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Behavior of concrete members constructed with SHCC/GFRP permanent formwork

Changli Yu, Christopher K.Y. Leung & Qian Cao
Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology

ABSTRACT: To enhance the durability of reinforced concrete structures, high performance concrete with low water/binder ratio is often employed. However, once cracking occurs in the concrete cover due to mechanical loading or shrinkage, water and chloride can penetrate easily to induce steel corrosion. The present study focuses on an alternative approach for the construction of durable concrete members, with the use of permanent formwork. To make the formwork, strain hardening cementitious composites (SHCC) is employed. With 2% of incorporated fibers, the SHCC exhibits multiple cracking behavior in tension, with crack openings controlled to below 60 micron at strain level up to several percent. ith such small crack openings, the transport properties are similar to those of the un-cracked material. n addition to SHCC, glass fiber reinforced polymer (GFRP) can be incorporated into the formwork to provide flexural resistance. n some applications, the member can be made by casting concrete directly on the formwork. n others, a reduced amount of steel reinforcement can be added. With steel protected by the GFRP/SHCC formwork (which acts as part of the cover), high durability can be ensured. In this paper, we will describe the material employed for making the permanent formwork and the method to fabricate U-shape formwork for slabs and beams. Test results on components made with the permanent formwork will be presented. Failure behavior will be discussed and failure load compared to analytical values. An example will also be provided to illustrate the use of GFRP/SHCC formwork in practice.

1 INTRODUCTION

SHCC, also referred to as Engineered Cementitious Composites (ECC), are fiber reinforced composites designed based on fracture mechanics concepts and with the help of micromechanical models (Li & Leung 1992, Li 1993, Leung 1996, Kanda &Li 1999). Through the proper ‘engineering’ of microparameters, the composite exhibits strain hardening behavior in tension with failure strain up to several percents. Tensile failure of the composite is accompanied by the formation of closely-spaced multiple cracks that are controlled to very small openings (normally below 60 microns). According to the experimental results in Wang et al. (1997) and Lepech & Li (2005), cracks with small openings have little effect on the transport properties of the material. In other words, for SHCC made with a matrix with sufficiently low water/binder ratio, high durability can be maintained even if the member surface is subjected to high tensile strain during service.

As the durability of a concrete member is governed by the quality of the cover, SHCC (which is more costly than normal concrete) can be used strategically to prepare permanent formwork first. The member is then constructed by the casting of normal concrete. With a surface layer exhibiting low permeability and high cracking resistance, penetration of corrosive agents can be resisted. Moreover, by replacing wooden formwork, construction efficiency is improved and site wastes are reduced.

To further facilitate construction and improve member durability, the concept can be extended to include glass fiber reinforced plastics (GFRP) rods inside the formwork. The use of GFRP rods with SHCC creates a synergy between the two materials. If normal concrete is employed, the low modulus of GFRP, low bond strength and mismatch in thermal expansion coefficient between concrete and GFRP in the transverse direction will require a minimum cover of 35 mm to prevent the formation of unsightly cracks. The formwork will then be relatively thick and heavy. With the use of SHCC, a small cover to the GFRP is sufficient as crack openings are well controlled. Also, as shown in Fischer & Li (2002), due to the multiple cracking of SHCC which produces fine and closely spaced cracks, the interfacial shear deformation and stresses induced by cracking is significantly reduced. The required bond strength is hence also a lot lower. For components under light or moderate loading, the GFRP rods inside the SHCC formwork will be sufficient to carry the required loading. When the applied loading is higher, steel reinforcements can be added to increase both the load-carrying capacity and the ductility. In this case, the steel is well protected from corrosion as it is far away from the member surface. As a result, high durability of the member can be assured.

When permanent formwork is employed, the interfacial bonding between the cast concrete and the formwork is always a concern. In an earlier paper (Leung & Cao in press), we have focused on the development of flat plate SHCC formwork, to be placed at the bottom of slabs/decks. When GFRP is not incorporated into the formwork, the introduction of transverse grooves on the inner surface is found to be effective in preventing debonding. However, for GFRP/SHCC formwork, interfacial debonding is found to be the dominant failure mode of the final component. To improve the interface bonding, a feasible solution is to introduce a U-shape Permanent formwork to increase the total area of the interface. Furthermore, as the formwork will have a higher moment of inertia with the contribution from the bend up legs, damage during construction handling and transportation can be minimized.

In this paper, the effectiveness of U-shaped formwork relative to flat plate formwork will be studied. In the following, we will first present the material design of SHCC and the preparation of U-shaped formwork. Then, bending test results on beams made with GFRP/SHCC formwork (and with or without additional steel rebars) will be reported, with special attention paid on the load capacity and failure mode. Finally, a design example will be given to illustrate the feasibility of GFRP/SHCC formwork in the construction of lateral spanning deck for footbridges.

2 SPECIMEN PREPARATION

2.1 *Materials*

From the literature, SHCC can be made with polyvinyl alcohol (PVA) fibers at a dosage of 2% in volume. The properties of PVA fiber is shown in Table 1. To ensure uniform fiber distribution and to control the toughness of the matrix, fine silica sand is used in the matrix and no coarse aggregates are incorporated. In this study, 80% by weight of the cement was replaced by fly ash. As fly ash is a waste material, the use of a large amount of fly ash in the SHCC can be considered a 'green' approach (Yang et al. 2007). Some of the fly ash will undergo pozzolanic reaction to improve the long-term transport properties. However, a significant part of the fly ash will not hydrate and can be considered as inert fillers. According to the results in Song & Van Zijl (2004), increased deformability and toughness can be obtained with fly ash addition beyond 40%. Such a trend can be ascribed to the spherical shape of the unhydrated fly ash particles, which can reduce friction along the matrix-fiber interface and facilitate fiber pull-out (rather than rupture). High fly ash content will decrease the compressive strength of SHCC and increase its porosity. In our mix, silica fume is also added, as mixes with silica fume are found to exhibit less ductility reduction in the long term. The mix portion chosen for our test is shown in Table 1. With high content of unreacted fly ash, we expect a high content of distributed pores in the matrix which can facilitate the formation of multiple cracks and thus improve the ductility (Wang & Li 2007). Permeability measurement has been performed on our SHCC mix and a value of $5x10^{-12}$m/s was obtained. In Lepech & Li (2005), a value of $1x10^{-11}$m/s was obtained for a SHCC mix with a much lower fly ash to cement ratio. The results indicate that the porosity in our mix is not highly connected, so it does not have detrimental effect on the permeability.

The stress vs. strain curves for five SHCC specimens tested at 28 days are shown in Figure 1. From the figure, one can define the first cracking strength as the point where the curve exhibits a sharp decrease in slope from the initial linear behavior. The ultimate strength is the maximum stress carried by the material and the ultimate strain is the strain corresponding to the ultimate strength. After the peak load, cracking starts to localize and the rapid opening of a single crack is observed. The ultimate strain is hence a good indicator of material ductility, as the SHCC can be considered as a damaged homogenous material before this strain is reached. As shown in Figure 1, the SHCC mix can reach a ductility of 4.4% in average.

Table 1. Properties of the PVA Fiber.

Diameter	Length	Elongation	Young's Modulus	Tensile Strength
μm	mm	%	GPa	MPa
38	12	6.5	33	1530

Table 2. Mix Proportion of the SHCC Mix.

Material	Proportion
Fly Ash	0.8
Cement	0.18
Silica Fume	0.02
Silica Sand	0.2
Water	0.22
Superplasticizer	0.0051
PVA Fiber	2% in volume

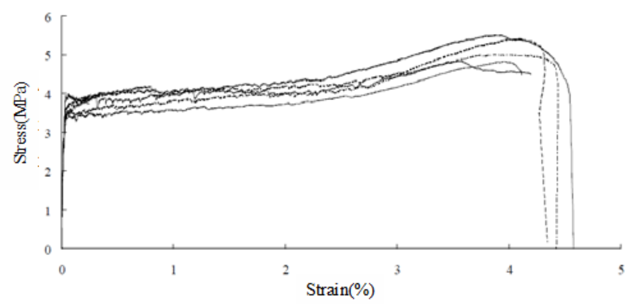


Figure 1. Stress vs. Strain Curves of SHCC Mix.

2.2 *Fabrication of the Permanent Formwork*

Permanent formwork was prepared with the use of wooden moulds. Before casting of SHCC, Aslan GFRP rods (with properties shown in Table 3) were inserted through holds in the end plates of the mould and supported intermittently with spacers. Since the selected SHCC had high workability, the formwork was fabricated without internal vibration or tampering. When the material was still fresh, lateral grooves were introduced on the surface. Flat plate formwork of 30mm thickness was prepared by direct casting into the mould. To make U-shape Formworks, a wood mould as shown in Figure 2 was employed. The mould is assembled of 3 planks connected by 2 hinges. The inner surface of the mould is lined with a rubber sheet so the joints (at the hinged locations) are properly sealed to prevent water and fine particles from leaking out. There is a wooden strip placed along each of the two side planks (See Fig. 2) to maintain a certain thickness of SHCC during casting. At the middle plank, an additional pair of strips (called the thickness adjuster) was placed to allow the casting of SHCC to a higher thickness than that on the sides. At a suitable time after initial setting (determined by trial and error), the thickness adjuster is removed. Since the concrete is stiff enough, the middle part will remain higher than the sides. The two side planks are folded up to form the U-shape formwork. Transverse grooves (Fig. 3a) can be introduced on the formwork surface before or after the sides are folded up. As shown in Leung & Cao (in press), such a simple surface treatment can effectively improve the bonding between the SHCC formwork and the concrete to be cast. For a beam made with plain concrete and SHCC formwork with no GFRP reinforcement, discrete cracks in the concrete are arrested at the concrete/SHCC interface and turned into multiple fine cracks within the SHCC layer (Fig. 3b).

In this study, the thickness at the bottom part of the U-shape formwork is 30mm to provide a proper cover to the GFRP rods inside. The two legs (formed by folding up of SHCC) are 20mm in thickness.

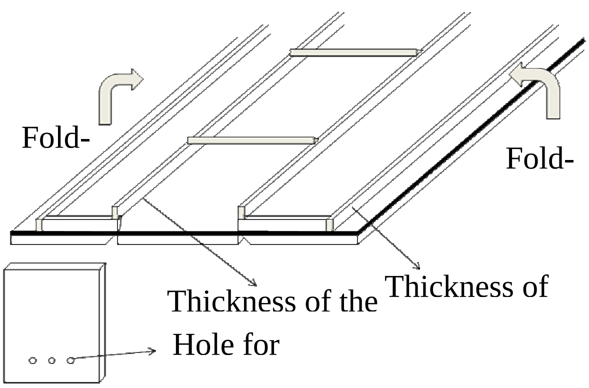


Figure 2. Wooden Mould for U-shape Formwork.

With a reduced thickness, transportation and handling is facilitated by a reduced weight. The formwork cost is also reduced.

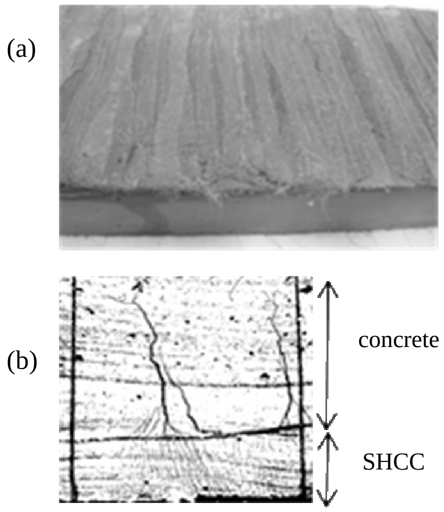


Figure 3. (a) Transverse grooves on the SHCC
(b) Crack control ability of the SHCC layer.

The formwork fabrication process described above has a major limitation. If the vertical legs are over a certain height, self weight of the SHCC will result in a collapse after the wood mould is folded up. A short leg is sufficient for the formwork of slab elements. To make a beam, the formwork can be made by attaching plate elements to the two sides of a U-shape formwork with relatively short leg. A simple demonstration of the idea is shown in Figure 4. The components can be connected by either epoxy or bolts.

Table 3. Properties of GFRP Reinforcement.

Diameter	Ultimate tensile strength	Tensile modulus of elasticity
mm	MPa	GPa
6	825	40.8

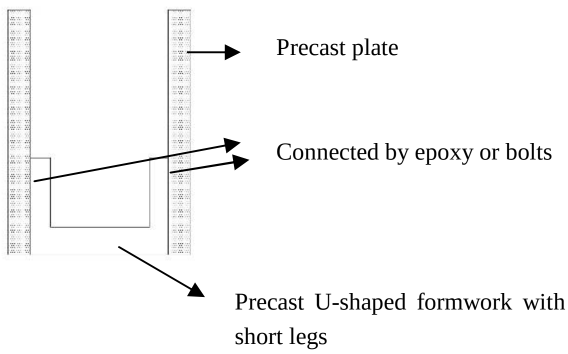


Figure 4. Assembling of formwork for a beam.

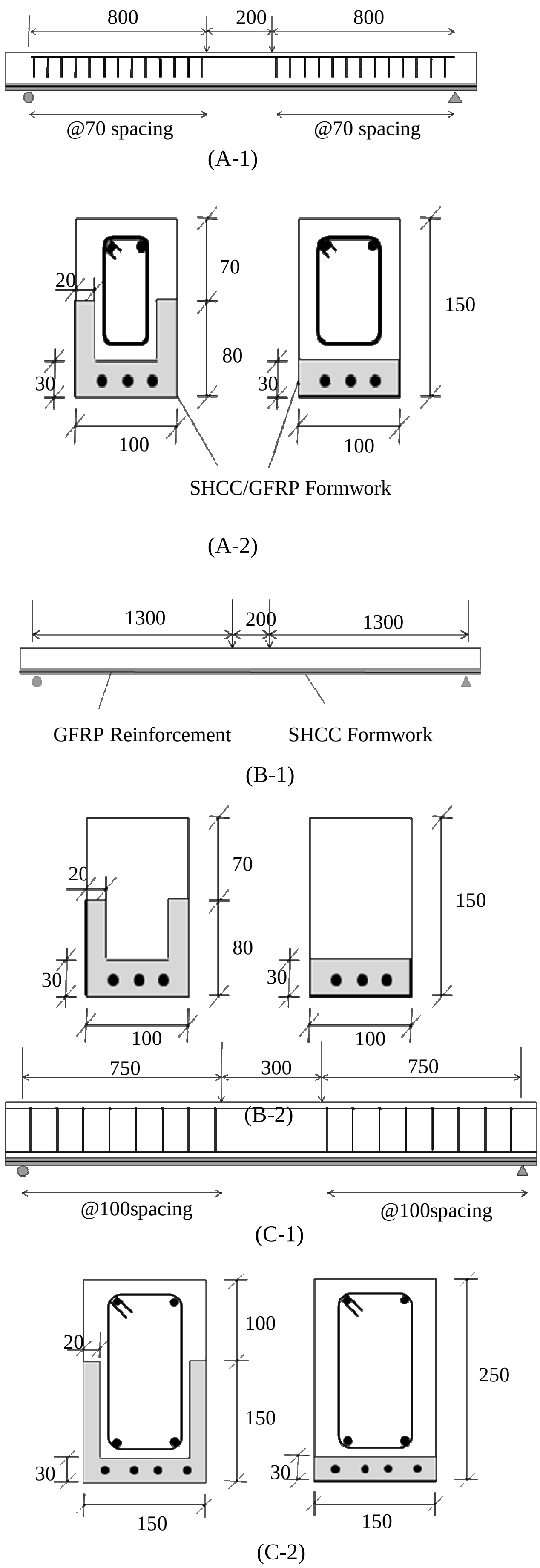


Figure 5. The Testing Configurations and Section Details of Specimens for Slab Specimens (units all in mm).

2.3 *Preparation of Test Specimen*

2.3.1 *Slabs made with GFRP/SHCC Formwork*

To study the application of permanent formwork for slabs, four specimens were prepared in two different shear/span ratios, and with both flat-plate and U-shape formwork. In each formwork element, 3 GFRP rods with 6mm diameter were embedded. The testing configurations and section details of SF1 (slab specimen with flat-plate formwork) and SU1 (slab specimen with U-shape formwork) are shown in Figure 5 (A-1) & (A-2). Mild steels with diameter of 6mm were used to prevent shear failure. Testing configurations and section details of SF2 and SU2 are shown in Figure 5 (B-1) & (B-2). With larger shear span-depth ratio, no stirrups are required for this case.

2.3.2 *Beams made with GFRP/SHCC Formwork*

To study the application for beams, two additional specimens were prepared. The testing configurations and section details of BF (beam specimen with flat-plate formwork) and BU (beam specimen with U-shape formwork) are shown in Figure 5 (C-1) & (C-2). Mild steel stirrups with diameter of 6mm were again used to prevent shear failure. Four GFRP rods (6mm diameter) were embedded in each formwork; two high yield steel bars with diameter of 10mm were used as additional longitudinal reinforcement. In the beam element, the vertical legs do not extend all the way to the top of the member, to simulate the situation with a slab above the beam. If the legs are further extended, the likelihood for debonding between formwork and concrete is further reduced.

3 TEST RESULTS

Load was applied centrally by a 500kN hydraulic jack under displacement control at the rate of 0.5 mm/min. LVDT was used to measure mid-span displacement. The test results for all members, in terms of failure load and failure moment, are summarized in Table 5. The load vs. displacement curves are shown in Figure 6. In both the table and the figure, a design load is shown. This value is calculated from the plane-section-remains plane assumption as in conventional reinforced concrete design. According to the calculation, failure occurs by crushing of compressive concrete in all cases.

3.1 *Specimens with Flat-plate Formwork*

All members made with flat-plate formwork showed significant debonding between the concrete and SHCC formwork. The physical mechanism leading to interfacial debonding is illustrated in Figure 7. When a flexural or shear/flexural crack is arrested by the SHCC layer, the discrete crack becomes bridged at the bottom by the GFRP/SHCC. Considering a free body between the crack and the closer support, one can observe tension in both the GFRP and SHCC that will induce concentrated shear stress along the SHCC/concrete interface. When the shear stress overcomes the interfacial shear resistance, debonding occur as a shear crack propagating along the interface.

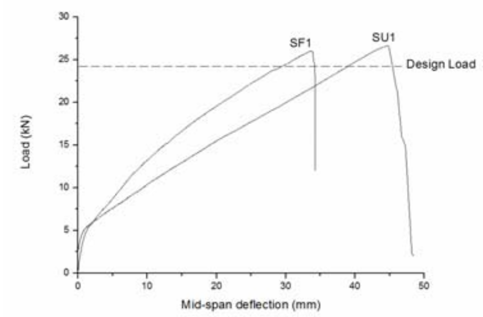
The failure modes of the three members made with flat-plate formwork are shown in Figure 8. Two different kinds of failure can be identified.

(i) Debonding failure

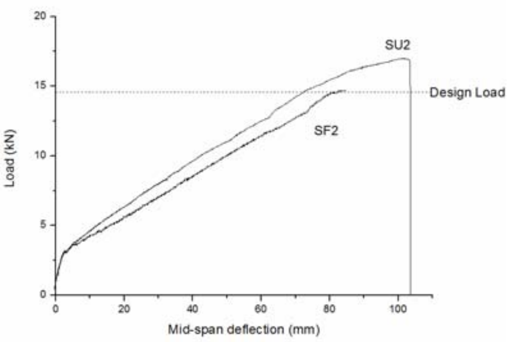
Debonding failure occurs when the interfacial crack propagates significantly along the SHCC/concrete interface to bring along a drop in the load. This kind of failure mode occurs for SF1 and BF members. As one can observe from Figure 6, the load capacity of SF1 reaches the theoretical value despite the debonding, while that of BF is significantly lower than the theoretical design load. If

Table 4. Theoretical Load Capacities and Test Results for all specimens.

Series	Designed flexural capacity	Designed load	Test moment	Test load
	kN*m	kN	kN*m	kN
SF1	9.5	23.7	10.3	25.8
SF2	9.5	14.6	9.6	14.7
SU1	9.5	23.7	10.6	26.5
SU2	9.5	14.6	11	16.9
SF	35.4	94.5	27.4	73
SU	35.4	94.5	39.8	106



(a) SF1&SU1



(b) SF2&SU2

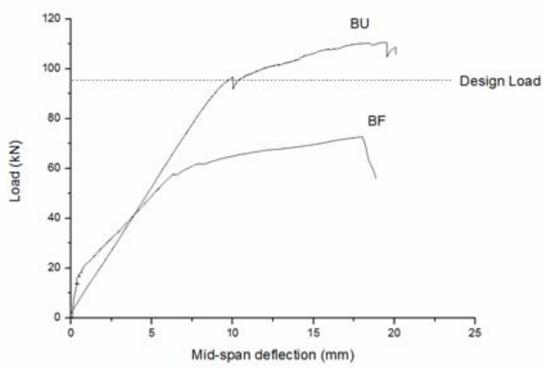


Figure 6. Load vs. Displacement Curves.

debonding does not occur, both members should fail by concrete crushing according to theoretical calculations. SF1 is more over-reinforced than BF. When concrete crushing occurs, the corresponding GFRP force is hence lower. According to the illustration in Figure 7, debonding is easier to occur with a higher force in the GFRP. This explains why debonding occurs pre-maturely in BF, while it takes place at a load similar to that for concrete crushing to occur.

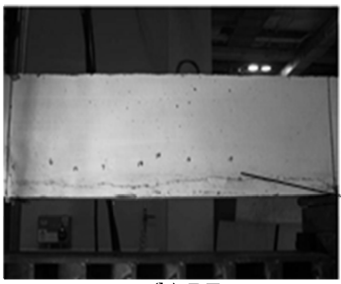
(ii) Flexural failure after debonding

For SF2, debonding was observed during the test, but it remained stable over a part of the interface adjacent to the beam. With increasing loading, the member eventually failed by concrete crushing. In this case, debonding is not the direct cause of member failure. However, as debonding occurs along the interface, the plane-section-remains plane assumption no longer holds. Actually, compared to the case with full bonding, the stress in the GFRP is averaged out over the debonded region and becomes lower in the section with maximum moment. Therefore, when concrete crushing occurs, the load is smaller than that for member SU2 with no interfacial debonding.

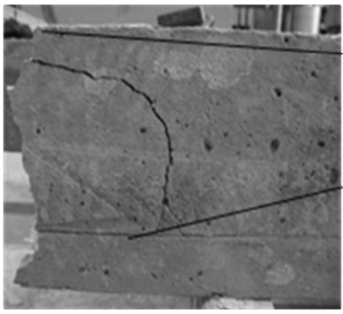
3.2 *Specimens with U-shape Formwork*

One major reason to introduce U-shape formwork is to increase the interfacial resistance, mainly by increasing the interface area. In this regard, the results have been very satisfactory. As shown in Figure 9, all specimens with U-shape formwork failed in flexure. No sign of debonding was observed in SU1&2, while only limited debonding (as shown in Fig. 9(c)) occurred in BU when the ultimate load was approached. In all cases, the load capacity of members made with U-shape formwork is higher than that for corresponding members with flat-plate formwork. The increase is most significant for the beam member (see Fig. 7(c)), where pre-mature debonding significantly reduced the load capacity of member BF. Figure 9(d) shows the typical fine multiple cracks distributed along the specimen besides the major

(a) SF1



(b) BF



(c) SF2

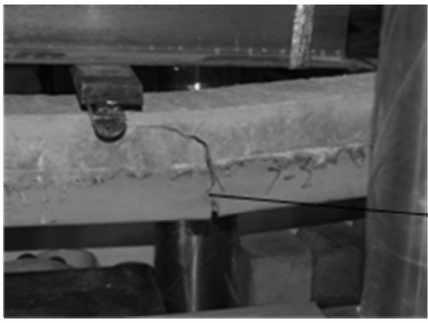
Figure 8. Failure modes of Flat-Plate Specimens.

crack that forms when final failure is approached.

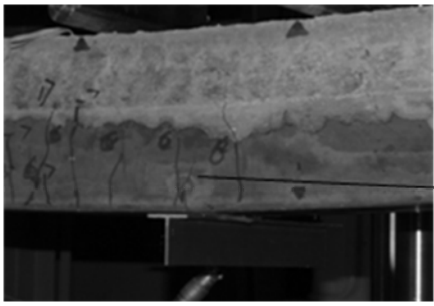
3.3 *Discussions*

Comparing the test results of both slab and beam specimens, the advantage of adopting the U-shape formwork is obvious. By increasing the bonding between the GFRP/SHCC formwork and cast concrete interfacial debonding is effectively prevented. Failure then occurs by concrete crushing in flexure, at an increased load. In practice, the flexural failure mode is also more desirable as debonding is sensitive to the interfacial condition which is difficult to control. As a result, if failure occurs by debonding, one can expect a higher variability in the load capacity, and a higher safety factor has to be used.

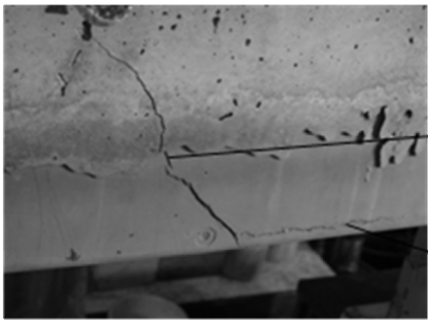
In addition to the prevention of debonding failure, the crack control ability of this U-shape formwork is also remarkably better. A comparison between flat-plate and U-shape Formworks after first cracking is shown in Figure 10. When the flat-plate formwork is used, although the crack is well controlled at the bottom, it can still open significantly on the sides in the concrete above the formwork (Fig. 10(a)). Such kind of cracking is absent above the U-shape formwork.



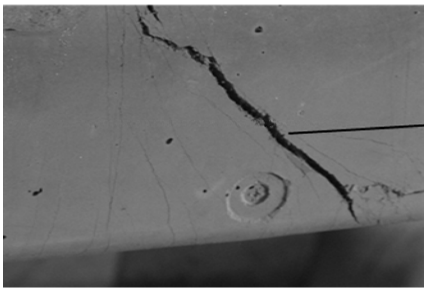
(a) SF2



(b) SF1



(c) BU



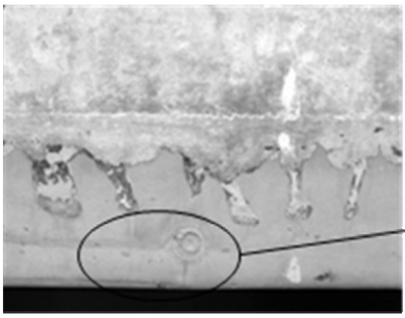
(d) Fine multiple cracks besides the major crack after failure

Figure 9. Failure Modes of U-shape Specimens.

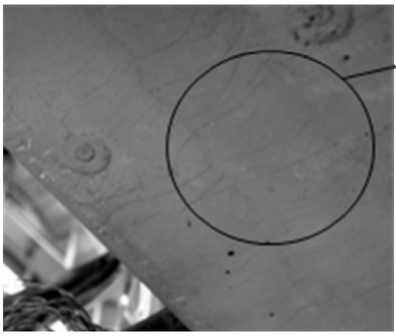
distributed multiple cracks can be observed at the bottom of the specimen (Fig. 10(c)).

In our research program, permanent formwork with both flexural and shear reinforcements has also been prepared. Such formwork is formed by a U-shape formwork with GFRP rods in the longitudinal direction and a pair of side plates with embedded GFRP reinforcements along the vertical direction, connected together as in Figure 3. Testing of these members will be performed soon.

(a) Flat-plate specimen



(b) U-shape specimen



(c) Multiple cracks at the bottom

Figure 10. Crack Control by the formwork.

4 AN EXAMPLE APPLICATION OF GFRP/SHCC FORMWORK

A potential application of GFRP/SHCC formwork is in the construction of the deck of a footbridge under aggressive environment (such as marine environment or cold region where salt is used for deicing). To see if the SHCC formwork investigated above is suitable for such an application, a footbridge of 4m wide and 30m long is taken as example. We assume the use of two edge beams along the longitudinal direction, and so the concrete deck is spanning in the lateral direction. The ultimate design moment is calculated according to BS 5400 (British Standard: Steel, concrete and composite bridges), which specifies a design load of 5kPa for loaded lengths of 36 m and under. For pedestrian traffic on bridges supporting footways and cycle tracks only, the live load shall be treated as uniformly distributed.

For ultimate limit state design, the loads to be considered are the permanent loads, together with the appropriate primary live loads. Under this combination, the partial load factor is 1.15 for dead load and 1.5 for live load. For the sake of calculation, one can consider the deck to be composed of laterally-spanning members 0.1m in width and 0.15m in height, which is identical to the beam members tested in our study. The required moment capacity can then be calculated in the following way:

$$G_k = 24 \times 0.1 \times 0.15 = 0.36\ kN/m$$

$$Q_k = 5 \times 0.1 = 0.5\ kN/m$$

$$DesignLoad = \gamma_k G_k + \gamma_q Q_k = 1.15 \times 0.36 + 1.5 \times 0.5$$

$$= 1.164\ kN/m$$

$$M = \frac{PL^2}{8} = 2.33\ kN \cdot m$$

All the tested slabs in this work failed at a moment beyond the design value of 9.5kN*m, which is about 4 times the required moment capacity calculated above. Even with an additional safety factor of 2.0, the design is still adequate for the footbridge. The above simple calculation therefore illustrates the feasibility of using the permanent formwork in practical applications.

While members made with both flat-plate formwork and U-shape formwork have enough load capacity for the above application, the use of U-shape formwork is preferable for two reasons. Firstly, with U-shape formwork, flexural failure can be assured and the failure load is less variable than the case with debonding failure. Secondly, since the U-shape formwork has a significantly higher stiffness than the flat-plate formwork, the amount of falsework required to support the formwork during construction can be reduced.

In the above example, the GFRP within the SHCC is already sufficient to provide the required load capacity. As no additional steel reinforcements (for both flexure and shear) are required, the site construction only involves the casting of concrete and this can be highly efficient. Also, since there is no steel, the corrosion problem which is a major cause of structural degradation is eliminated.

5 CONCLUSIONS

In this paper, the concept of using GFRP/SHCC permanent formwork to make durable concrete structures is first introduced. Test specimens are prepared with both flat-plate and U-shape formwork. The specimens can be divided into two groups, for slabs which are generally under relatively light or moderate loading, and beams under a higher load which possibly require additional steel reinforcement. With the flat-plate formwork, significant interfacial debonding occurs along the SHCC/concrete interface. On the other hand, members made with U-shape formwork fail in flexure, at a higher failure load. In particular, the failure load of the beam member increases by over 40% when the failure mode changes from debonding to concrete crushing under flexure. A simple design example is then presented to illustrate the use of permanent formwork for making the lateral spanning deck of a footbridge The potential of the GFRP/SHCC permanent formwork for practical applications is hence demonstrated.

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