Mechanical behavior of UHPFRC thin plate reinforced with externally bonded CFRP sheet

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Abstract:

The objective of this paper is to investigate the mechanical behavior of external CFRP sheet reinforced ultra-high performance fiber reinforced concrete (UHPFRC) thin plate. The CFRP sheet serves as the tensile component and works together with UHPFRC top layer that aims to act as the exterior surface of the thin wall-roof integrated structural curved panel. Tensile properties of CFRP material were obtained from the material supplier and through uniaxial tensile tests while the compressive tests were conducted to obtain the properties of UHPFRC. Twelve plate specimens with one or two layers of CFRP sheet and different end anchorage designs were tested under four-point flexural tests. Most reinforced specimens failed due to debonding at the interface while the reinforced plate with sufficient end anchorage failed in shear. The test results on these thin plates were used to calibrate the finite element model, especially the simplified material models. The calibrated model was then used to predict the structural behavior of single curved panel. It was found out that the thin plate made of UHPFRC and external reinforcing CFRP sheet can resist the combination of self-weight and design wind load.

Keywords:

Four-point flexural test, end anchorage, simplified finite element model

1. Introduction

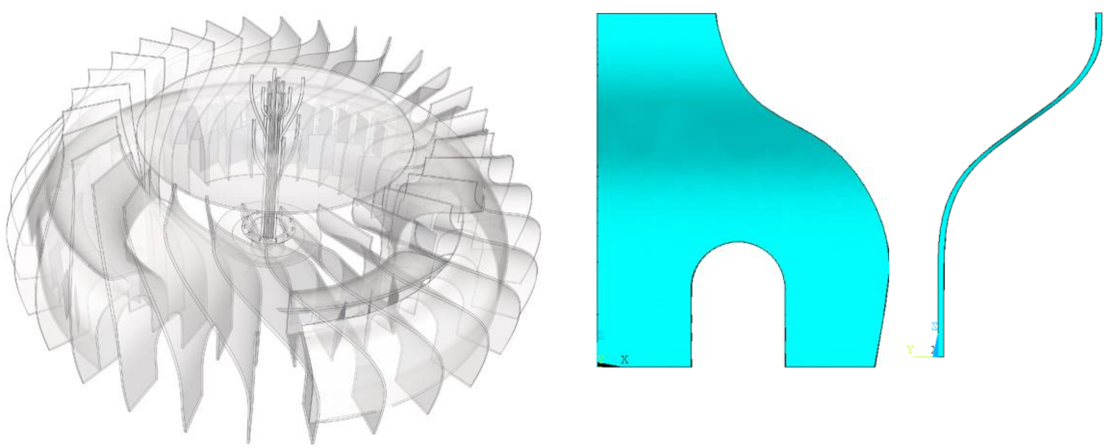
In the last decade, ultra-high performance fiber reinforced concrete (UHFRPC) has been used in buildings and infrastructure (Resplendino and Toulemonde 2011). Due to the high mechanical property, workability and durability, UHPFRC is now accepted in the construction industry (Rossi 2005; Hassan, Jones and Mahmud 2012). Meanwhile, the application of UHPFRC is restricted as a result of the high embodied energy consumption, high material cost, and high carbon dioxide emission over the life cycle (Graybeal 2006). Considering the sustainability requirement, the effective use of UHPFRC material becomes even more important.

UHPFRC has high compressive strength over 150 *MPa*. However, its tensile strength is much lower and is only about one-eighth of its compressive strength. Steel rebar or fiber reinforced polymer (FRP) rebar are usually used in UHPFRC flexural member. However, both steel rebar and FRP rebar post requirements in terms of minimum concrete cover thickness, which limits the minimum dimensions of structure components. The internal reinforcement using steel or FRP mesh is possible. However, the effectiveness of internal layer is not as good as external layer. Moreover, it creates a weak spot that induces cracks on the UHPFRC exterior surface.

In this paper, the mechanical behavior of UHPFRC thin plate reinforced with exterior carbon fiber reinforced polymer (CFRP) sheet was investigated with the aim to provide a potential solution for a strong, lightweight, and durable thin structure component. The bond between CFRP sheet and UHPFRC is critical in order to ensure the successfully load transfer (Grelle and Sneed 2013). Therefore, the effectiveness of two different end anchorage designs was also investigated.

2. Background

A conceptual architecture design is shown in Figure 1 a) and the unit single curved panel is shown in Figure 1 b). Thin plate structure is used to simulate the petals of the flower with an overall height of 7.5 *meters* and out of plane cantilever for 4.4 *meters*. In order to achieve the visual effect, the thickness of plate should be less than 100 *mm* and ideally at 60 *mm*. This poses difficulty on the aspect of structural design with regard to the total height and curved shape. As one of the potential solutions, the structural behavior of CFRP reinforced UHPFRC thin plate was investigated in this paper.



a) b)

Figure 1. ***Architecture Model*: a) *Architecture design*, b) *Shape of single flower unit***

3. Testing Methods

3.1. Raw Materials and characterization

Raw material for generating UHPFRC include Portland cement (P·II containing 3.5% limestone), fine sand aggregates, silica fume, ground quartz, copper coated steel fiber, and superplasticizer. All these raw materials were acquired from the local market. The steel fiber used has an aspect ratio of 64 and length of 12-14 *mm*. On the other hand, uniaxial carbon fiber fabric Db-300 (high strength type I), was used in this study with two-part epoxy resin that has a gel time of 30 minutes and viscosity of 11000-12000 cps at 25 degree Celsius.

All raw material preparation and mixing were performed in the structural lab at Xi'an Jiaotong-Liverpool University. The mix design of UHPFRC follows Table 1. The solid raw materials, such as cement, fine sand, silica fume, and ground quartz were added together and premixed for around four minutes. Then water and part of the superplasticizer were added into the mixer. Mixing was kept running until the color of raw material changes from gray to dark black. Then, rest of the superplasticizer was added to improve the consistency of the cement paste. Steel fibers were added gradually during the last stage.

Table 1. Mix design

Materials	Cement	Silica fume	Water	Fine sand	Ground quartz	Superplasti cizer	Fiber (2% vol.)
kg/m^3	712	231	130	1020	211	40	156
lb/yd^3	1200	389	219	1719	355.6	67.4	263

The uniaxial tensile test was performed using UTM machine. Due to technical limitations, only double layer coupons were tested with plastic tabs glued at both ends. The machine was controlled by table movement at a rate of 0.1 mm/min. The extensometer was used to obtain the strain readings before rupture. 100 *mm* cubes specimens were used to obtain the compressive strength of UHPFRC by using uniaxial compression machine with 3000 *kN* capacity.

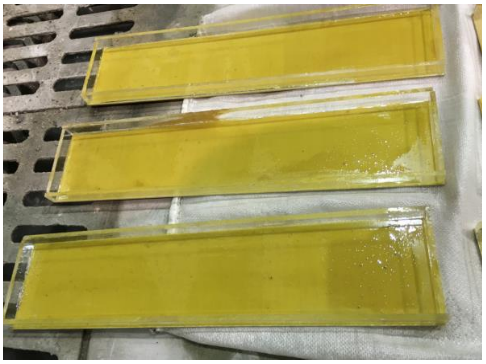
3.2. Design of specimens

A series of UHPFRC thin plates were cast either with or without 2% volume fraction of steel fiber, and some of them were reinforced with either single-layer or double-layer CFRP sheets. Details about each specimen are shown in Table 2.

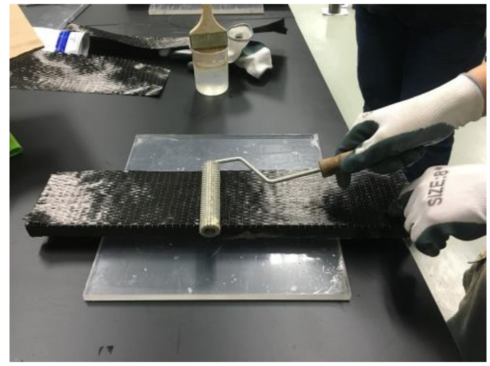
Table 2. Specimen Matrix

Specimen ID	UHPC fiber content	FRP sheet reinforcement	FRP anchorage	Number of specimens
S-F0-P0	0%	N	N	2
S-F2-P0	2%	N	N	2
S-F2-P1	2%	One-layer	N	2
S-F2-P2	2%	Two-layer	N	2
S-F0-P2	0%	Two-layer	N	2
S-F2-P2-W	2%	Two-layer	Wrap	1
S-F2-P2-H	2%	Two-layer	Notch	1

The formwork and wet-layup procedure are shown in Figure 2 a) and b). The thin plate was 500 *mm* long and simply supported with a span of 450 *mm*. The thin plate was cast and cured under 20-degree water for 28 days before applying CFRP sheet.



a)



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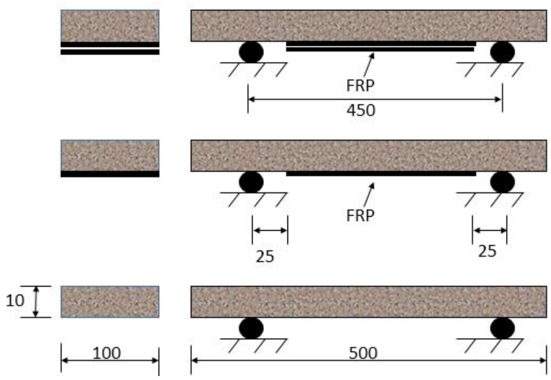

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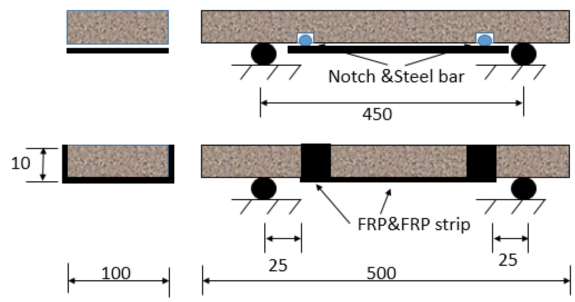
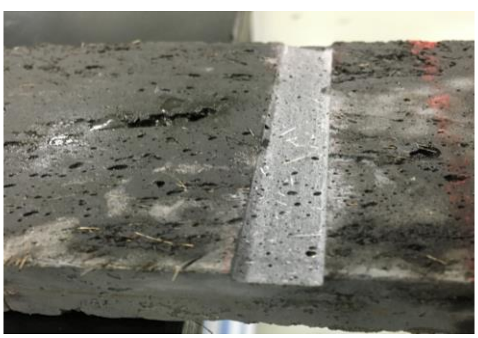


d)

Figure 2. Specimen Sketches: a) Form Work, b) Wet-layup procedure, c) Design scheme d) Anchorage design (1 in. = 25.4 *mm*)

The two anchorage designs are shown in Figure 3. For notched plate, two notches that are close to the support were introduced on both sides of the plate. Two small steel bars were clamped within the notches that fill with epoxy resin. For another scheme, CFRP strip was used to wrap around the plate over the existing CFRP sheet at end edges in order to enhance bond strength.



a)

b)

Figure 3. Design Anchorage: a) Shallow notch, b) End wrap (1 in. = 25.4 mm)

4. Test Results

4.1. Material Properties

Uniaxial test results on CFRP coupons are listed in Table 3. The values obtained from the experiment are different from those provided by the supplier. The difference is mainly attributed to the wet layup manufacturing process.

Table 3. Uniaxial coupon tests results

Results	Theoretical Thickness (mm)	Width (mm)	Modulus of elasticity (GPa)	Maximum stress (MPa)	Ultimate strain
From experiment	0.330	14.7	187	1350	-
From Supplier	0.167	15.0	244	3794	0.017

Compressive strength tests for UHPFRC material were conducted on 100 *mm* cubes after heat treatment in hot water at 90 degrees for 48 hours. The compressive strength from cube specimen that cast with slab specimens were summarized in Table 4.

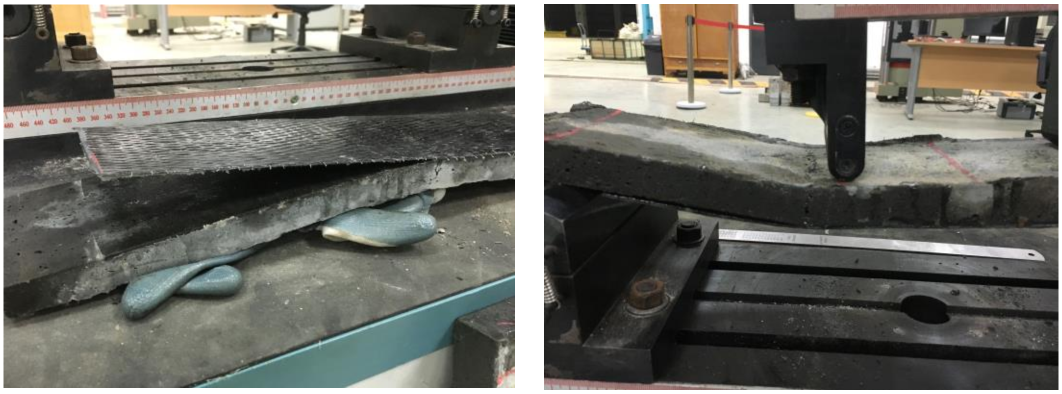
4.2. Flexural Test Results

The peak load from each specimen is summarized in Table 4. Due to technical issues existing in fabrication, the thickness of some specimens were different from the design values as indicated in the table.

Table 4. Peak load and thickness of all specimens

Specimen ID	Compressive strength	Specimen1		Specimen 2	
	MPa	Thickness (*mm*)	Peak load (*kN*)	Thickness (*mm*)	Peak Load (*kN*)
S-F0-P0	135	20.1	0.89	20.1	0.76
S-F2-P0	154	22.0	3.00	20.0	1.90
S-F2-P1	154	17.0	3.15	13.0	2.60
S-F2-P2	154	25.0	3.20	28.0	4.20
S-F0-P2	121	20.7	2.49	20.0	2.26
S-F2-P2-W	167	20.2	4.26	19.8	3.27
S-F2-P2-H	167	19.0	4.49	--	--

All CFRP reinforced UHPFRC plates without specially designed anchorage failed due to debonding as shown in Figure 4. For specimen S-F2-P2, small cracks at mid-span were visible during the test before the debonding happens and the specimens failed in shear after debonding.



(a) (b)

Figure 4. Typical bond failure of plate specimen: a) Debonding of CFRP sheet, b): Shear failure after debonding

The failure modes for specimens with end anchorages are shown in Figure 5 a) and b) for notched and wrapped specimens, respectively. Both specimens failed due to shear cracks, either at the notched region or outside of the wrap zone. While the failure of the specimen with notches was abrupt, the failure of wrapped specimen was ductal with the shear crack widened gradually.

(a) (b)

Figure 5. The failure mode of specimens with end anchorage: a) with notch b) with end wrap.

During the test, table movement was recorded as the average movement of the two loading points. The load versus such deformation are plotted in Figure 6. Some of the curves are moved horizontally to minimize the influence of localized seating at supports.

It was found out that the stiffness of plate reinforced with CFRP sheet increased and the appearance of first crack and corresponding stiffness degradation stage were delayed. Both end anchorage designs improved the bond between UHPFRC and CFRP sheet, thus lead to a higher ultimate load and higher post crack stiffness. The ultimate load capacity for specimen S-F2-P2 is similar to that for the anchorage plate specimen due to the larger thickness as reported in Table 4.

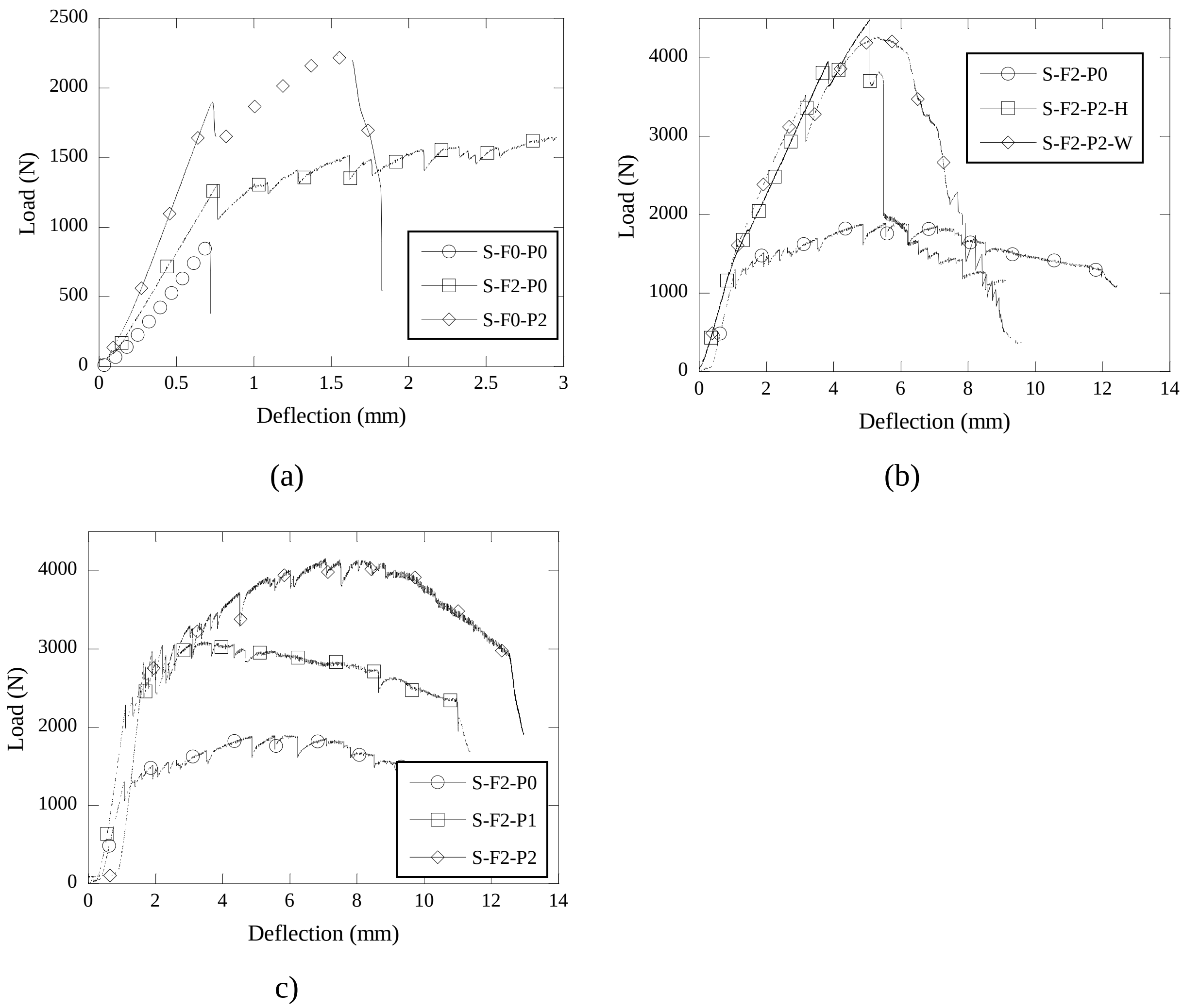


Figure 6. Load versus deflection for specimens with end anchorage

(1 in. = 25.4 mm, 1 lbf = 4.448 N)

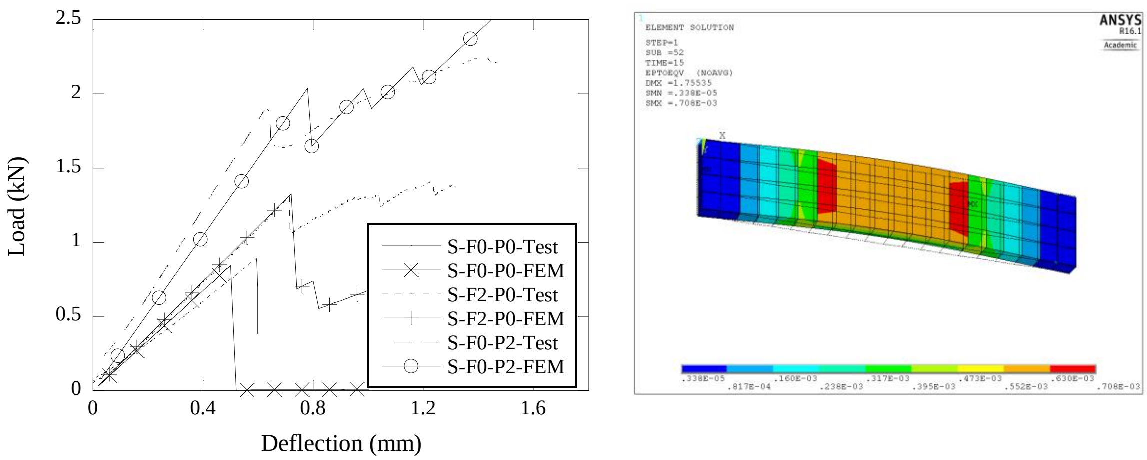
5. Finite Element Analysis

Ansys® software is used to simulate the flexural behavior of reinforced and unreinforced thin plates. The calibrated model was utilized to predict the structural behavior of single curved panel as shown in Figure 1. The solid model is used which involves utilizing of Solid65 elements and corresponding material models for concrete and steel. Solid65 element, an eight-node, 3D solid element built in Ansys®, were used to simulate concrete material. It supports features such as cracking and crushing behaviors of concrete that requires input parameters of uniaxial compressive strength and uniaxial tensile strength. In order to avoid the potential issue, the crushing checking of solid65 elements was turned off and a von Mises yielding criteria with the bilinear hardening rule was used to simulate the stress and strain behavior of UHPFRC on the compressive side. In addition, by defining real constants that specify the volume fraction and orientation of reinforcing layer, the effect of fiber or CFRP sheet can be considered within solid 65 elements. The additional reinforcing layer will not only contribute to the post cracking responses, but it will also add additional stiffness terms to the elastic stiffness matrix of the concrete material. The properties of materials for the finite element model were calibrated, and the parameters are shown in Table 5.

Table 5. Calibrated material models

Parameters	Unit	S-F0-P0	S-F2-P0	S-F0-P2
Modulus of elasticity (GPa)	*GPa*	35	35	35
Uniaxial compressive strength	*MPa*	125	150	150
Uniaxial tensile	*MPa*	6	8.5	8.5
Fibre material modulus of elasticity	*GPa*	--	200	200
Fibre material yielding stress	*MPa*	--	1500	1500
Fibre material volume fraction	-	--	0.02	0.12

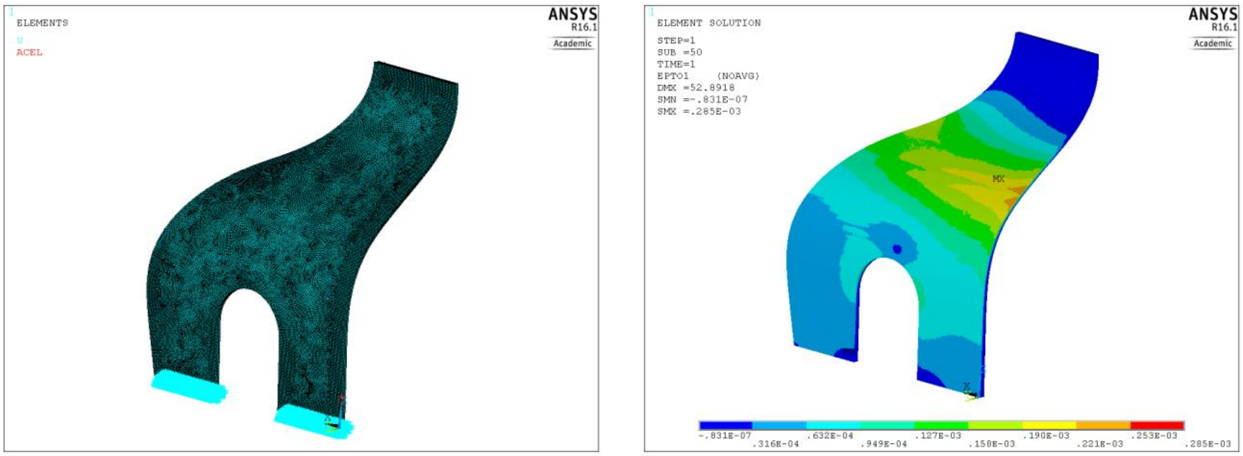
The load versus loading point displacement curves from experiment and calibrated models are shown in Figure 7 a), which demonstrated the appropriateness of the parameters adopted. Figure 7 b) presents the first principle strain distribution for specimen S-F0-P2 at 1.5 mm deflection.



(a) (b)

Figure 7. Finite element analysis results: a) Comparison of calibrated results and b) First principle strain for S-F2-P2 at 1.5 mm deflection

The structural behavior of the single curved panel was simulated using the calibrated finite element model. The total thickness of the panel is 60 *mm*, which is divided into three 20 *mm* layers through the thickness direction. The material model for S-F0-P2 is used for both inner and outer layers while the S-F2-P0 model is used for the middle layer. Both self-weight and wind pressure of 0.5 kN/m^2 were applied to the single curved panel. The wind pressure was applied perpendicular to the exterior panel surface. The nodes at the bottom were fully constrained for all three translational degrees of freedom as shown in Figure 8 a). The maximum deflection of the curved panel is around 53 *mm*, which happens at the top corner. The first principle strain plot is shown in Figure 8 b), which is lower than the cracking limit.



(a) (b)

Figure 8. Finite element analysis results: a) Mesh and boundary conditions and b) First Principle strain distribution of the single panel

6. Discussion and Conclusion

The load capacity of thin UHPFRC plate reinforced with external CFRP sheet under four-point bending was investigated experimentally. The test results were used to calibrated the finite element model. The contribution of fiber and CFRP sheet are both important with regard to its overall structural responses. The effectiveness of CFRP sheet was confirmed by comparing load versus deformation curves from specimens with and without external reinforcement. It was confirmed that the end anchorage plays an important role on enhancing the effectiveness of the reinforcing external layer. Transverse wrapping is a better anchorage solution than the notch method because it is easier to apply on the UHPFRC surface and equally effective. The failure mode of the reinforced plate is either debonding or shear, which is depending on the condition of end anchorage of reinforcing layer.

Based on the results from mechanical test and finite element analysis, CFRP reinforced UHPFRC plate can be a viable structural solution to form the thin curved panel. The deformation of the 60 mm thick, 7.5-*meter* height curved panel is approximately 53 *mm* based on finite element analysis. However, the current solution can be further improved by removing CFRP reinforcement from unnecessary locations.

7. References

Graybeal, Benjamin A. *Material Property Characterization of Ultra-High Performance Concrete*: Federal Highway Administration, 2006.

Grelle, Stephen V., and Lesley H. Sneed. "Review of Anchorage Systems for Externally Bonded FRP Laminates." *International Journal of Concrete Structures and Materials*. (2013):7(1):17-33.

Hassan, A. M. T., S. W. Jones, and G. H. Mahmud. "Experimental Test Methods to Determine the Uniaxial Tensile and Compressive Behaviour of Ultra High-Performance Fibre Reinforced Concrete (UHPFRC)." *Construction and Building Materials*. (2012): 874-82.

Resplendino, Jacques, and Francois Toulemonde. *Designing and Building with Uhpfrc*. 2011. Wiley-ISTE.

Rossi, P. "Development of New Cement Composite Materials for Construction." *Proceedings of the Institution of Mechanical Engineers -- Part L -- Journal of Materials: Design & Applications* 219.1 (2005): 67-74.