The overall nominal shear flow capacity of panel tested in this research study is calculated using Eq. 2

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

(2)

where, \( q \) is shear flow capacity, \( F \) denotes the maximum force at the interface of the critical section at the ultimate-load level, and \( L \) represent the total length of CFRP grid connecting concrete wythes along the height of the panel.

A design equation is proposed to assist designers in calculating the shear flow capacity of CFRP grid/foam used as a shear transfer mechanism for any combination of the parameters considered in this research. The overall average shear flow capacity of the carbon grid/EPS rigid foam shear mechanism is calculated using following equation

\[ q_{\text{Average shear flow}} = q_{\text{baseline}} \cdot f_{\text{type}} \cdot f_{\text{thickness}} \cdot f_{\text{spacing}} \]  

(3)

where \( q_{\text{Average shear flow}} \) is the predicted shear flow capacity of CFRP grid/foam, \( q_{\text{baseline}} \) is the shear flow strength of CFRP grid alone; \( f_{\text{type}}, f_{\text{thickness}} \) and \( f_{\text{spacing}} \) represent the factors for the type of foam, insulation thickness and CFRP grid spacing, respectively.

Testing of de-bonded panels helped to evaluate the shear flow capacity of the CFRP grid with no contribution from the bond between the rigid foam to the concrete. Test results reported that the shear flow capacity of de-bonded panels was nearly 17.5 N/mm. Hence, this obtained value was considered as a baseline for this design equation approach. Eq. 3 modifies the baseline shear flow capacity of the panels based on established factors for the type of foam, thickness of the foam, and spacing between the vertical lines of CFRP grids.
Based on the results of a total of forty-six panels tested in this program, in combination with panels tested previously [24], a spreadsheet program was 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 17.5 N/mm. The initial analysis resulted in a shear flow capacity of 17.5 N/mm for all panels. The absolute error of the predicted nominal shear flow value, in comparison to the measured values was determined for each panel. The absolute error was squared and summed, for all panels. A multi-variable solver tool was used to minimize the summed error by first adjusting the factors for the foam type. After the minimization routine was complete, the factors were rounded to two decimal places for these values. The same procedure was used for the remaining parameters to determine the other factors. In each case, the factors were rounded to two decimal places and the process was repeated to minimize the error. The same process was also repeated to set the values for $f_{\text{type}}$, $f_{\text{thickness}}$ and $f_{\text{spacing}}$. The analysis resulted in the factors for the different parameters as given in Table 7. Note, author’s work on the other types of rigid foam can be found in Ref. [23].

6. Parametric Study

A parametric study was conducted to predict shear flow strength of different FRP materials. In addition to CFRP grid, the study focused on BFRP and GFRP grids. The sandwich panels used in the parametric study had the same overall dimensions as the ones tested in the experimental study. BFRP and GFRP grids were assumed to have the same overall dimensions as the CFRP grid reported in this paper. The FE model developed in Chapter 3 was used to perform this parametric study. Material properties obtained from literature are included in the model [39]. Results of the performed parametric study for various types of FRP grids are shown in Fig. 22.

The results showed that panels with CFRP grid have superior shear flow strength in comparison with panels with vertical BFRP and GFRP grids. In general, a loss between 5 to 10 % of shear flow strength was observed for panels with vertical BFRP grids and between 10 to 25% for panels with vertical GFRP grids. Increasing the EPS thickness leads to significant decrease the shear flow strength of the panel. Fig. 22 also
shows that increasing the FRP grid spacing increases the overall shear flow strength of the panel due to increased bonded area.

7. Conclusions

The research includes an experimental program designed to investigate the behaviour of forty-six small segments representing typical sandwich panels using the CFRP grid/rigid foam as shear mechanism. Various parameters believed to affect the shear flow strength for this CFRP grid/foam system were examined. The parameters that were considered are the spacing between lines of CFRP grids and the thickness of the rigid foam. The experimental program was conducted to determine the characteristics of the shear transfer mechanism of the CFRP grid/rigid foam. The observed failure modes were shear cracking and/or shear sliding for rigid foam; whilst the CFRP grid exhibited rupturing of the CFRP grid in tension and buckling of the CFRP grid in compression. Increasing the spacing between vertical lines of CFRP grid increased the overall shear flow strengths due to increase of the bonded contact concrete/rigid foam interface area. However, it showed a decrease in overall shear stresses due to the increase of the interface surface area in comparison to the increase of the measured load capacity. A non-linear 3-D FEM analysis was performed to model the behaviour of the test specimens and to study the behaviour of PCSP. The FEM results were in good agreement with measured values. A spreadsheet program was used to establish the factors for design equations to predict the shear flow strengths for given CFRP grid/EPS foam systems. A parametric study was performed to predict the shear flow strength of different FRP materials. The results showed that panels with CFRP grid have higher shear flow strength in comparison with panels with vertical BFRP and GFRP grids. Panels with vertical BFRP and GFRP grids have lower shear flow strength than panels with CFRP grids by 5 to 10% and 10 to 25%, respectively, using the same cross section of the strands and spacing of the grid.

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References:


### Tables:

#### Table 1. Mechanical properties of concrete

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Table 2. Mechanical properties of EPS foam

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Table 3. Mechanical properties of CFRP grid

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<td>Panel Height [mm]</td>
<td>Panel Width [mm]</td>
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### Table 6. Tests of de-bonded panels

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<th>Panel Height [mm]</th>
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Table 7. Factors for each parameter of design equation

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Fig. 1 Field application of typical wall panel
Fig. 2 a) Typical specimen tested in double shear b) Cut away of typical CFRP grid push test specimen
Fig. 3 Rigid insulation tested in compression
Fig. 4 Typical CFRP grid reinforcement as shear connectors
Fig. 5 Typical panel without CFRP grid a) Elevation b) Top view
Fig. 6 Typical panel with CFRP grid a) Elevation b) Top view
Fig. 7 Insulation for de-bonded panels with plastic layers prior to casting
Fig. 8 Test Setup
Fig. 9 Test instrumentation - Locations of linear potentiometers #1-10 for all tests
Fig. 10 Multi-linear stress-strain constitutive model of concrete
Fig. 11 Pure tension and compression test of the panel specimens
Fig. 12 Rigid foam/concrete interface constitutive relationships
Fig. 13 Connection CFRP grid to concrete
Fig. 14 Bond-slip relationship for CFRP grid/concrete interface [37]
Fig. 15 Typical failure modes of the tested panels
Fig. 16 Typical failure modes of CFRP grid
Fig. 17 Comparison of experimental and numerical results for panels without CFRP grid; a) Horizontal displacements b) Vertical displacements
Fig. 18 Comparison of experimental and numerical results for de-bonded panels; a) Horizontal displacements
b) Vertical displacements
Fig. 19 Comparison of experimental and numerical results for panels with CFRP grid – 24EPS.12.2; a) Horizontal displacements b) Vertical displacements
Fig. 20 Comparison of experimental and numerical results for panels with CFRP grid – 48EPS.24.2; a) Horizontal displacements b) Vertical displacements
Fig. 21 Comparison of experimental and numerical results for panels with CFRP grid – 96EPS.48.2; a) Horizontal displacements b) Vertical displacements
Fig. 22 Parametric study for various types of FRP grids