Structural Behavior of Laterally Loaded Precast Foamed Concrete Sandwich Panel

Y. H. Mugahed Amran, Raizal S. M. Rashid, Farzad Hejazi, Nor Azizi Safiee, A. A. Abang Ali

Abstract**—**Experimental and analytical studies were carried out to investigate the structural behavior of precast foamed concrete sandwich panels (PFCSP) of total number (6) as one-way action slab tested under lateral load. The details of the test setup and procedures were illustrated. The results obtained from the experimental tests were discussed which include the observation of cracking patterns and influence of aspect ratio (L/b). Analytical study of finite element analysis was implemented and degree of composite action of the test panels was also examined in both experimental and analytical studies. Result shows that crack patterns appeared in only one-direction, similar to reports on solid slabs, particularly when both concrete wythes act in a composite manner. Foamed concrete was briefly reviewed and experimental results were compared with the finite element analyses data which gives a reasonable degree of accuracy. Therefore, based on the results obtained, PFCSP slab can be used as an alternative to conventional flooring system.

Keywords**—**Aspect ratio (L/b), finite element analyses (FEA), foamed concrete (FC), precast foamed concrete sandwich panel (PFCSP), ultimate flexural strength capacity.

I. INTRODUCTION

PRECAST CONCRETE SANDWICH PANEL (PCSP) has been prefabricated as a non-load bearing system called a "cladding panel" which consists of two thick internal and external concrete (wythes) layers, designed as a load-bearing and non-load-bearing walls respectively [1], [2]. These layers are separated by an insulation medium (i.e. Polystyrene). Many shear connectors were used to hold concrete wythes together, but, steel truss-shaped shear connector was reported to be the most effective [2]-[4]. Thus, the typical geometry of PCSP including the steel truss-shaped shear connector is depicted in Fig. 1. The structural behaviour of PCSP depends on the mechanical shear connector's strength and stiffness. But, the required numbers, arrangement and spacing varies based on the applied load, desired composite action, span of the panel and the material used to design the shear connector [3], [5]. The degree of composite action of PCSP is commonly termed as fully composite, semi-composite, and non-composite; which highly depends on the shear connector used [6]. PCSP are commonly used to construct the outer shells of numerous typical buildings such as residential, commercial, and warehouses; and as they are vertically spanned between foundations and floors or roofs that mostly resist the axial/compression loads [1]-[4], [6], [7]. Furthermore, the western countries, especially Europe and North America where sandwich panels were developed and been proprietary; therefore, investigators and manufacturers are unwilling to share the designs and formulations of their PCSP products with their competitors [1], [2]. Also, since the majority of current PCSP application is fabricated using conventional concrete material, the study on the feasibility of PCSP as a slab element is rather rare. Hence, this study is aimed to conduct a full-scale flexural test to determine the ultimate flexural strength using a lightweight material in order to reduce the self-weight of the PCSP application for flooring element called Precast Foamed Concrete Sandwich Panel (PFCSP).

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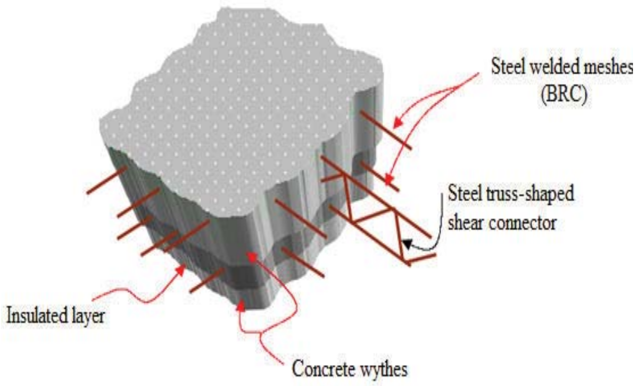


Fig. 1 3-D partial-cut section of PCSP

II. FOAMED CONCRETE: A REVIEW

Foamed Concrete (FC) is defined as a light cellular concrete which can be classified as lightweight concrete (density of 400 – 1850 kg/m^3) with random air-voids created from the mixture of foaming agent in mortar. FC is recognized for its high flow-ability, low cement content, low aggregate usage [8]-[10] and excellent thermal insulation [11]. Also, FC is considered as an economical solution in the fabrication of large scale lightweight construction materials and components found in structural elements; partitioning, filling grades, and road embankment infill. This is due to its simple production process from mobile central plants to final position of the applications [11]-[13]. Therefore, foamed concrete is a potential material used instead of the conventional concrete especially for low load-bearing construction applications.

Applications of foamed concrete have become popular worldwide, especially at the regions suffering from housing shortages or subjected to adverse weather, hurricanes and earthquakes [14]. In the UK, the estimated annual market size of foamed concrete is about 250,000-300,000 m^3 including one very large mine stabilization project. Western Canada has estimated the year market size of approximately 50,000 m^3 [15], [16]. In Korea, foamed concrete with a construction volume of approximately 250,000 m^3 is used annually as an essential component in a floor heating system [17]. But in North America, the overall demand was higher than the South and to be equal to the actual production. But, in Canada, cement-based foam use has been widespread for tunnel annulus grouting, flowable fills and in some geotechnical applications. This growing interest seems to be partially due to a significant increase in the cost of other lightweight building materials; such as dry wall and wood; apart from the environmental issues [13], [18]. Besides, an additional feature of foamed concrete encourages it to be more appropriate for large volumes of supplementary cementing admixtures because of the manufacturing and environmental cost associated with cement production [14].

III. Experimental Investigation

FC was chosen as a potential concrete material used for the developed PFCSP slab specimens. A deformed steel welded-wire mesh (BRC) of 6 mm diameter with 100 mm × 100 mm opening was used to reinforce both top and bottom concrete wythes. A steel round bar of 6 mm diameter was also used to shape the truss shear connectors. Five shear connectors were laid over a full width, b, of 1200 mm of the panels. Polystyrene was used as a proper insulation material between concrete wythes. A total of six (6) PFCSP slab specimens were developed, cast, and tested. The panels span, L, was varied between 2750 mm to 4000 mm with 250 mm constant increment between the former and subsequent specimen as depicted in Fig. 2. The chosen overall depth, d, of the panel was 150 mm, divided into 60 mm thickness of the top and bottom wythe each and 30 mm thickness of the insulation layer. Also, concrete cover was maintained at 20 mm. Hence, the adopted aspect ratio (L/b) was limited to 2.29 – 3.33.

A. Material Properties and Specifications

The adopted ratio used to select the weight of mix design constituents of foamed concrete was 1:2, denoting OPC: fine sand, respectively, and with a water-cement ratio of 0.50 by weight. The type of foam agent used was a protein foam agent, with a dosage of 77 liters per 1 meter cube. The average values of cube compressive strengths (f_{cu}) and modulus of elasticity (E_c) of foamed concrete, together with the splitting tensile strength of concrete cylinders (f_{ct}) at 28 days were 25.73 MPa, 21.71 kN/mm^2 and 2.13 MPa, respectively. The tensile strength and elastic modulus of BRC and shear connector were (500 MPa, 210 kN/mm^2) and (303 MPa, 112 kN/mm^2), respectively.

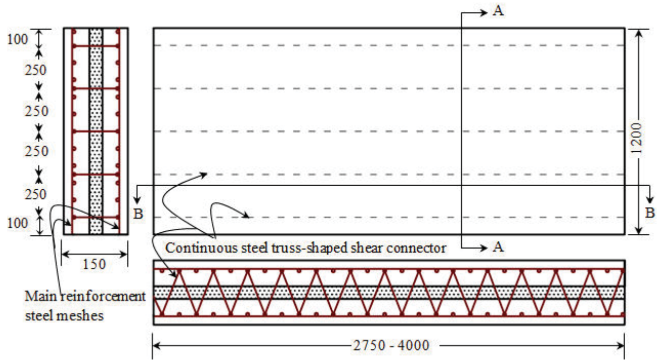


Fig. 2 Details of the one-way PFCSP slab (e.g. L/b = 2.292)

B. Preparation, Fabrication, and Casting Procedures

A wood timber of 18 mm thickness was used as formwork. All panels were designed as one-way slab specimens. The foamed concrete was poured in to shape the bottom concrete wythe and was self-compacted without any external aids. Then, the BRC was inserted into the concrete to the bottom wythe with a cover of 20 mm. The polystyrene insulation sheets were implanted between the shear connectors, after which the BRC of the top wythe was then laid and tied to shear connectors to hold both wythes together. The surface was trowelled to a smooth finish. Therefore, the overall process of preparation, fabrication, and casting of PFCSP specimens is shown in Fig. 3.

Fig. 3 Preparation, fabrication, and casting of PFCSP specimens

C. The Setup and Testing Procedures

PFCSP slab specimens were tested using a universal testing machine of 2000 kN capacity under lateral load. All the PFCSP specimens were horizontally seated and tested and were simply supported at the shorter sides as illustrated in Fig. 4.

The applied force was transferred from the jack as a one-point load, and then distributed into two line-loads across the width of specimen using I-beams. The instrumentation preparations were checked and adjusted properly prior to applying the load. 1 kN load was applied as the first load as a means of calibrating the instruments. Loads were applied constantly and gradually with increments of 2.5 kN until the specimens reached failure. At every stage, strains in steel reinforcement, shear connectors, and concrete were automatically recorded using a Data Logger UCAM-70A|KYOWA and scanner USB-70A-10. Cracking patterns were observed, marked on the surface of the specimen at each load stage, with the corresponding load indicated. However, in this full-scale experimental investigation, the structural behaviour of the test specimens was examined during the time of applying lateral load. In addition, the linear variable displacement transformers (LVDTs) were positioned at three different locations (L/4, L/2, and 3L/4) depicted as FD1, FD2 and FD3 in Fig. 5 along the full span of the test slab specimen subjected to lateral loads as described in Fig. 5. However, the arrangement of these LVDTs was based on ASTM-C78 standard, which mainly used to measure the deflection of the concrete wythes.

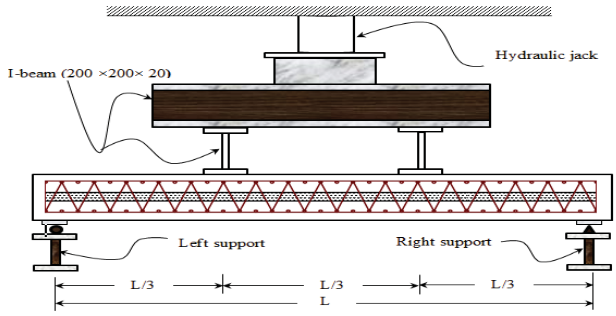


Fig. 4 Details of the test setup frame

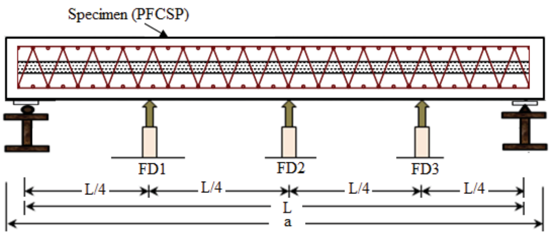


Fig. 5 Details of LVDTs arrangement along the span of the test slab

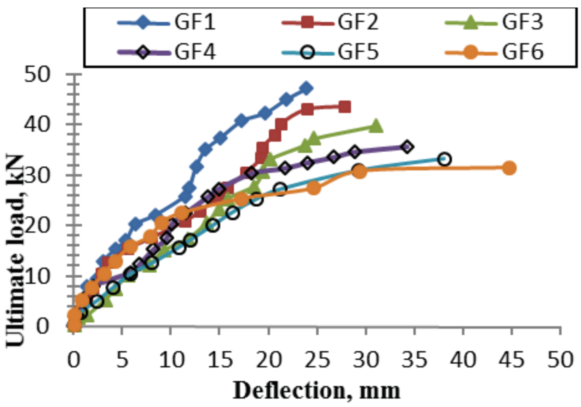
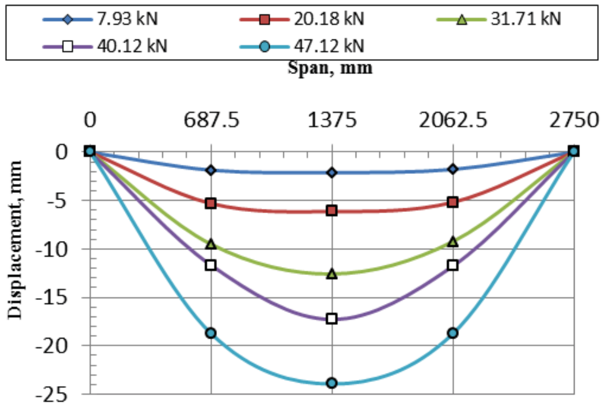
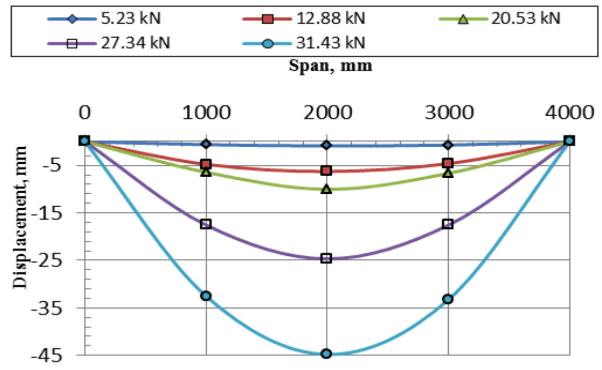


Fig. 6 Load against deflection, at mid-span



(a) Deflection against span for panel GF1



(b) Deflection against span for panel GF6

Fig. 7 Deflection along the span of panels GF1and GF6 at different load stages

IV. Experimental Investigations

The experimental results obtained were analysed using the load-deflection profile, load-strain relationship, and strain variation across the slab depth, effects of aspect ratio, cracking patterns of concrete and load at failure.

A. The Load-Deflection Profile

The load-deflection curves of the six panels tested are illustrated in Fig. 6. At the initial stage of testing, the panels behaved in a linear elastic manner until cracks starts, at a load of 40%-51% of the failure load, and a mid-span lateral deflection of 13%-15% of the ultimate deflection. This trend was observed for all the test panels. Therefore, the first flexural cracks marked at this point illustrated a relatively distinct drop in the load. Also, the formations of the second flexural cracks occurred at a load of 50%-67% of the failure load and a lateral deflection of 18%-23% of the ultimate deflection. In general, the deflection mode increased rapidly for a given increase in load beyond the load of the second flexural crack. The panels were loaded until ultimate failure load at the ultimate deflection mode.

The deflection profile along the span of the slab panels at different load stages of experimental testing is shown in Fig. 7. It is seen that the deflection increments were found to be higher only before the ultimate load at failure in FD1 and FD3 and more critical at FD2 of mid-span of the test panels, especially in more slender panels. For example, panel GF6 at a load of 27.34 kN, the deflection was 24.66 mm and suddenly increased to 44.77 mm at failure load of P = 31.43 kN. The deflection for panel GF1 is 23.95 mm while that of panel GF6 is 44.77 mm. Therefore, the deflection difference between GF1 and GF6 is approximately 86.9%. Nonetheless, the deflection profiles depict a uniform curves which explained that the reason of the two concrete wythes to behave as one structural unit during the loading stages, otherwise, it will show irregular behaviour.

B. The Load-Strains on Steel

Two strain gauges were installed on both truss shear connector legs at the mid-span of the test panel to measure the efficiency of the shear connectors, as shown in Fig. 8. It is shown that very small strains, not exceeding 823 με are developed in the legs of the truss shear connectors in panel GF6 (in SC1). Shear connector starts to change its original form after approximately 86.3% of the failure load. Therefore, shear connectors are utilised to transfer the forces between wythes efficiently until failure point, so as to empower the composite behaviour between two concrete wythes. Also, the maximum strains recorded in the steel bars are 1725 με and 3237 με at the top and bottom wythes of panel GF5, respectively, as illustrated in Fig. 9. Subsequently, the concrete strain, which is the maximum strain at the bottom wythe is 3334 με in CSb and strain at top wythe of panel GF6 is found to be 2413 με in CSt.

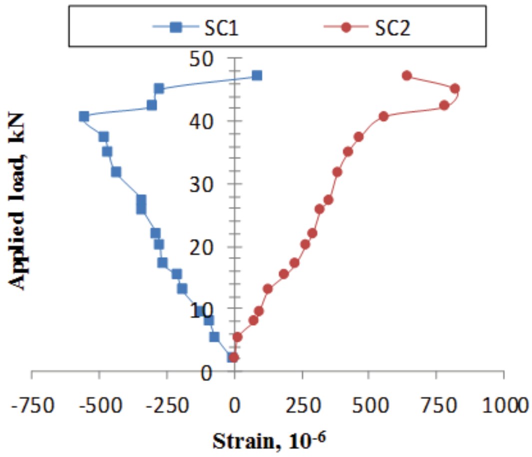


Fig. 8 Load against strains on shear connector legs

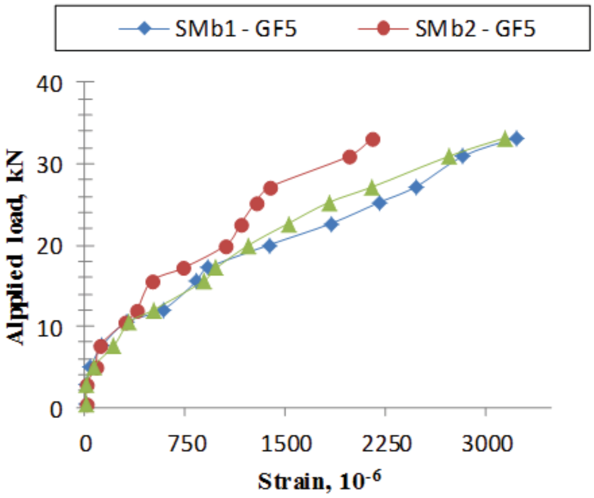
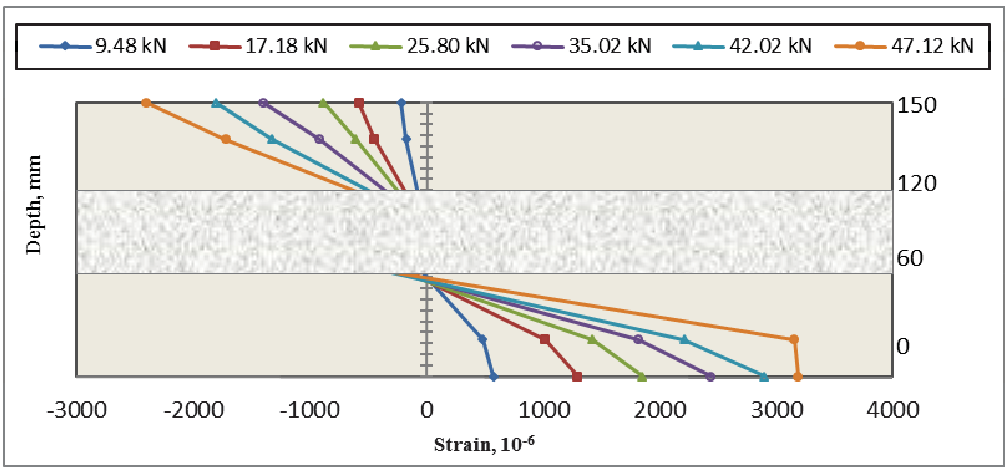
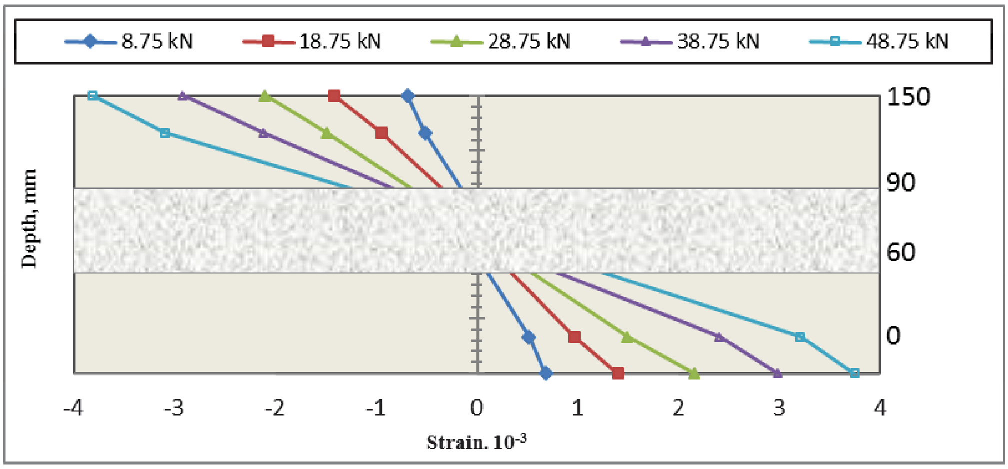


Fig. 9 Load against strains on steel bars



(a) Strain distribution on panel GF1: From experimental test



(b) Strain distribution on panel GF1: From FEA

Fig. 10 Strain distribution across the depth of the panels, at mid-span

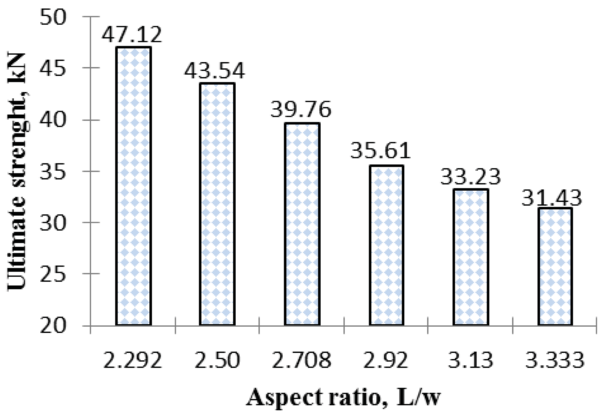


Fig. 11 Ultimate load against aspect ratio (L/b)

C. The Load-Strains on Concrete

The strains distribution across the depth of the panels at mid-span for panel GF1 of L/b = 2.29 at different load stages as obtained experimentally and analytically using FEA models are shown in Figs. 10 (a) and (b), respectively.

At initial load stages, a very small discontinuity of strain across the full depth of wythes for panels GF1 is observed as depicted in Fig. 10. However, the discontinuity changes to become larger just before failure, when the load applied is proportional with the loads approaching. Noticeably, the panels tend to behave more likely as a full composite, as both concrete wythes have only one neutral axis. Hence, this approves that the shear connectors provide an effective stiffness which in turn help to achieve high degree of composite action for the panels. It can be concluded that all panels have achieved full composite action.

D. The Effect of Aspect Ratio (L/b)

The influence of aspect ratio of panels GF1 through GF6 under lateral load applications is shown in Fig. 11. All PFCSP slab specimens had similar dimensions in terms of depth and differed only in span. In the design of PFCSP slab, 0.208 was adopted as a constant increment in aspect ratio (L/b) between the former and subsequent specimen as depicted in Fig. 11. Shorter panels were observed to have a higher capacity in resisting lateral loads than longer panels. The ultimate strength capacities of GF1 of L/b = 2.29 and GF6 of L/b = 3.33 are capable of resisting loads of 47.12 kN and 31.43 kN respectively. Therefore, panel GF1 can resist approximately 50% higher than that of panel GF6, with 1.04 differences in aspect ratio (L/b). Further, the average increase in the ultimate strength capacity of the tested panels was 8.5% with reduction in aspect ratio (L/b) by increasing the span length with only 250 mm difference between previous to the subsequent slab.

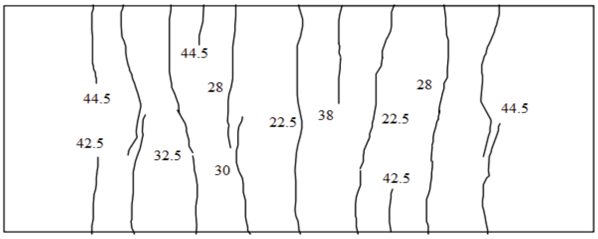
E. Cracking Patterns and Failure Loads

The load was applied with constant increments until failure. The cracking patterns were observed and marked in proportional with the applied load. At each incremental load level, crack lengths were marked and recorded. The first crack and load at failure were recorded together with the corresponding cracking pattern and flexural loads applied. The first cracks appeared at loads of 20 kN, 18 kN, 18 kN, 16 kN, 15 kN, and 16 kN for panels GF1, GF2, GF3, GF4, GF5, and GF6, respectively, at a load of 40%-51% of the ultimate load at failure, as listed in Table I.

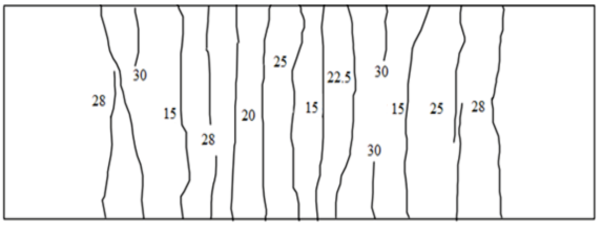
TABLE I
CRACKING PATTERNS AND ULTIMATE FLEXURAL CAPACITY FOR PANELS

Panel	L/b	1st crack, kN	Ultimate Lateral load, kN
GF1	2.29	20	47.12
GF2	2.50	18	43.54
GF3	2.71	18	39.76
GF4	2.92	16	35.61
GF5	3.13	15	33.23
GF6	3.33	16	31.43

The record of crack patterns was initially observed emanating from bottom wythe extending to the top concrete wythe without de-bonding of the top concrete wythe. However, a minor de-bounding was seen in panel GF6 in Fig. 12 (b) which might have occurred due to of the effect of aspect ratio (L/b). In overall behaviour, this is proven that the composite action of the PFCSP slab was highly achieved. The first cracks of the lightweight PFCSP working as one-way slab were observed at a load of 40%-51% of the ultimate load capacity as shown in Fig. 12. All flexural crack patterns were also mostly very minor except that located at the center of the test panel at mid-span line. These cracks widths are increased corresponding to the load increments, especially at ultimate failure load. The reason for the small forms of the developed cracks might be due to the actual behaviour of lightweight in nature as a ductile concrete material used for casting concrete wythes.



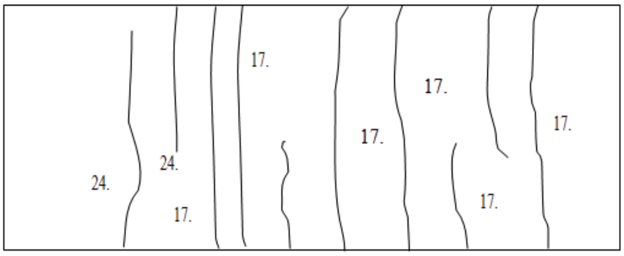
(a) Typical crack pattern for panel GF1 as one-way slab – bottom wythe



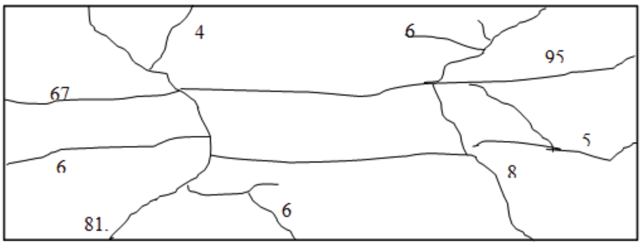
(b) Typical crack pattern for panel GF6 as one-way slab – bottom wythe

Fig. 12 Typical cracking patterns of PFCSP as slab

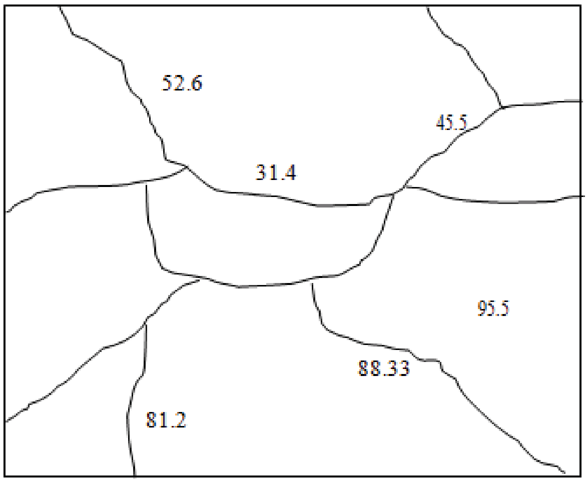
For the sake of clarity, Fig. 13 depicts the typical crack patterns of the PCSP acting as one-way and two-way slab specimens cast using conventional concrete [19]. Reportedly, the cracks were initiated at the bottom wythes for the test panels. However, the one-way panels were revealed typical flexural cracking as displayed in Fig. 13 (a). Flexural cracks appeared in the bottom wythe along the width of the panel. The first crack occurred nearly at a load of 55% of the load at failure. After increasing the loads, it was reported that minor cracks were also seen in the top wythe. Noticeably, the majority of the flexural cracks were exactly developed under the applied line loads and the maximum bending moment was critically at mid-span. Therefore, this report is similar to those recorded in the one-way PFCSP slabs as well as solid slabs. But, in the case of two-way panels, the test panels were simply supported on four sides. The flexural cracks pattern tension zone was found to be similar to those of the two-way solid slabs as illustrated in Figs. 13 (b) and (c). Furthermore, the initial cracks occurred approximately at a load of 60% of the ultimate load at the corner of specimens. In conclusion, it is observed that all tested PCSP slabs failed in a ductile mode because of the tension steel failure due extreme cracks in the tension zone of the bottom wythe.



(a) Typical crack pattern for panel as one-way slab – bottom wythe



(b) Typical crack pattern for panel as two-way slab – bottom wythe



(c) Typical crack pattern for panel as two-way slab – bottom wythe

Fig. 13 Typical cracking patterns of PCSP as slab [19]

V. Analytical Study: The Finite Element Analysis (FEA)

A non-linear finite element analysis (FEA) had become an essential technique to simulate the structural behaviour of reinforced concrete structures for a sustainable and continuous development. The attributes of FEA is employed to verify the degree of accuracy of structural applications used in the engineering practice. In this study, LUSAS was used as application software to carry out the analytical study. The 2-D FEA model of a one-way PFCSP slab was modelled as a 2-D continuum by adopting a 240 mm horizontal cross-section across the full span of the panel as shown in Fig. 9. Foamed concrete and steel (with main reinforcement bars and shear connectors) were modelled by assigning a four noded 2-D isoparametric plane stress element and a 2-D isoparametric bar element, respectively. The areas of steel reinforcement bars and compressive strength values of foamed concrete were inserted and the adopted depths were similar to the actual specimen's details.

A. The One-Way FEA Models

In this model, the one-way slab was simulated in a 2-D continuum by considering a horizontal cross-section along the span, as described in Fig. 14. The FEA idealisation, the boundary conditions and lateral loading are as illustrated in the same figure. The boundary conditions were a roller at one end and assumed hinged support at the other end, where it's similar to experimental test setup as illustrated in Fig. 4. Besides, the vertical translation in (y_{axes}) was restrained at both vertical ends while the horizontal translation in (x_{axes}) was also restrained at only one end which aims to present the actual test arrangement detailed above as shown in Fig. 4. In the study, a non-linear analysis was carried out by assuming the concrete and steel materials chosen are non-linear. However, Multi-Crack and Von Mises plastic models were chosen to model concrete and steel (reinforcement bars and shear connectors), respectively. The crushing failure in compression was neglected and only tensile cracking was taken into consideration. However, this study is aimed to study the influence of aspect ratio (L/t) on the ultimate lateral strength capacity of the one-way PFCSP slab.

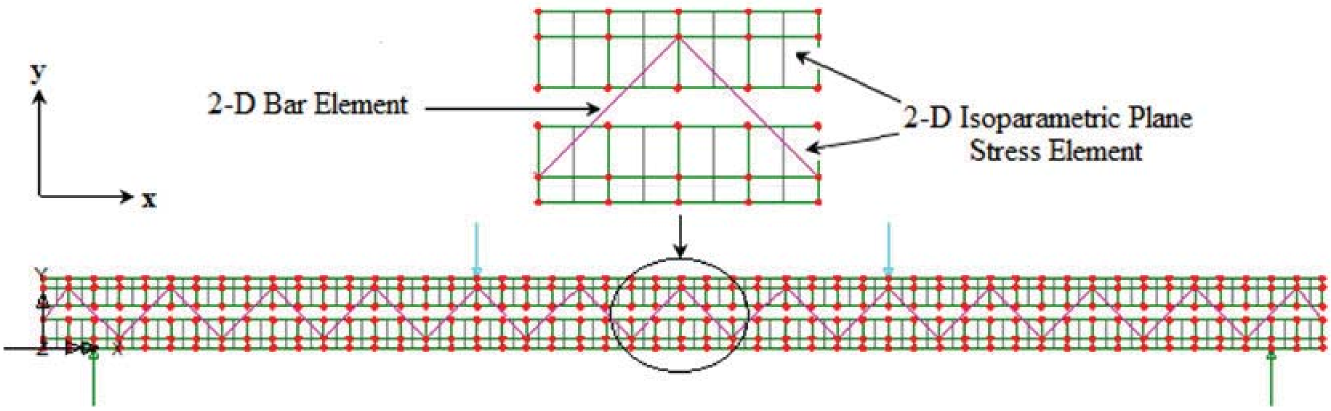


Fig. 14 One-way PFCSP slab idealisation, boundary conditions and loading

B. Validation Using FEA Model

The ultimate load versus mid-span deflection curve of both studies; FEA models and experimental tests at different load stages including the curves of theoretical extremes of fully composite and non-composite actions using classical elastic theory are shown in Fig. 15. Experimentally, it has been observed that the panel GF6 exhibits significant composite behaviour in the early stages till the first crack load, but, after massive cracking occurred, the panels tend to behave as semi-composite until failure.

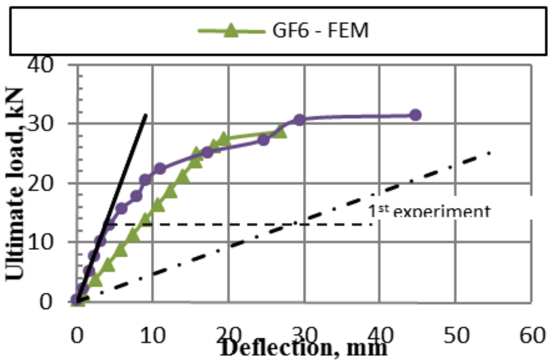


Fig. 15 Load-deflection profile for panel GF6 at mid-span

Analytically, FEA models become considerably stiffer than the actual tested specimens after the cracking occurred, specifically at the final load at failure. However, both studies approach presented a perfect bonding between the concrete and the steel. The difference in the deflection curves might be due to either FEA models had behaved in a stiffer manner or because of unintended errors in setting-up of the laboratory experimental testing. However, the increase in ultimate flexural strength and deflection of experimental results were about 8.5% and 35.7% respectively, in contrast to the FEA data. The comparison of results between the experimental tests and the 2-D FEA models for panels GF1 to GF6 are shown in Table II. In conclusion, the values obtained from experimental tests and FEA models had a significant agreement and high degree of accuracy which is due to the integration by aid of five truss-shaped shear connectors (stiffeners).

TABLE II
COMPARISON OF RESULTS BETWEEN EXPERIMENT AND 2D FEM MODELS

Name of panel	L/b	Ultimate capacity, kN		$\frac{F_u^{Exp} - F_u^{FEM}}{F_u^{Exp}}$
		FEM	Experiment	
GF1	2.29	48.8	47.1	3.46
GF2	2.50	43.0	43.5	1.20
GF3	2.71	36.3	39.8	8.83
GF4	2.92	33.8	35.6	5.22
GF5	3.13	31.3	33.2	5.96
GF6	3.33	28.8	31.4	8.53

VI. Conclusion

`In this paper, the performance of six specimens of PFCSP, acting as a one-way working slab under lateral loads was studied experimentally and analytically. Results obtained from these approaches have led to the following conclusions:

a. An increase in aspect ratio (L/b) from 2.29 to 3.33 has caused a decrease of approximately 50% on the ultimate flexural strength.
b. Experiments show that the first cracks occurred at about 40% –51% of the ultimate flexural load and those cracks were very similar to those in solid slab acting in one-way direction and PCSP as one-way slab.
c. It was discovered that at elastic stage, the panels behaved in a composite manner and semi-composite at ultimate stage due to strengthening by steel truss-shaped shear connectors of 6 mm diameter round bar.
d. All PFCSP slab specimens have shown their ductility, revealing a large deformation just before failure due to its lightweight material origin.
e. An acceptable degree of accuracy is exhibited between experimentally obtained results and analytically using FEA models data.

Acknowledgment

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