Pultruded fibre reinforced polymer planks as stay-in-place formwork for concrete structures

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A feasibility study in which a pultruded fibre reinforced polymer (FRP) plank was used as stay-in-place (SIP) form serving as formwork during wet stage and as reinforcement during hardened stage is presented here. First, the strength and stiffness of the FRP plank serving as formwork for concrete casting under construction stage was verified by sand-filling test. Then shear tests were carried out to develop proper bond technique between FRP and concrete, so that they can perform as composite structural member. Thirdly, static tests on beams were conducted to evaluate the load-carrying capacity and failure modes of the proposed hybrid beam. The overall investigation showed the feasibility of using the FRP plank as a SIP formwork.

Keywords: Adhesive and aggregate bonding, fibre-reinforced polymer, stay-in-place formwork.

ONE of the key objectives of construction research is to develop an innovative, economical and efficient method of construction. In recent years the use of composite fibre reinforced polymer (FRP) materials has gained wider acceptance in the civil engineering sector, due to some desirable characteristics such as lightweight, high strength, resistance to corrosion and durability[1–3]. FRP composites, as a mature technology, have been widely used to repair/retrofit/reinforce damaged/degraded concrete structures[4,5], such as steel reinforced concrete (RC) beams or columns by externally bonding FRP sheet(s) onto the surface of substrate concrete structures[6,7].

Developments in the use of FRP in construction have led to the concept of FRP structural stay-in-place (SIP) formwork systems. This is a permanent participating formwork system which is structurally integrated with concrete. It acts as self-supporting formwork during construction, and as structural reinforcement once the concrete hardens. The concept of using FRP composites for structurally integrated SIP formwork maximizes the advantages of both FRP and concrete while simplifying the construction process and reducing construction time and labour cost. Structural system will make appropriate use of FRP in tension and concrete in compression. A significant cost-saving can be achieved using FRP SIP forms, as they reduce labour cost and time related to putting and stripping of conventional formwork. In flexural members, the FRP plank act as primary reinforcement, thus reducing the need for steel reinforcement. The inherent durability of FRP can increase the lifespan of structures[8]. Thus, its use will reduce life-cycle cost and frequency of replacement[9].

Recently, a state-of-the-art article that provides a broad perspective of FRP SIP formwork specifically for bridge decks has been published[10]. Several field applications have been reported in the literature, including the Salem Avenue Bridge in Ohio[11], Route US-151 Bridge in Wisconsin[12], Greene County Bridge in Missouri[13], and the Black River Falls Bridge in Wisconsin, USA[14]. Several studies have been carried out with FRP SIP forms of various configurations. These include flat plates[15], flat plates stiffened by bonded hollow square sections[16–18], flat plates with T-shaped ribs[19–22], thin plates bonded to the bottom of a layer of grid reinforcement[23], corrugated plates with pin-and-eye interlocking joints[24], and FRP box section[25]. The studies show a huge potential for the hybrid FRP and concrete construction, where each material is optimally used. The cost and time effectiveness using SIP formwork promises a great impact on the Indian economy. New FRP profile manufacturing industries using the pultrusion process are now coming up in India. Pultrusion is an economical and continuous method of fabricating FRP profiles of a constant cross-section by pulling out a mixture of fibres with a thermosetting resin through a heated dye that compacts and cures the material into the desired shape. With the manufacturing of FRP planks in India, the construction cost is expected to reduce further, and hence overall economy will be achieved.

However, the major challenge in this construction is the interface bond developed between prefabricated FRP and cast-in-place concrete after the setting of concrete, called wet bond. Studies have been carried out to develop means to improve the wet bond between cast-in-place concrete and FRP. Aggregate bonding, adhesive bonding and mechanical anchors are some of the bonding methods that can be used to secure composite action between cast-in-place concrete and FRP plank. In aggregate bonding, first a layer of adhesive is applied on the plank and then

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aggregates are spread over it[19,26–28]. The plank is allowed to cure for 2–3 days and then concrete is poured over it. In adhesive bonding, adhesive is applied on the plank and concrete is poured over it within the pot life of adhesive[20,22,24,29,30]. In case of mechanical anchor bonding, FRP or steel rods are used as studs projecting out from the FRP plank to be used as formwork[15]. Since FRPs are designed as thin-walled structural members, stress concentration introduced by the mechanical anchors could be large that leads to premature failure of the section[15].

It has been observed that both aggregate and adhesive bonding systems lead to significant increase in the ultimate load[19,20,22,24,26–30]. Also, in both these bond mechanisms, adhesive plays a significant role in achieving bonding and hence choice of adhesive can be crucial. All the previous studies regarding the bond between FRP stay-in-place formwork and concrete concentrate on the mechanism used for bonding the two materials[19,20,22,24,26–30]. The studies were performed using only one adhesive without any justification relating to the choice of a particular adhesive. Also, the authors relied on the specifications provided by the manufacturer of the adhesive. However, Zhang *et al.*[31] concluded that the choice of adhesive has the great impact on wet bond. Therefore, there is a need for proper testing of adhesives for their suitability under wet bond.

This article presents results of an investigation aimed to check the feasibility of FRP profile manufactured in India as SIP formwork. Due to high initial tooling cost for fabrication, the plank was chosen out of already available FRP configurations. The plank was originally designed to be used as a walkway. Experimental investigation regarding the suitability of the profile as SIP formwork was done in three stages. In the first stage, sand-loading test was conducted to check if the deflections under concrete weight were within the permissible limits so that it can be used as a formwork during casting of concrete. In the second stage, different kinds of commercially available adhesives were studied for their efficacy in developing wet bond with concrete through aggregate and adhesive bonding. Finally, in the third stage, the role of the SIP formwork as reinforcement was investigated through a flexural test.

Experimental investigation

A commercially available glass FRP (GFRP) plank with a base plate integrated with *T*-ribs, normally used for short walkways, was selected for SIP formwork (Figure 1). This profile was selected because the *T*-shaped longitudinal ribs will not only increase the section stiffness when compared to a flat sheet, but will also serve as an embedded mechanical anchor at the FRP–concrete interface. Tensile test (according to ASTM D 3039) and volume fraction test (according to ASTM D 2584) were conducted separately for the FRP base plate and *T*-ribs. The base plate and stiffeners had average tensile strength of 375.5 and 352.3 MPa respectively, and fibre volume fraction for these two parts was determined to be 0.35 and 0.30 respectively. Young's modulus was tested for the base plate and stiffeners separately at various levels and the average values were found to be 27.9 and 23.8 GPa respectively.

Stage 1 – Performance verification of FRP SIP formwork under construction stage

The formwork should be designed so as to remain perfectly rigid during placing and compaction of concrete. According to Indian Standard IS 14687–1999, falsework for concrete structures guidelines, the total calculated deflection (δ) of the formwork shall not exceed 3 mm up to a beam span length of 3000 mm. For beam span length greater than 3000 mm, permissible deflection should be least of 30 mm or $L/1000$.

Sand-loading test: To check the strength and stiffness of the proposed pultruded section as formwork, concrete cast was simulated by sand-filling test. For this, 3.2 m length of the pultruded plank was used and both ends were rested on supports. The test was conducted for two different support arrangements. In the first arrangement (three-span test), 3.2 m plank was used as three-span formwork system with two intermediate supports (Figure 2 *a*). In the second arrangement (two-span test), the plank was used as two-span formwork system with one intermediate support (Figure 2 *b*). Steel side forms of height 0.15 m were placed around the plank to facilitate uniform sand-loading condition up to a height of 0.15 m. The load was further increased using ten 50 kg cement bags, placed one by one in two layers over the complete plank

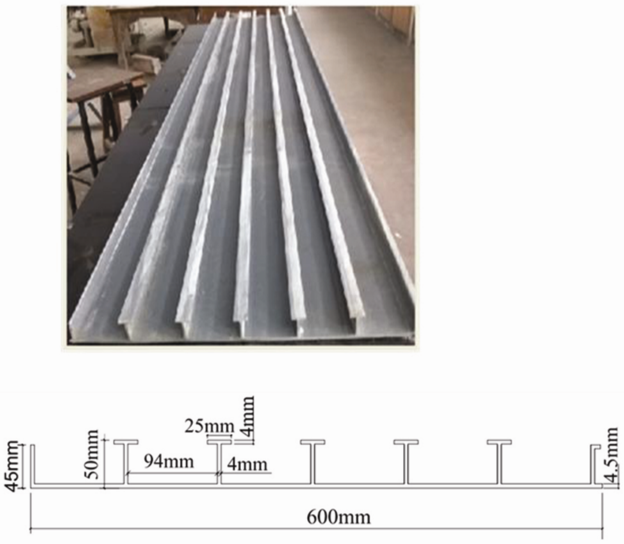

Figure 1. The fibre-reinforced polymer plank.

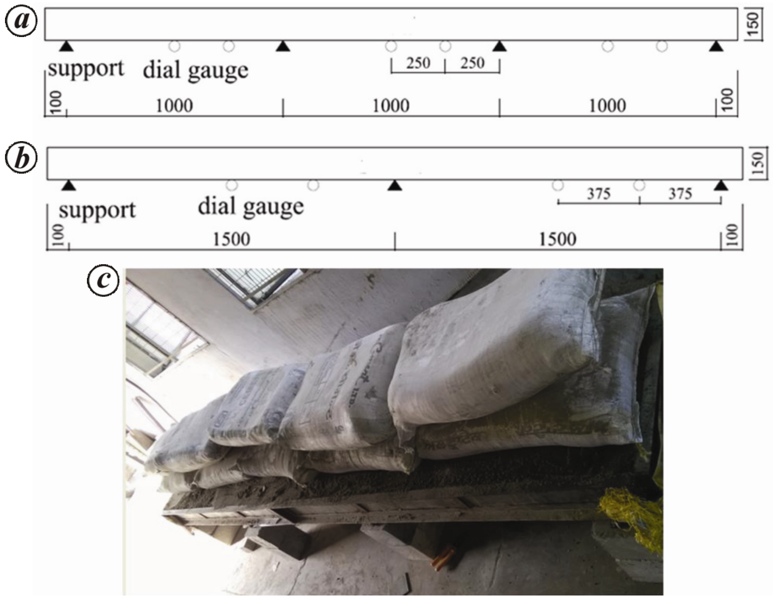

Figure 2. Sand-loading test. ***a***, Three-span testing (all dimensions in mm); ***b***, Two-span testing (all dimensions in mm); ***c***, Experimental set-up for three-span testing.

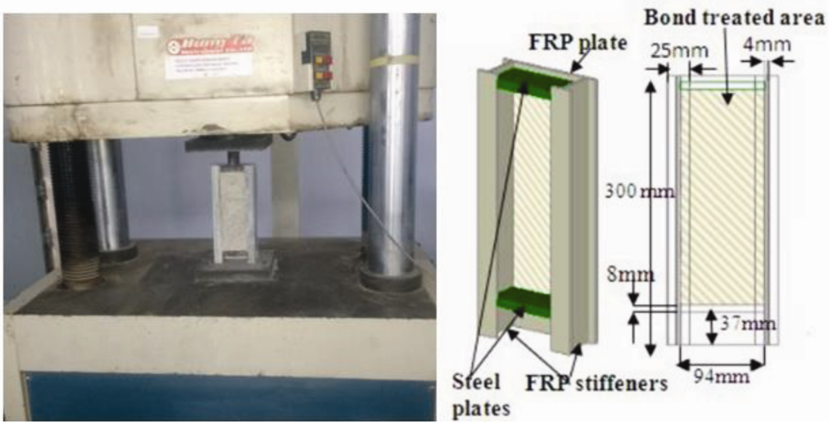

Figure 3. Shear test set-up and specimen details.

(Figure 2 *c*). Vertical deflection was monitored using digital dial gauges at one quarter and one half of each span in both test set-ups (Figure 2 *a* and *b*).

During sand loading, deflections were measured after pouring and spreading a batch of 50 kg of sand uniformly on the plank. Deflection increased almost linearly with load for all dial gauges in both test set-ups. After 400 kg sand-pouring, maximum deflection obtained was 0.37 mm for the three-span test and 0.89 mm for the two-span test. After placement of 10 cement bags (500 kg), maximum deflection reached 1.1 mm in the three-span test and 2.85 mm in the two-span test. Deflection obtained in both tests was within the permissible limit of 3 mm for 3 m span, according to Indian Standard IS 14687–1999. The limited deflection obtained during sand-loading test demonstrates the structural feasibility of the plank to be used as SIP formwork.

Stage 2 – Bond between cast-in-place concrete and FRP formwork

Sound bond between FRP formwork and wet concrete is the most influential parameter in the concrete–FRP hybrid system in which concrete is used in compression and FRP in tension. In this study, comparison is made between untreated FRP–concrete interface and bond-treated FRP–concrete interface through shear test. In bond-treated interface, two different bond techniques have been examined: (1) aggregate bonding and (2) adhesive bonding.

Three types of adhesives were chosen for both aggregate bonding and adhesive bonding in the present study. Table 1 presents the mechanical properties of epoxy resins provided by the manufacturer. Adhesive *A* was selected as part of the test matrix as it possesses excellent

Table 1. Mechanical properties of adhesives

Properties	Adhesive nomenclature *A*	 *B*	 *C*
Epoxy content	Two-part epoxy	Three-part epoxy	Two-part epoxy
Glass transition temperature (°C)	65	62	–
Elasticity modulus (GPa)	1.27	1.1	5
Tensile strength (MPa)	40	45	15
Elongation at break (%)	4.5	2.2	0.4
Pot life	120 min	30 min at 25°C	45 min at 25°C
Viscosity	Flowable	Viscous	Viscous

water and alkali resistance, and has long tack-free time (pot-life) of 120 min of application of bond layer. This would help in laying concrete even after 120 min, whereas in other two adhesives, concrete has to be poured within 30–40 min of mixing of base with the hardener. Moreover, it is flowable in comparison to adhesives *B* and *C*; so it is comparatively easy to apply on the FRP surface. Adhesive *B* is an epoxy structural adhesive used for bonding of GFRP plates to concrete substrata. Adhesive *C* is a solvent-free, moisture-tolerant, thixotropic, two-part structural adhesive and is used as repair mortar.

The first step of the fabrication was to cut the FRP planks to appropriate dimensions (length 300 mm and width 120 mm) with a horizontal base and two vertical ribs (Figure 3). The average thickness of the base plate was 4.5 mm and that of the *T*-ribs was 4 mm. Vertical *T*-ribs served the purpose of two side forms, and for the other two side forms, steel plates of comparable dimensions were placed between the vertical ribs on both sides. The steel plates were placed such that the concrete could be cast for a length of 240 mm, giving a clearance of 15 mm from the top and 45 mm from the bottom of the specimen. The clearance at the top was provided so as to accommodate the *T*-section loading plate used to transfer the load to concrete. The clearance at the bottom helped in the free movement of concrete after shear failure of interface bond.

Thereafter, bond coating was applied on the surface of the plank so as to make aggregate bonding or adhesive bonding specimen. In order to create aggregate-bonded interface, the adhesive was first applied on the desired surface of the plank and then aggregates of size 1.18–2.36 mm were scattered on the wet adhesive to cover almost the total area. Aggregates were then hammered lightly so that maximum contact between aggregate and adhesive was achieved. The adhesive–aggregate hybrid plank was allowed to cure for three days and then concrete was cast on the plank. In adhesive bonding, adhesive was applied first and then concrete was poured within the pot-life period of the adhesive, when it was in the wet stage.

It is to be noted that bond treatment was applied between the ribs of the plank on the bottom horizontal surface only. No epoxy or aggregate was bonded to the protruding vertical ribs on either the flanges or the webs of the ribs. Concrete was then cast over the aggregates and cured for 14 days. Self-compacting concrete with strength 42.5 MPa was used and all samples were cast using the same batch of concrete so that its properties were same for all specimens. After 14 days of casting, shear tests were carried out in duplicate on the specimens. Untreated interface specimens were referred as control specimens (C). Bond-treated specimens were abbreviated using the two alphabet and one digit notation: first alphabet corresponds to the bond type, second alphabet refers to adhesive type followed by digit specifying specimen number. Bond type refers to *D* for aggregate bond and *W* for adhesive bond. For example, *DA1* represents specimens with aggregate bonding using adhesive *A* and first sample of that type.

The test was carried out under force control mode of loading and the rate of loading was 5 kN/min. Each specimen was installed in a universal testing machine vertically (Figure 3) and was subjected to pure compressive force, causing direct shear at the interface. Stress versus strain was plotted and failure mode was observed for each sample.

Test results and discussion: Ultimate capacity and failure modes were observed for all seven test series. Different failure modes were obtained for specimens failing at different load-level range. Table 2 shows the ultimate load and deflection for each specimen. FRP–concrete interface failure was observed in control samples. In FRP interface failure, clean FRP sheet was obtained with no traces of concrete and clean concrete prism was obtained without any shear or flexural crack at very low load, i.e. around 5 kN. No noise was heard during failure.

With interface treatment, failure load increased considerably, depending upon the adhesive used and mode of treatment. However, interface failure was still observed in some specimens at various load levels depending upon bond strength. Interface failure of these specimens can be further divided in two categories.

(i) FRP–adhesive interface failure: In this type of failure, clean FRP sheet (Figure 4 *a*) was obtained with almost no traces of adhesive. The adhesive layer remained attached to the concrete and the FRP surface was totally

Table 2. Specimen summary and load capacity

Specimen ID	Bond mechanism	Adhesive used	Ultimate load (kN)	Deflection (mm)	Failure mode
C1	–	–	5.25	0.50	Fibre-reinforced polymer (FRP)–concrete interface failure
C2			5.3	0.45	
DA1	Aggregate bonding	*A*	23.91	1.19	FRP–adhesive interface failure
DA2			23.08	1.08	
WA1	Adhesive bonding	*A*	41.19	1.52	FRP–adhesive interface failure
WA2			44.07	1.54	
DB1	Aggregate bonding	*B*	62.3	1.04	Mixed-mode interface failure
DB2			63.59	1.05	
WB1	Adhesive bonding	*B*	69.91	1.30	Adhesive–concrete interface failure
WB2			72.53	1.26	
DC1	Aggregate bonding	*C*	72.56	1.23	Adhesive–concrete interface failure
DC2			75	1.18	
WC1	Adhesive bonding	*C*	89	1.27	Concrete failure
WC2			79.32	1.53	FRP failure

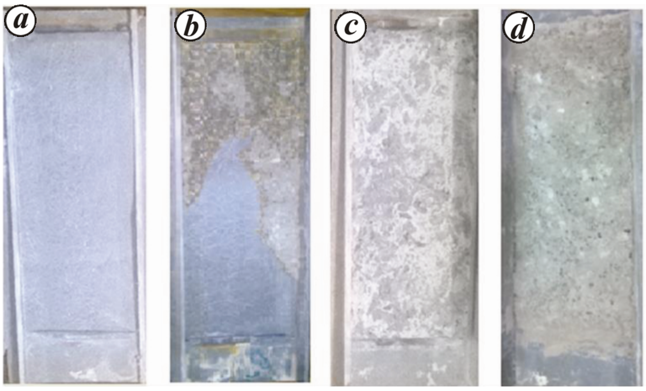

Figure 4. FRP plate after shear test in case of (***a***) FRP–adhesive bond failure; (***b***) mixed failure; (***c***) Adhesive–concrete bond failure and (***d***) concrete failure modes.

clean, indicating a poor interface bond between concrete and FRP. Failure was sudden with a loud noise. Specimens with adhesive *A* (both *DA* and *AA*) failed due to FRP–adhesive interface failure. This indicates that adhesive *A* shows good bond with concrete, but not with FRP. Thus, it is unsuitable for concrete–FRP bonding. From Table 2, it can be seen that *DA* series specimens failed at relatively low load levels of around 20 kN and *WA* series specimens failed at around 40 kN load. Adhesive *A* is flowable in nature with a very low viscosity, so a very thin adhesive layer might have been created. The thin layer was not able to bond sand grains securely with FRP. Thus *DA* series showed poor interfacial bond. In case of adhesive bonding using adhesive *A*, when wet concrete was poured over the adhesive due to its flowable consistency and higher pot-life some of the adhesive floated up, leaving the FRP–concrete interface. This resulted in weak interface. Though performance of adhesive *A* was better than the control specimen (in terms of stiffness and ultimate stress), it showed a poor performance in comparison to the other two adhesives with higher viscosity.

(ii) Concrete–adhesive interface failure: Failure plane shifted to adhesive–concrete interface with increase in the bond strength. In this type of failure, FRP was essentially covered by the adhesive and a thin layer of mortar with very fine aggregates (Figure 4*c*). Failure was sudden with a loud noise, but few warning noises were heard which might be due to concrete mortar separation. This type of failure was shown by two types of bonding procedures: adhesive bonding using adhesive *B* (*WB*) and aggregate bonding using adhesive *C* (*DC*). The *DB* series showed a mix failure mode, i.e. a part of the adhesive–concrete interface and the FRP–adhesive interface failed (Figure 4*b*). In case of adhesive *B* also, adhesive bonding showed a 12% higher load-carrying capacity in comparison to aggregate bonding.

The *WC* series specimens showed the highest load-carrying capacity and exhibited material failure, i.e. failure either in concrete or in FRP. Thus, it was not bond failure and so the limit of interfacial bond strength was achieved with adhesive bonding using adhesive *C*. Thus, for any further enhancement in the load capacity of the specimens the strength of the constituent materials has to be increased. In *WC*1, concrete failure occurred (Figure 4*d*). Occasional low-intensity cracking sounds became continuous as the failure load approached. Ultimately, the specimen failed with a very loud noise. In concrete failure, cracks passed through the concrete disintegrating it and a thick concrete layer remained attached to the FRP. In *WC*2, delamination in the FRP plate and consequent local buckling were noticed. These started in the bottom portion of the specimen, i.e. in the area between the loading platen and concrete.

In this region, FRP alone carries all the load in compression. Thus, FRP buckling occurred with FRP delamination separating the base from the stiffeners (*T*-ribs). This is the outcome of non-uniformity in the quality of commercially available FRP. Throughout the buckling period, continuous cracking noise was heard. However,

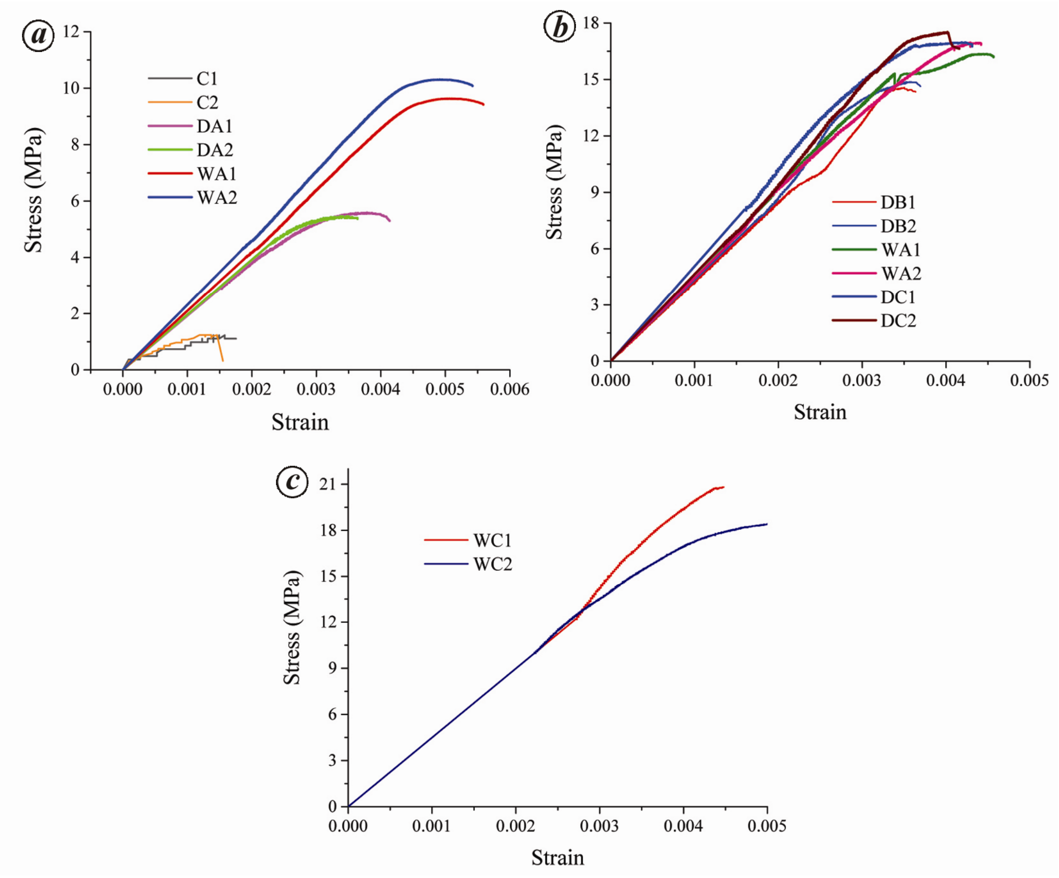

Figure 5. Stress–strain plot for different failure modes. ***a***, FRP–adhesive interface; ***b***, Concrete–adhesive interface; ***c***, Material failure.

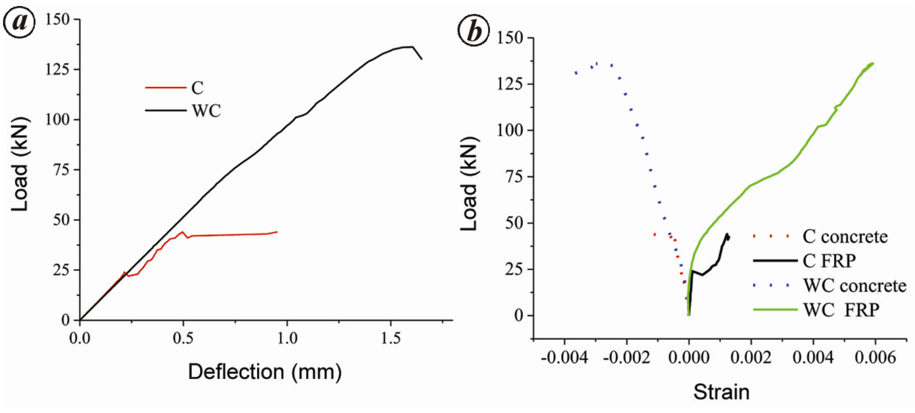

Figure 6. Comparison between bond treated and untreated specimens. ***a***, Load–deflection plot; ***b***, Load–strain plot.

*WC*2 specimen carried at least 90% load compared to that of *WC*1. Thus, this defect in FRP has not cut down the capacity of the specimens by a large extent. Moreover, in the SIP formwork, FRP is used as the tension reinforcement. Therefore, compression force is not anticipated in it.

Stress vs strain was plotted for all specimens showing the same failure mode (Figure 5). Here stress represents force per unit cross-sectional area. Strain was calculated as measured deflection (UTM readings) per unit length of the specimen. Samples with adhesive *C* showed the best results. Adhesive bonding showed better performance than aggregate bonding in terms of ultimate load and failure mode, irrespective of the type of adhesive used. There was not much difference in the stiffness of aggregate bonding and adhesive bonding. FRP–concrete bond strength varied greatly depending upon surface treatment and type of adhesive. Thus bond treatment is essential for the role of FRP as SIP formwork. It is to be noted that the properties claimed by manufacturer (Table 1) are not in accordance with the results obtained. This might be due to different test methods adopted by the manufacturer or due to the difference in bonding properties in wet and dry concrete bonding. The properties specified by the manufacturer are for dry bonding.

Stage 3 – Role of FRP SIP formwork as reinforcement

The feasibility of using the system as structural formwork, i.e. to act as reinforcement was investigated experimentally by conducting flexural test. The most effective bond mechanism (adhesive bonding technique using adhesive *C*) was used for casting concrete over FRP planks. Beams of dimensions 700 mm × 150 mm × 150 mm were cast using the FRP SIP formwork. No other tensile or shear reinforcement was used in the beam. The first step of the fabrication was to cut the plank according to the dimensions of the beam. A 150 mm wide portion of the plank was cut from the centre consisting of one *T*-section in the middle. Thereafter, adhesive was spread on the base plate and on top surface of the *T*-section of the plank (*WC* beam). No epoxy was applied on the vertical rib of the *T*-section. Side forms were then put around the FRP specimen. Casting of the beam was done using self-compacting concrete with 28 days compressive strength as 50 MPa. Along with the adhesive-bonded specimen, a control beam (C) with no bond mechanism was also cast. The control specimen was cast as it was intended to show the difference between the specimens with or without bond techniques. The beams were tested after 28 days of casting and curing. The testing was done on UTM under three-point load configuration. The centre-to-centre spacing of the support was 650 mm. Deflection was recorded using digital dial gauges at the centre of the span. Longitudinal strains of concrete and FRP at the centre were measured using strain gauges.

Figure 6 *a* shows the load–deflection plot and Figure 6 *b* shows load–strain plot for the tested specimens. Three criteria, i.e. initial cracking load, crack pattern and ultimate load were considered to investigate the role of FRP as reinforcement and to justify the need of proper bond mechanism for the composite action between FRP and concrete. The initial cracking load was identified by change in slope of load deflection curve and a visual crack was observed near that load. In control specimens, initial crack was observed near the centre at 20 kN load. The adhesive-coated specimen showed much higher cracking capacity of 85 kN. This indicates that the bond treatment can significantly increase the moment capacity of the concrete beam. The crack observed in the control specimen was flexural in nature, with a major vertical crack at the centre. In case of adhesive-bonded specimen, shear-inclined crack was observed starting near the end support. The control specimen showed lesser ultimate capacity (44 kN) than that of adhesive-coated specimen (136 kN). In case of adhesive-bonded specimen, the compressive strain level at the top surface of concrete reached 0.003, which is generally accepted as the failure strain of concrete (Figure 6 *b*). Failure strain in concrete was around 0.0015 for the control specimen, which provided evidence that there was no concrete crushing in the control specimen. Failure mode for control specimen was flexural failure with significant visible slip at the SFRP–concrete interface (Figure 7). Shear-type failure mode was observed in case of bond-treated (*WC*) specimen. Bond treatment helped in achieving perfect bond between FRP and concrete, and FRP played the role of reinforcement. The failure was due to horizontal shear failure at the junction of the *T*-section and the bottom plate. The ultimate capacity of bond-treated specimen was around four times that of control specimen. Thus, FRP plank using adhesive bonding can serve as an effective tensile reinforcement.

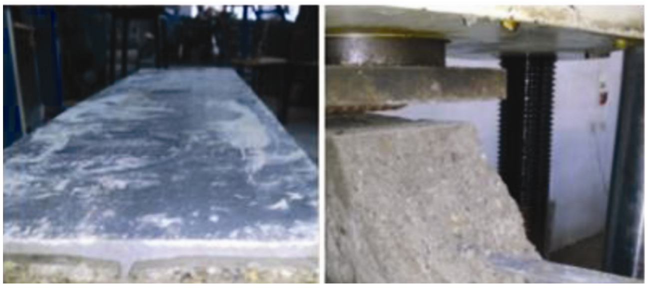

Figure 7. Failure modes in flexural testing.

Conclusion

This article investigated the feasibility of GFRP plank for the role of SIP formwork. A commercially available plank was used to limit the cost of the system.

(1) Using readily available GFRP planks as SIP formwork is feasible provided suitable bond treatment is provided to ensure sufficient bond strength between FRP and concrete. The plank performed within the Indian Standard IS 14687–1999 recommended limited deflection for formwork. This confirms that GFRP plate has sufficient strength and stiffness to bear construction loading.

(2) FRP–concrete interface bond strength is strongly dependent on bond treatment technique and choice of adhesive. Both aggregate and adhesive bonding improved the bond between FRP and concrete. However, adhesive bonding performed marginally better than aggregate bonding in terms of ultimate load and failure mode. It is more convenient to use and with adhesive bonding it was possible to shift the failure from the interface to concrete. Thus, a limit of interfacial strength was reached.

(3) Use of the FRP plank without bond treatment as a tensile reinforcement resulted in significant slip between

concrete and considerably less capacity during testing. The adhesive-coated plank with suitable adhesive performed well as tensile reinforcement. Thus, it can be used as SIP formwork.

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