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# An investigation on bond between FRP stay-in-place formwork and concrete

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## HIGHLIGHTS

- Experiments on bond between FRP stay-in-place formwork and concrete are conducted.
- Effect of adhesive type has been explored using both adhesive bonding and aggregate bonding.
- The interfacial strength has been estimated using a finite element model.
- Failure mode and ultimate strength depends upon the type of the adhesive.
- At the limiting state the failure mode shifted from the interfacial to concrete failure.

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## ABSTRACT

FRP stay-in-place (SIP) formworks are designed to act as a support for casting concrete and as a tension reinforcement when the concrete is cured. For composite action between the formwork and concrete, proper bond between them is essential. This investigation focuses on the role of adhesives for the bond development. Two different bond mechanisms, aggregate bonding and adhesive bond, are investigated using three different adhesives. A novel experimental set up is prepared to evaluate the bond. The load capacities and failure modes were examined. Load–deflection, load-slip and load-strain curves have been plotted to evaluate the bond mechanisms. A finite element model is developed that is able to accurately predict the ultimate pullout load and load-slip relationships. The results show that the types of resins have a great impact on the bond. It is recommended to use the wet-bond technique with special adhesives.



## 1. Introduction

Fibre Reinforced Polymers (FRPs) have proved to be useful to structural engineers due to their excellent physical and mechanical properties, including corrosion resistance, low self weight, and high tensile strength [1]. In the last few decades research has demonstrated its capability in enhancement of bending and shear [2–5] capacities of flexure elements. Its ability in improving concrete confinement in compression members is demonstrated [6]. In these applications FRP sheets or laminates are bonded externally on the concrete surface. More recently, FRP have been used in new construction in the form of pultruded sections such as plates, rods and gratings that can be near-surface mounted or externally bonded [7–10]. The inherent resistance to electrochemical corrosion of FRPs makes them particularly well suited for infrastructure applications subjected to harsh environmental exposures [8,9]. This advantage makes FRP structural stay-in-place (SIP) formwork systems particularly useful. SIP formwork is a permanent participating formwork system which is structurally integrated with the concrete and acts as a self-supporting formwork during construction. They may remain exposed to environment with little loss of service life of the structure. Nelson et al. [11] have reported several field applications of SIP including the Salem Avenue Bridge in Ohio [12], Route US-151 Bridge in Wisconsin [13], Greene County Bridge in Missouri [14] and the Black River Falls Bridge in Wisconsin [15]. Use of FRP SIP can benefit tremendously for two reasons 1) speed of construction and 2) resistance to environmental corrosion. Prior research [16–23] has demonstrated that the use of FRP SIP formwork can leverage the advantages of FRP in tension and concrete in compression. However, the bond between the prefabricated FRP and cast-in-place concrete must be ensured for the composite action.

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The commercially available bonding agents have been developed for application on solidified concrete to adhesively bond a thin FRP sheet or strip. However, in the SIP application concrete is poured over the FRP. Thus, the bond mechanism is fundamentally different. Researchers have reported two kinds of bonding: 1) adhesive bonding and 2) aggregate bonding. In case of adhesive bonding the surface of the formwork is coated with the resin and concrete is poured over it while the resin has not hardened. In case of aggregate bonding a layer of aggregates is applied on top of the resin and allowed to cure. Concrete is poured over the bonded aggregates. Hall and Mottram [16] found that adhesive bonding leads to considerable increase in ultimate bond strength while Shao et al. [24] revealed that wet bond using epoxy adhesive has similar load carrying capacity as the dry bond (FRP bonded to already cured concrete). Keller et al. [20] performed flexural tests on FRP-concrete bridge deck panels and concluded that adhesive bonding leads to 104% increase in load capacity. Nelson et al. [25] reported 30% increase in deck strength and 73% increase in initial stiffness by using adhesive bonding at the FRP–concrete interface. On the other hand, Fam and Nelson [26] reported that adhesive bonding on corrugated plates used as SIP formwork led to significant increase of stiffness but very little improvement in ultimate strength. Through double shear tests Zhang et al. [27] pointed out that the type of adhesive has a great impact in case of adhesive bonding.

In aggregate bonding, the formwork is first prepared with adhesively bonding one of the aggregates of concrete prior to pouring concrete. This results in a polymeric bond between the FRP and the aggregate, while the concrete and the aggregate are bonded mechanically. Thus aggregate bonding develops of two interfaces, one between the FRP and aggregates and the other between the aggregate and fresh concrete. Dieter [28] highlighted the need of uniform coverage of aggregates on the SIP. It was perceived that the regions where the aggregate bonding was missing suffered severe slippage. Bank et al. [19] revealed that as flexural members, the FRP planks with aggregate bonding as bond mechanism, performed better than the steel reinforcements in initial cracking moment capacity, flexural crack distribution and ultimate load carrying capacity. Chao et al. [29] pointed out that shear bond performance can be improved by using smaller aggregate sizes with high distribution density. Experiments by He et al. [30] led to conclusion that shear bond of sand coated surface treatment was better than that of cross bars penetrated through the T stiffeners.

Our survey shows that FRP SIP formwork has been used mainly in large bridge projects. The main aim of this research is to explore its use as a simple solution to culverts and crossovers of spans limited to 3 m. To avoid additional cost of development a combination of a commercially available FRP plank and standard adhesive systems have been used. Prior research also reveals that application of the resin plays a pivotal role in the success of the system. This paper accomplishes two principal objectives (a) examining performance of three different adhesives and (b) two different techniques of application, adhesive bonding and aggregate bonding. A novel experimental setup has been developed to perform the pull shear test. Load–displacement, load-slip and load-strain curves along with failure modes have been compared. Finally, a finite-element numerical simulation was conducted using ATENA software to capture the experimental phenomena and facilitate design of the concrete-FRP composite structure.

## 2. Experimental investigation

A commercially available GFRP plank is used in this investigation as SIP. Two different kinds of bond mechanisms are used: adhesive boning and aggregate bonding. Each bond mechanism is investigated through three different kinds of adhesives. In adhesive bonding only adhesive was applied on the FRP and then concrete was poured within the pot life of adhesive. In aggregate bonding at first adhesive was applied on the FRP followed by sprinkling of the aggregate. The adhesive was allowed to cure for specified periods. Concrete was poured over the aggregate and cured. The specimens were subjected to a pull force that produces shear at the concrete-FRP interface. The modes of failure, displacements and strains have been observed.

### 2.1. Materials

The FRP used as SIP is a commercially available pultruded GFRP profile consisting of plates with T-shaped ribs (Fig. 1). The plank with T-ribs was selected as T-ribs stiffen the plate and help it to bear the weight of wet concrete. Moreover, the ribs would also offer mechanical anchorage with the cured concrete. Different samples of the plate and the stiffeners of the SIP taken from different locations were tested for volume fraction, tensile strength and Young's modulus according to ASTM D 2584 and ASTM D3039. The results show that the tensile strength of the strips are lower than expected based on the fibre volume fraction. After the layers of the pultruded section were separated it was noticed that it had facing layers of chop strand mat, which adds to the fibre volume but not to strength. Several samples were tested to examine the variation in strength and it was found to be within the acceptable limits (see Table 1).

Manufacturer's specifications for the properties of the adhesives are in Table 2. The selection of adhesives was based on properties like tensile strength, Young's modulus, bond strength and ease of application. Adhesives with longer pot life are easier to apply as they allow more time at site. Adhesive A has a long pot life of 120 min along with low viscosity and flowable consistency. This results in laying of concrete with ease. B is an epoxy based structural adhesive with considerably lower pot life of 30 min at 25 °C and is used for structural bonding of GFRP plates to concrete substrates. C is also a two part epoxy resin system and is solvent-free, moisture tolerant and thixotropic with a pot life of 45 min at 25 °C.

All specimens were cast using concrete of compressive strength of 50 MPa. All casting were from the same batch to maintain low tolerance levels in the specimens. Self compaction was used to avoid the use of vibrators as it would have affected the bond treatment and moreover to ensure uniform flow of concrete underneath the T-stiffeners. The concrete mix proportion was 1 (cement):0.43 (water):1.5 (fine aggregate):0.94 (coarse aggregate with maximum size 10 mm):0.015 (water-reducing admixture). A sulphonated naphthalene polymers based admixture was used as water reducing admixture.

### 2.2. Specimen preparation

The GFRP planks have been cut to a U shape profile consisting of the base plate and two stiffeners at the two sides. The schematic view of section is presented in Fig. 2. The length of the sample was 300 mm and width 120 mm. To fit the specimen in the tensile testing machine a rectangular cut was made in the bottom 40 mm base plate along with the stiffener. To maintain symmetry, other stiffener was also cut at that location. The corners of the cut were carefully rounded off to minimise stress concentration. The GFRP plank was used as formwork for concrete with stiffeners as side supports. The other two ends were supported with steel plates. Thereafter, the bond treatment was applied on the surface of the plate. The bond was applied on the plate only and not on the stiffeners. Concrete was cast for a length of 240 mm leaving a distance 45 mm from bottom and 15 mm from the top. Two types of bond treatments were applied, aggregate bonding and adhesive bonding. In adhesive bonding only a thin layer of the adhesive was applied directly on the plate without roughening or sanding and then after about 10 min, concrete was poured over it. In case of aggregate bonding initially the adhesive was applied on the surface of the plate and then sand grains (sieved to obtain size between 1.18 and 2.36 mm) were scattered evenly over the entire surface of the wet adhesive. To ensure proper contact of sand grains with the adhesive they were lightly pressed. The adhesive was allowed to cure till it hardened completely for two days. The loose

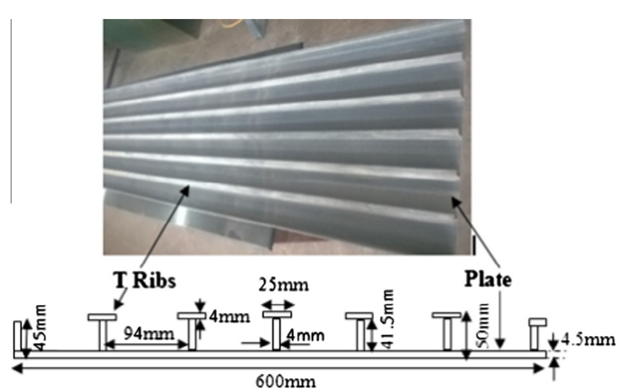


**Fig. 1.** The FRP plank.