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STEEL FIBER REINFORCED CONCRETE SANDWICH PANEL USING A FOAM CORE: FLEXURAL INVESTIGATION AND PREDICTION

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ABSTRACT:

The precast concrete sandwich panel made of foam core and fiber reinforced concrete wythes is the innovative lightweight construction material which has advantage over the conventional concrete panel based on its strength to weight ratio. In this research, the simple production method was introduced to improve the constructability of the precast concrete sandwich panel. The shear tests were performed on 5 cm-cubic specimens with foam in one half and concrete in the other half to investigate their bonding resistance. The 3-point flexural tests were conducted on precast concrete sandwich panels with the dimensions of 30 cm x 10 cm x 120 cm. Three parameters, including connection types, thickness of foam and FRC layers, and volume fraction of steel fiber, on their flexural strength and stiffness were studied. Based on the test results, it was found that all three parameters affected the flexural strength and stiffness of the sandwich panels. Their thickness of FRC layers influenced both of their flexural strength and stiffness before and after the first crack. Their connection type affected only their stiffness before and after the first crack, whereas their volume fraction of steel fiber mainly affected their flexural strength and stiffness only after the first crack. Moreover, the flexural failure caused by major crack at the mid-span area was found in all tested sandwich panels.

KEYWORDS: Precast concrete sandwich panel, EPS Foam, FRC, Shear connection, First crack

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1. Introduction

Precast concrete sandwich panel is a lightweight construction material which has gained the popularity in United State since 1960s. This innovative composite section consists of two materials: thick foam layer as a core and thin concrete layer as facings. With its high strength- to-weight ratio and ductility, it facilitates the construction time and erection work. Moreover, it is sustainable for cycling load, dynamic load, and blast load. From architectural point of view, sound insulation and heat insulation are also its advantages which can yieldin the energy saving.

Generally, the mechanical behaviors of precast concrete sandwich panel significantly depend on those of the core layer and the facing layers as well as the bonding resistance between each layer. Concrete facing is the outer layer whose function is to experience the tensile/ compressive stress from bending moment, direct impact load, and other environmental loads. Thus, the concrete facing must have suitable resistance and durability. Rebar or fiber reinforcement has been widely used to enhance concrete properties, including its strength and environmental resistanceas presented in [2], [7], and [9]. Steel fiber reinforced concrete (SFRC) is a suitable material for thin facing layer of sandwich panels because of its strength and durability. SFRC has good resistance against impact load and abrasion. Moreover, it can reduce and efficiently control the crack width of concrete. The behavior of SFRC is mainly governed by the volume fraction of the fiber according to [10] and [11]. To transfer the load from the top facing layer to the bottom one, foam core is introduced. Expanded polystyrene foam (EPS) and extruded polystyrene (XPS) are the most common used foam in the construction field regarding to their mechanical properties, their bonding resistance with concrete, and their insulation capacity as demonstrated in [5]. The strength of the foam and its bonding resistance with concrete increase with its density according to [3]-[5], [8], and [9]. The bonding resistance can be improved by using the foam layer which has the high adhesion with the concrete or using the connecting devices such as glass fiber reinforced polymer (GFRP) shear grid, carbon fiber reinforced polymer (CFRP) pin, double steel shear truss, or concrete region connection type as illustrated in [9], [7], and [6], respectively. For an example, Sham et al. [9] conducted the experiments on the sandwich panels by increasing the strength and the performance of the concrete facing layer using ultra high performance fiber reinforced concrete (UHPFRC) (f'_c = 175 MPa) and textile reinforced concrete (TRC) (f'_c = 67 MPa).

In this study, the shear tests were performed on 5 cm-cubic specimens in which one half was foam and the other half was concrete with different mix proportions to investigate their bonding resistance. Moreover, three-points loading flexural tests were also conducted on precast concrete sandwich panels with the dimensions of 30 cm x 10 cm x 120 cm to study parameters affecting its flexural behavior. These parameters included connection types, thickness of foam and FRC layers, and volume fraction of steel fiber.

2. Objective and Research Significance

The main objectives of this research study are:

- To investigate the flexural behavior of the precast concrete sandwich panels.
- To examine parameters affecting the flexural strength, ductility and stiffness of the precast concrete sandwich panels.

The significance of this research was to introduce the new type of lightweight sandwich precast panel, using a foam core with fiber reinforced concrete (FRC) facing layers, to replace the conventional concrete panel. The experimental testswere conducted on 10cm-thick sandwich panel which met the actual size of wall panel, floor panel, and flat roof panel of the building. This research also introducessimple production method and lightweight material which will facilitate the construction process, and the panel transportation as well as reduce the labor force requirement and cost expense.

3. Experimental Program

3.1 Material

3.1.1 Concrete

Concrete was made usingfour different mix proportions to find the mix proportionthat gave the highest concrete compressive strength and asuitable bonding resistance with the foam layer. Table 1 shows the mix proportions and their corresponding tested compressive strengths using ASTM C109 [1].

Table 1 Concrete Mix Proportion and Properties

Mix Proportion	Cement [kg/m^3]	Fine Aggregate [kg/m^3]	Water [kg/m^3]	Actual f'$_c$ [MPa]
1:1	1,021	1,021	358	51
1:1.5	842	1,263	295	48
1:2	716	1,433	251	46
1:2.5	623	1,558	218	41

3.1.2 Foam

Mechanical behavior of foam increases with its density. In this study, the properties of expanded polystyrene foam (EPS) are shown in Table 2. Three foam thicknesses used were 7 cm, 7.5 cm, and 8 cm.

Table 2 Properties of EPS foam

Density [kg/m^3]	Thermal conductivity [W/mk]	Combustibility [second]	Compressive stress at 5% stain* [kPa]
32	0.026	0.7-2	120

*Testing method is according to Norwegian Directorate of Public Road: 484E

3.1.3 Steel Fiber Reinforcement

Steel fibers are important for concrete facing because they improve the mechanical behavior of the concrete facing such as tensile strength, compressive strength, and ductility. Hooked steel fibers HF65/35 (3D Dramix), shown in Figure 1, were used in this study.Their properties are presented in Table 3.

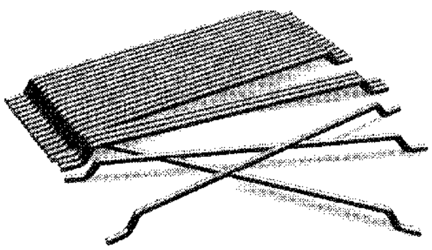

Figure 1 Hooked steel fibers HF-65/35

Table 3 Properties of hooked steel fiber

Fiber ID	Length, L_f [mm]	L_f/D	Diameter, D [mm]	Tensile Strength [MPa]
HF-65/35	35	65	0.58	1,100

3.1.4 Steel Fiber Reinforced Concrete

Steel fiber reinforced concrete (FRC) was used to fabricate the sandwich panel facings. Based on its highest compressive strength and relatively high bonding resistance (see Section 3.2 for testing details) achieved during the test (see Table 5), the concrete with mix proportion of 1:1 was used with steel fiber volume fractions of 0.5%, 1%, and 1.5% for FRC.

3.2 Shear Test

3.2.1 Specimen Preparation

Specimens for shear test, shown in Figure 2, were prepared by first inserting one half of foam cube vertically into a 5 cm-cubic mold. Next, fresh concrete was poured into the other half of the cube. After concrete hardened, the specimens were demolded. Finally, 28-day wet curing processwas conducted for all specimens before performing shear tests.

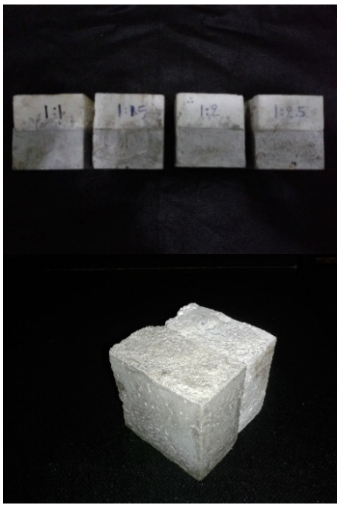

Figure 2 Specimens for shear test

3.2.2 Shear Test Setup

The direct shear tests, shown in Figure 3, were performed on foam-concrete specimens to study their bonding resistance which was calculated using an equation below:

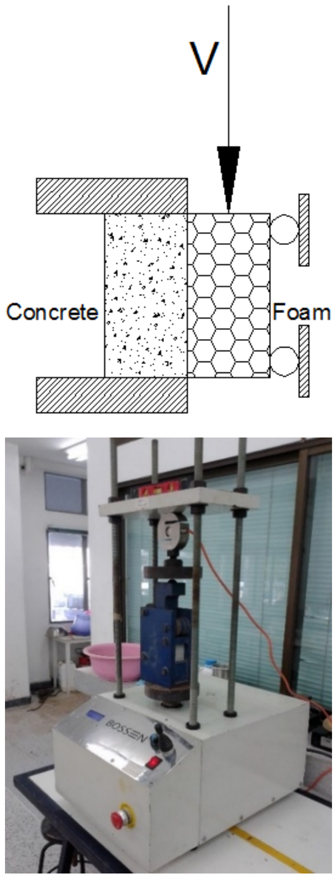

Figure 3 Shear Test Setup

$$\tau = \frac{V}{b \cdot h} \qquad (1)$$

τ: Bonding Resistance (kPa)
V: Maximum Shear Force (kN)
b: Width of the concrete in contact to the foam (m)
h: Height of the concrete in contact to the foam (m)

3.3 Flexural Test

3.3.1 Specimen Preparation

Seven sandwich panel specimens consisting of a foam core and two outer FRC layers had their final dimensions of 30 cm x 10 cm x 120 cm as shown in Figure 4. The differences between the composite panels were the connection type, the thickness of foam and FRC layers, and the volume fraction of steel fiber. Details of all seven sandwich panels are described in Table 4 and discussed below.

Table 4 Precast sandwich panel properties

Panel ID	Foam Thk. (cm)	FRC Thk. (cm)	V_f (%)	Type of Connection
F8-BC-V1	8	1	1	Bonding
F8-RC-V1	8	1	1	Ribbed Concrete
F8-CC-V1	8	1	1	Concrete Column
F7.5-BC-V1	7.5	1.25	1	Bonding
F7-BC-V0.5	7	1.5	0.5	Bonding
F7-BC-V1	7	1.5	1	Bonding
F7-BC-V1.5	7	1.5	1.5	Bonding
F8	8	-	-	-
F7	7	-	-	-

Three types of connections used in this study were bonding connection, ribbed concrete connection, and concrete column connection. Bonding connection was prepared by using a typical foam core as shown in Figure 5. The next two connections were introduced by modifying foam core section to enhance load transfer mechanism between the concrete facing layers and the foam core. For ribbed concrete connection, the foam core surface was partially cut to form multiple grooves as shown in Figure 6. For concrete column connection, the foam core was drilled through its section to form four square holes as shown in Figure 7.

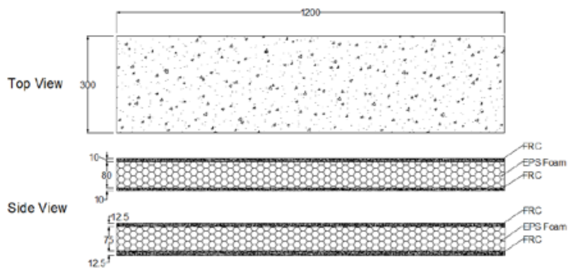

Figure 4 Dimensions of sandwich panel (dimensions in mm)

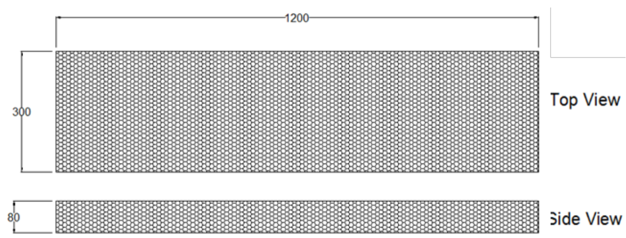

Figure 5 Detail of a typical foam core (dimensions in mm)

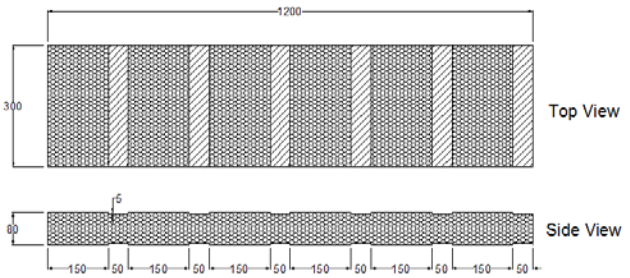

Figure 6 Detail of a ribbed foam core (dimensions in mm)

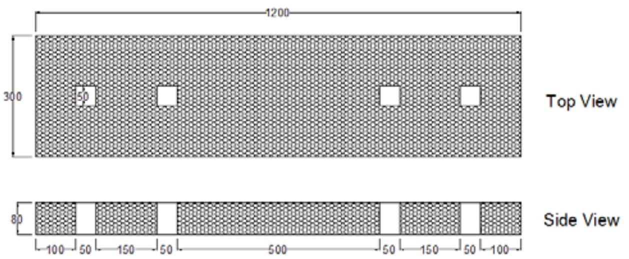

Figure 7 Detail of a drilled foam layer (dimensions in mm)

The first three specimens, namely F8-BC-V1, F8-RC-V1, and F8-CC-V1, had the same foam core thickness of 8 cm, and the same steel fiber volume fraction of 1% in FRC layers, but different types of connection which were bonding connection, ribbed concrete connection, and concrete column connection, respectively. The next three specimens, namely F7-BC-V0.5, F7-RC-V1, and F7-CC-V1.5, had the same foam core thickness of 7 cm, and the same bonding connection, but different steel fiber volume fraction of 0.5%, 1%, and 1.5% in FRC layers, respectively. Specimen F7.5-BC-V1with 7.5 cm thick foam core and bonding connection was later added into this study to investigate the effect of FRC layer thickness by comparing its flexural behavior with those of Specimens F7-BC-V1 and F8-BC-V1.

To cast the sandwich panel specimens, firstly, a foam core was placed in the middle position of the mold. Then, fresh FRC was poured on one side of the foam core to cast the first facing layer. Twenty four hours later, fresh FRC was poured on the other side to cast the other facing layer. After concrete hardened, all specimens were kept in wet curing process for 28 days.

3.3.2 Flexural Test Setup

To investigate their flexural behavior, the precast concrete sandwich panels were tested under 3-point loading with 1.0 m long clear span as shown Figures 8 and 9. Load was applied linearly across the mid-point of the panel. Data of load and deflection were transmitted to a data logger and then recorded in a computer. After the test, load-deflection curves were plotted so that the flexural strength and stiffness of the sandwich panel before and after first crack, and the load carrying capacity could be investigated.

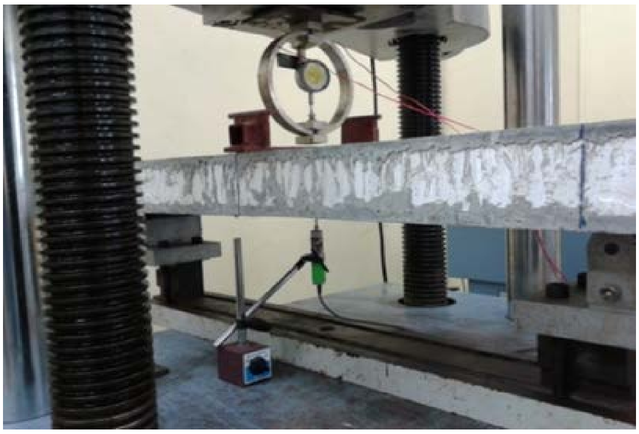

Figure 8 Flexural Testing Setup

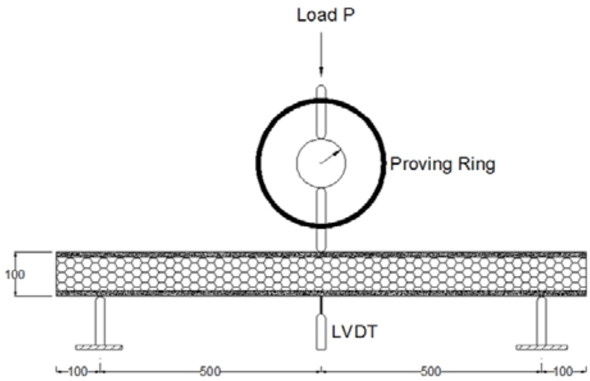

Figure 9 3-point loading configuration

A comparison between the theoretical and the tested bending moment capacities was also made. The theoretical bending moment capacity was predicted based on a formula for determining the ultimate bending moment capacity of the beam. The predicted theoretical bending moment ($M_{n,predicted}$) equals to the forces (F) developed in FRC layers times the lever arm between the centroids of the upper andthe lower FRC layers (see Figure 10) as follows:

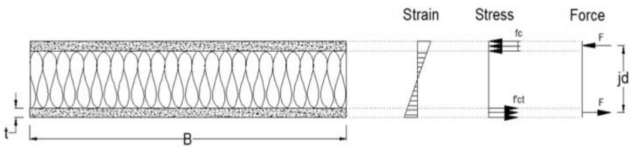

Figure 10 Stresses and forces developed on sandwich panel section

$$M_{n,predicted} = F \cdot jd = (f'_{ct} \cdot B \cdot t) \cdot jd \quad (2)$$

where:

F: tensile force of FRC

B: width of the sandwich panel

t: thickness of sandwich panel

jd: lever arm between the centroids of the upper and the lower FRC layers

f'_{ct}: post-cracking strength of FRC given by Sujivorakul, C. [10]

where:

$$f'_{ct} = \sqrt{f'_c}(-0.0014 \cdot V_f^2 + 0.0046 \cdot V_f) \cdot \frac{L_f}{D} \cdot L_f^{0.2} \cdot \beta \quad (3)$$

V_f: steel fiber volume fraction

L_f: length of steel fiber

D: diameter of steel fiber

L_f/D: aspect ratio of steel fiber

β : fiber orientation coefficient

4. Result and Discussion

4.1 Direct Shear Test Result

The foam-concrete bonding resistance obtained from the direct shear test of 5 cm cubes is presented in Table 5.

Table 5 Foam-concrete bonding resistance

Concrete Mix Proportion	Concrete Compressive Strength [MPa]	Bonding Resistance [kPa]
1:1	51	140
1:1.5	48	159
1:2	46	130
1:2.5	41	162

It can be seen from the table that while concrete compressive strength depends on its mix proportion, the bonding resistance between concrete and foam does not. The bonding resistance was found to range from 130 kPa to 162 kPa with the mean value of 148 kPa.

4.2 Flexural Test Result

From the 3-points flexural test, the load-deflection curves of the tested precast concrete sandwich panels were plotted to investigate their flexural behavior such as their strength (the first cracking load and the ultimate load capacity), their stiffness (the slopes of load-deflection curve before (k_1) and after (k_2) first cracking as shown in Figure 11. Moreover, the effect of connection type, thickness of FRC facing and foam core, and volume fraction of hooked steel fibers on the flexural behavior of the panels were also discussed.

4.2.1 Effect of FRC Facing and Connection Types

A comparison of the flexural behavior between the foam core with FRC facing (Panels F8-BC-V1 and F7-BC-V1.5) and without (Panels F7 and F8) FRC facing is shown in Figure 12. As expected, the foam panel (control sample) could deform elastically even at the large deflection (as large as 10 mm or L/100).

Figure 12 clearly indicated that even with the thin layers of FRC (1 cm and 1.5 cm thick on each side of Panels F8-BC-V1 and F7-BC-V1.5, respectively), they had tremendous effects on both flexural strength and stiffness of the foam panel. A significant increase in ultimate load capacity was achieved as they increased from 100 N to 3,270 N and from 80 N to 4,895 N for 8 cm- and 7 cm-thick foam, respectively.

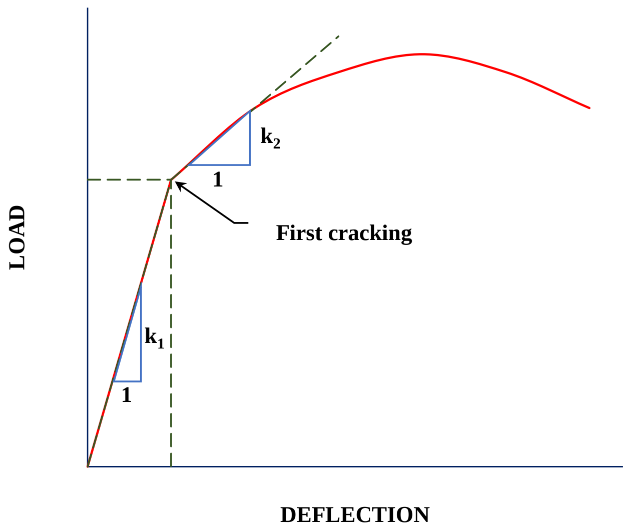

Figure 11 A typical flexural behavior of a precast sandwich panel

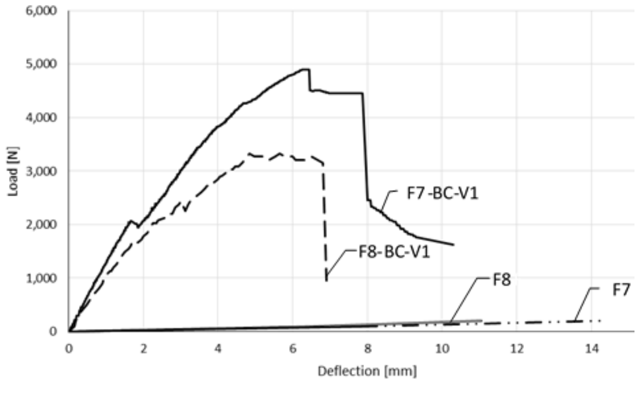

Figure 12 Comparison of Load-deflection curve between sandwich panels and foam panels

Figure 13 shows load-deflection curvesof the sandwich panels with different connection types. The cross section (8mm thick foam core) and the volume fraction of steel fibers (V_f = 1%) for these panels were the same. Figure 14 shows a comparison of the first cracking load and the ultimate load capacity, and Figure 15 shows a comparison of the slopes of load-deflection curve (or stiffness) before and after the first crack of these sandwich panels.

As seen in Figures 13 and 14, these three sandwich panels had a similar first cracking load and ultimate load capacity. The first cracking loads were around 1,540 N for all panels, and the ultimate load capacities ranged from 3,270 N to 3,330 N. It indicates that their flexural strengths were not affected by the connection type because they were mainly governed by the thickness of FRC facing layers, but their stiffness were, as indicated by Figures 13 and 15.

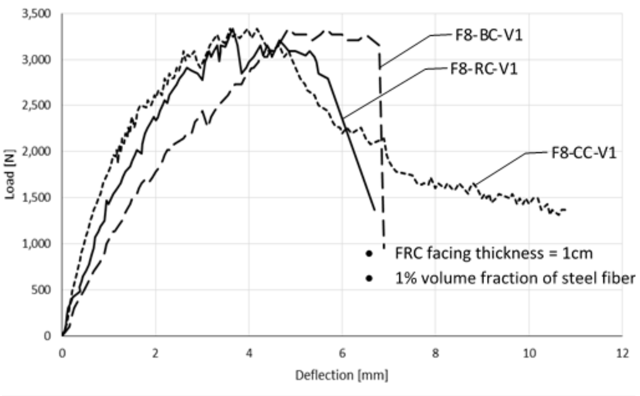

Figure 13 Load-deflection curves of sandwich panels with different connection types

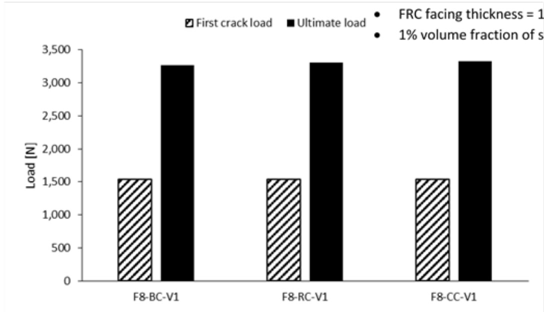

Figure 14 First cracking load and ultimate load capacity of panels with different connection types

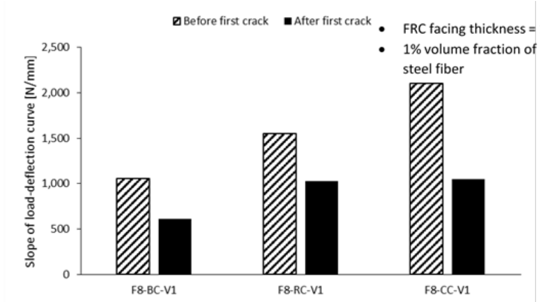

Figure 15 Slopes of load-deflection curve of panels with different connection types

It is seen in Figure 15 that Panel F8-BC-V1 had the lowest slopes of load-deflection curve before and after the first crack (1,053 and 614 N/mm, respectively), and Panel F8-CC-V1 had the highest ones (2,104 and 1,053 N/mm, respectively). An increase intheir stiffness was the result of the modification on foam core contact surfaces for Panels F8-RC-V1 and F8-CC-V1. It enhanced the load transfer mechanism between the face and the core layers. Thus, the types of connection significantly influence the stiffness of the precast concrete sandwich panel and its ability to deform under a large deflection but not the strength.

4.2.2 Effect of FRC Facing Thickness

Figure 16 shows load-deflection curves of the sandwich panels with different thickness of FRC facings and a foam core. The same bonding connection type and the same volume fraction of steel fiber (V_f = 1%) were applied for these panels. Figure 17 shows a comparison of the first cracking load and the ultimate load capacity,and Figure 18 shows a comparison of the slopes of load-deflection curve before and after the first crack of these sandwich panels.

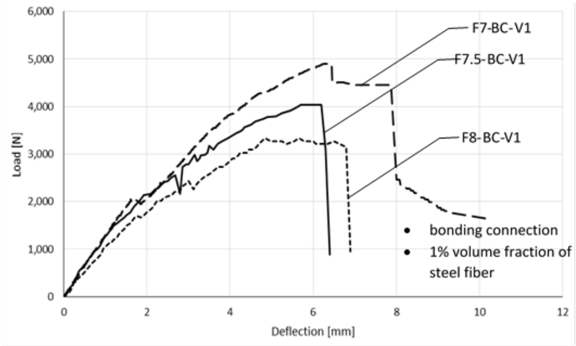

Figure 16 Load-deflection curves of sandwich panels with different FRC facing thickness

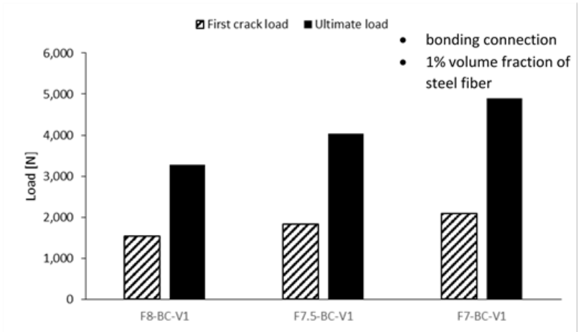

Figure 17 First cracking load and ultimate load capacity of sandwich panels with different FRC facing thickness

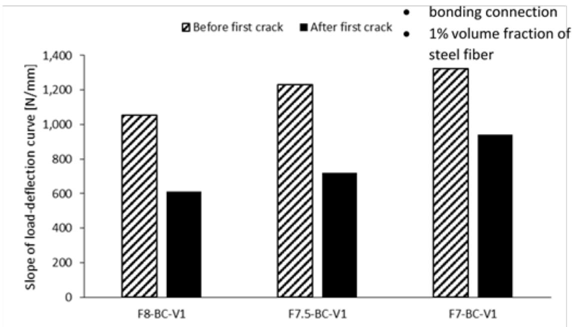

Figure 18 Slopes of load-deflection curve of panels with different FRC facing thickness

As shown in Figures 16 to 18, the thickness of FRC facing affected both the flexural strength (the first cracking load and the ultimate load capacity), and the flexural stiffness (the slope of load-deflection curve before and after the first crack) of these sandwich panels. As expected, both of their flexural properties varied with the thickness of FRC facing. The thicker FRC layers were used, the better flexural properties were achieved. Furthermore, flexural cracks were found at the bottom of FRC facing layer near mid-span, while there was no sign of compression failure in the top FRC facing layer. This indicated that the failure took place only in tension zone and large ductility could be achieved.

For Panels F7-BC-V1 and F8-BC-V1,

- the first cracking loadswere 2,080 N and 1,540 N, respectively,
- the ultimate load capacities were 4,895 N and 3,270 N, respectively,
- the slopes of load-deflection curve before 1,325 N/mm and 1,053 N/mm, respectively,
- the slopes of load-deflection curve after the first crackwere 942 N/mm and 614 N/mm, respectively.

The thickness of the FRC facing had a significant influence on the strength and the stiffness of the precast sandwich panels because the FRC facing in the tension zone was the main factor identifying the failure stage. The larger cross section of FRC was, the greater force developed.

4.2.3 Effect of Volume Fraction of Steel Fiber

Figure 19 shows load-deflection curves of the sandwich panels with different volume fractions of hooked steel fiber. The same cross section (7 mm thick foam core) and the same bonding connection were used for these panels. Figure 20 shows a comparison of the first cracking load and the ultimate load capacity,and Figure 21 shows a comparison of the slopes of load-deflection curve before and after the first crack of these sandwich panels.

In these figures, it is indicated that the volume fractions of steel fiber affected the strength and the stiffness of these tested panels clearly after the first crack. Their first cracking loadswere around 2,080 N, and their slopes of load-deflection curve before the first crack ranged from 1,312 N/mm to 1,480 N/mm.

After the first crack, significant different characteristics between these three sandwich panels were noticed as their ultimate load capacity and slope of load-deflection curve increased with the fiber volume fraction.The panel F7-BC-V1.5 had the highest ultimate load capacity and the slope of load-deflection after the first crack of panel which were 6,459 N and 1,117 N/mm respectively. Whereas panel F7-BC-V0.5 had the lowest ultimate load capacity and the slope of load-deflection after the first crack of panel which were 2,696 N and 562 N/mm respectively.Therefore, the volume fraction of steel fiber has a significant influence only on the ultimate load capacity and the slope of load-deflection curve after the first crack. This is because the steel fiber effectively involved in the action after the concrete had cracked.

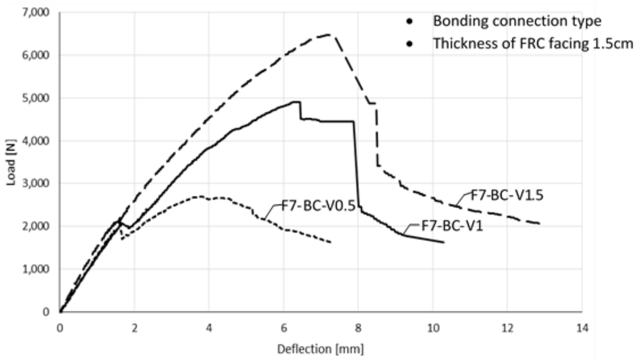

Figure 19 Load-deflection curve of sandwich panels with different volume fractions of steel fiber

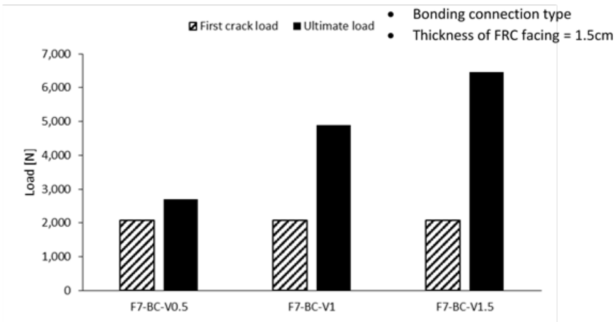

Figure 20 First cracking load and ultimate load capacity of sandwichpanels with different volume fractions of steel fiber

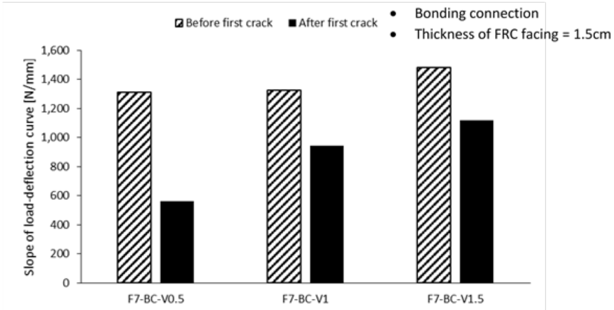

Figure 21 Slopes of load-deflection of sandwich panels with different volume fractions of steel fiber

4.2.4 Failure Mode

As shown in Figure 22, all the tested sandwich panels had the same mode of failure. All specimens failed in flexure where major cracks formed and concentrated near mid-span. Cracking of the FRC layer in the tension zone initiated the failure mechanism. As the applied load increased, the crack grew bigger, and propagated deeper into the foam core and then to the top FRC layer. There was no delamination found at the FRC- foam interface and no sign of compression failure of FRC facing in the compression zone.

Figure 22 (**a**) and (**b**) Major cracks at the bottom, (**c**) crack on the side view

Comparison between the maximum shear stresses developed at the FRC–foam interface and the bonding resistance obtained from the direct shear test is shown in Figure 23. The shear stress at the interface was calculated based on the principle of shear effect in the bending member. It can be seen that the shear stresses at the FRC–foam interface from all sandwich panels were smaller than the bonding resistance. As a result, they did not cause the delamination of FRC facing layers.

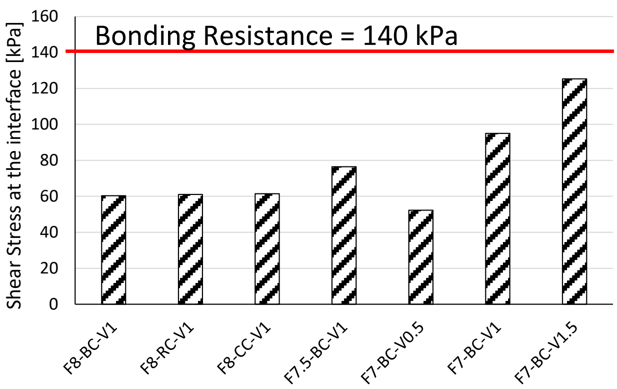

Figure 23 Comparison of maximum shear stresses at the FRC – foam interface of all sandwich panels

4.2.5 Comparison between analytical prediction and tested results

The bending moment capacities obtained from the test ($M_{n,test}$) were compared to those determined

($M_{n,predicted}$) based on the predicted tensile strength of the FRC developed by Sujivorakul, C. [10] as shown in Figure 24. It is found that the analytical prediction matched well with the tested resultswith the difference between those two ranging from 1% to 4%. for V_f = 1%. However, when higher volume fraction of fiber was used (V_f = 1.5%), The significant different was observed. The predicted moment capacity of panel was about 17% less than the tested result. This is because the prediction for tensile strength of FRC given in eq. (3) used quadratic equation, whichconcerns about the steel fiber group effect for high volume fraction.Thus, an increase in V_f would decrease the tensile strength of FRC, and then lead to fall short of prediction. As a result, the predicted bending moment will give conservation results when the higher volume fraction of fiber is used.

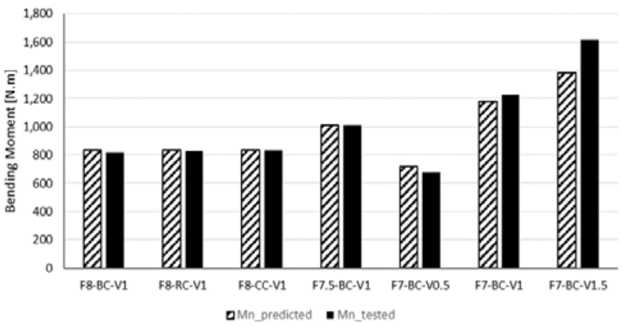

Figure 24 Comparison between analytical predicted and tested bending moment

Moreover, it was also found that the sandwich panels in this study have an advantage on higher flexural strength to weight ratio than the RC panels. In general, the flexural strength [unit : N.m] per weight [unit : N/ m] ratio of RC panels having 1% reinforcement is about 0.68 m^2, whereas the flexural strength per weight ratio of our sandwich panel having 1% fiber is about 1.68.

5. Conclusion

Based on the experiment test data obtained in this study, the following conclusion was made:

1. All three parameters, including connection type, thickness of FRC layer, volume fraction of steel fiber, affected the flexural behavior of the precast sandwich panels.
2. Thickness of FRC facing in the tension zone significantly affected both flexural strength and flexural stiffness of the sandwich panel before and after the first crack. This is because the resultant tensile force of FRC facing in the tension mainly took action and created the bending moment resistance against the applied bending moment.
3. Connection type had a significant influence on the stiffness of the sandwich panel for both before and after the first crack because the modification ofthe foam core section resulted in a better load transferring between the layers .
4. Volume fraction of steel fiber mainly influence the flexural behavior of the sandwich panel after the first crack because the steel fiber effectively took the load after section cracked.
5. At failure, flexural cracks formed at the bottom FRC layer near mid-span. No compression failure in the compression zone and no surface delamination between each layer were found.
6. Analytical model matched well with tested result and the difference was in the acceptable range. However, for higher volume fraction of steel fiber in FRC facing, the predicted bending moment will be more conservation because the tensile strength of FRC formula developed by Sujivorakul, C. (2011) concerning about the steel fiber group effect for higher volume fraction.

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