SPLICING OF FRP STAY IN PLACE STRUCTURAL FORMS IN FLEXURAL MEMBERS

A Thesis Submitted in Partial Fulfillment of the Requirement for the Award of the Degree of

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Submitted by

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DECLARATION

I, Devansh Jindal hereby declare that the work presented in this thesis entitled **"SPLICING OF FRP STAY IN PLACE STRUCTURAL FORMS IN FLEXURAL MEMBERS"** in partial fulfilment of the requirement for the award of degree of **Master of Engineering** in the field of **Infrastructure Engineering** submitted at Civil Engineering Department, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala is an authentic record of work carried out under supervision of **Dr. Reema Goyal, Lecturer** and **Dr. Shruti Sharma, Associate Professor,** Department of Civil Engineering, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala from January to July,2019.
The matter presented in this has not been submitted either in part or full to any other university or institute for the award of any other degree.

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ABSTRACT

One of the important purposes of construction research is to develop a creative, ingenious, economical and efficient method of construction. Stay-in-place (SIP) formwork is such a system that is not required to be removed upon hardening of concrete. SIP structural formwork is a permanent formwork system which is structurally integrated with concrete. It acts as self-supporting formwork during construction and remains to act as reinforcement after the concrete hardens.

This research broadly investigated the role of FRP stay in place formwork for concrete straight slabs. In this study aim was to check the behaviour of GFRP planks having Butt joint as SIP formwork for beams & slabs.

Experimental investigation regarding the suitability of the FRP SIP with single cover Butt joint using adhesive (Ark 336) and bolts has been done by flexural testing of beams and slabs.

First of all, suitability of adhesive for making the Butt joint was investigated by tension coupon test. Strength of joint using Ark 336 adhesive was more than that by using Araldite as adhesive. In first stage, five beams and two slabs were casted having Butt joint with different configurations using bolts and adhesive (Ark 336). Ultimate load carrying capacity and deflection were measured under two-point loading.

Load carrying capacity of beam having Butt joint in longitudinal direction using adhesive (Ark 336) is more than that of control beam. Similarly for Slab having Butt joint in longitudinal direction using adhesive (Ark 336) is more than that of Slab having Butt joint in longitudinal direction with bolts. From the failure mode of the two slabs, it was concluded that failure mode is brittle. This study demonstrates that the Butt jointed FRP plank has the potential to serve as formwork and as tensile reinforcement for concrete slabs.

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CHAPTER 1: INTRODUCTION

1.1 FRP STAY IN PLACE

In civil engineering, the applications of sophisticated composite materials have been increasing slowly, especially for financial reasons. High manufacturing costs lose their main advantages, such as strength to weight ratio, custom design attributes and free form that exceed those of the conventional civil engineering products, and the high level of chemical resistance in most of the civil environments. In addition, full replacement of standard structural member with general sophisticated composite parts has shown that the use of sophisticated composites in civil building is hard to justify, not only economically but also structurally . However, over the previous few years, several innovations have altered this situation. Methods such as filament winding, resin transfer molding, pultrusion and semi-automated large part manufacturing have led in improvements in the production of low-cost FRP (Fiber Reinforced Polymer). In combination with conventional structural elements rather than the individual component replacement or the complete advanced composite designs, designs of these new materials have also shown that the technical efficiency can be achieved within competitive financial constraints.

Fiber-reinforced polymer composites, primarily created for an aerospace and defence industries, are a class of materials with excellent potential for civil building use. Since the very first composite bridge superstructure was built in Miyun, China in 1982, a broad variety of civil engineers ' recognition as a fresh composite construction material has resulted . In recent years, strengthened polymer composites from fibre have proven their usefulness in a few fields of application: primarily in the form of strips and sheets for retrofitting current bridge structures, as well as reinforcing bars and removing steel as reinforcing used in concrete. In latest years large number of structures have been made in which traditional materials for structural components have been substituted by FRP composite materials.

The development of a creative, ingenious, economical and effective construction technique is one of the significant purposes of construction studies. Conventional strengthened concrete structures are manufactured using temporary forms usually made of wood or steel where concrete casting is performed. Temporary shoring or scaffolding structures usually hold these forms in location. Once the concrete is hardened, the formworks are separated and the concrete structure within is exposed. In latest years, the use of FRP SIP formwork, which is also known as permanent formwork that remain structurally integrated with the concrete and provide the general structure with structural strength, has become popular . These forms are component of the permanent structure instead of being removed after setting. During the construction phase, the forms act as a self-supporting formwork and act as structural strengthening throughout the structure's lifetime. The main benefit of SIP type form construction’s is that, its extra velocity and easy way of construction of which they provide over standard formwork. These SIP forms are the most frequently form prefabricated concrete. The erection and removal of standard formwork and its related false work is often costly, possibly dangerous, and poses important technical issues in some instances. In some circumstances, using continuous formwork from SIP could considerably reduce these expenses and hazards. Furthermore, removing conventional rebar cages can simplify the engineering and detailing method significantly (Ralph and Denton, 2004), as well as save significant time and energy during building. It can also help improve the sustainability of the system by eliminating reinforcements of corrosion-prone steel.

The structural system with FRP SIP forms would make the use of FRP in the tension and in the compression it uses concrete appropriately. Eliminating typical strengthening can considerably simplify the process of engineering and detailing as well as save considerable time and effort during construction. It can also assist enhance the system's longevity by eliminating corrosion-prone steel reinforcements. Several open structural formworks have been studied in latest years that can be used as SIP formworks and have a corrosion resistant property. It should be observed that in structural applications, relative to steel, FRP materials still have a comparatively short track record. As such, there is yet to be verified their long-term durability. These formwork kinds are prefabricated in factories using a method called pultrusion and their mass manufacturing is essential as they must be used in large numbers at the site. It is also comparatively light weight, so forms can be transported, maneuvered and assembled without the help of heavy equipment by a few workers. Because these shapes have great rigidity and dimensional stability, the need for scaffolding or shoring is significantly decreased or totally eliminated. In order to compensate for the high initial price of FRP forms, it is necessary to take into account its multiple benefits such as sophisticated construction activity and erection speed, and decrease of the structure's maintenance cost owing to superior life cycle and durability

1.2 ORIGIN

It has been discovered from prior research that the use of FRP planks as continuous formwork serving as both formwork and reinforcement works well when some bond treatment is given between concrete casting and FRP formwork. To obtain composite action between the two, the perfect bonding between the two is needed. The earlier research, however, was restricted to straight flexural members. Therefore, in order to cast structural members with complex setup from an aesthetic and with structural point of perspective, study of FRP plank performance as SIP formwork is needed for practical considerations of joints and splicing.

In this study, 5 beams & 2 slabs having splices with different configurations have been selected. The most important parameter is to check strength of the joint under flexure loading of GFRP formwork. Experimental investigations according the suitability of plank as SIP formsfor beams & slabs was to done in single stage. Basic purpose of this investigation is to check the efficiency of different splices when using GFRP planks as permanent flexible formwork. Different splicing arrangements have been suggested and check for flexural performance.

1.3 OBJECTIVES

The main purpose of this study is to explore the efficiency of pultruded GFRP segments as a structural open formwork on-site for concrete flexural members and to research the logistic detail that emerge during the development of such a structural system. The primary subjects of this research are:

1. To investigate experimentally the ability of proposed GFRP plank as formwork and as reinforcement for beams & slabs.
2. To compare the mechanical performance of different joint arrangements of GFRP planks.
3. To monitor the cracks and failure pattern in GFRP planks in different joint arrangements in beams and slabs during flexural testing.

1.4 OUTLINE OF THESIS

Chapter 2: In this chapter, literature review of various properties of GFRP plank like bond performance, durability, flexural properties , FRP SIP forms in bridges & splicing of FRP SIP structural forms is presented.

Chapter 3: Details of the experimental program and various experimentation procedure conducted with GFRP plank are given in this chapter.

Chapter 4: The results of the experimental analysis are presented and discussed.

Chapter 5: In this chapter various conclusions drawn from the present research work is presented.

CHAPTER 2: LITERATURE REVIEW

2.1 GENERAL

This section usually reviews the studies carried out on open structural formwork stay-in-place for flexural strengthened concrete members. First, a short introduction is provided on staying in place formwork. A short introduction is then provided on open stay in place formwork. The section discusses in specific the different processes of bonding between FRP SIP formworks and concrete, as well as the FRP profiles that can be used as structural forms. It also reviews the different new methods used in bridge decks by FRP SIP formwork . Fiber-reinforced polymers (FRPs) include load-bearing fibers implanted in a polymer matrix and the reason for using strengthened polymers is to achieve maximum benefit from the reinforcement fibres. Due to the large selection of fiber reinforcements, orientations, and polymer matrices, the characteristics of FRPs can be developed across a broad spectrum. The reinforcement fibres generally dominate the mechanical characteristics, in particular the composite's tensile strength and rigidity. The fiber volume fraction determines dimensional stability and creep resistance under load. In FRPs, two polymer resin kinds are used as matrices: thermoplastics and thermosetting polymers. When heated, thermoplastics melt and when cooled solidify. In comparison, thermosets heal indefinitely at high temperatures through irreversible cross-linking. The most significant of these are unsaturated polyester (UP) resins, phenolic resins ,epoxy (EP) resins and vinylester (VE) resins. The polymer encapsulates the fiber to fix the fibers in the required direction, to transfer the loads to the fibers and to stop the fibers from buckling. It also seals the surface of the fiber and prevents moisture from dropping down along the fiber.

After casting the concrete, SIP formwork is not needed to be removed. Using permanent formwork construction velocity rises as time is saved to remove the formwork. It also leads to labor cost savings. The durability characteristics of concrete are also improved with the use of SIP formwork. The formwork is assembled on site, linked to various accessible connections, bracing is also performed and concrete is then poured. The bracing is set aside after the concrete setting and the SIP formwork remains at its place and provides external casing. The accidents that occurred while removing forms are avoided with the use of SIP formwork. Using SIP formwork therefore results in quick, cost-effective and secure construction.

The Stay-In-Place (SIP) formwork divides into two classifications:

(a) Stay in place Structural formwork – These are the types of formworks that demonstrate composite behaviour with the structure and participate in resisting live loads during service as well as loading during casting. It can simply be said that they act both as reinforcement and formwork for the framing system.

(b)Stay in place Non-structural formwork – These are the sort of formwork that only withstands the loads that come at the time of casting and also the live loads during construction until concrete is laid. Economically compared to non-structural SIP forms, structural SIP forms are better as they reduce the quantity of material owing to the decrease in the price of material needed as reinforcement .

As a material for retrofitting and structural integrity, FRP has labeled its position in the construction industry in latest years (Ramana et al. (2000); Hadi et al. (2003)). In the current scenario, FRP is not limited to retrofitting material, but also as structural material (Alagusundaramoorthy et al. (2006); Grace et al. (2013)). The abstraction of FRP structural stay in place forms scheme was taken into consideration due to the advances in the FRP sector . A state-of - the-art paper on the implementation of FRP SIP for bridge decks (Nelson et al. (2014)) has been disseminated. There are numerous field applications discussed in the FRP literature, including the Greene County Bridge built in Missouri (Matta et al. (2006)), the Salem Avenue Bridge built in Ohio (Reising et al. (2004)), the Black River Falls Bridge built in Wisconsin (Olivia et al. (2007)) and the US-151 Bridge built in 2007.

2.2 BOND BETWEEN FRP SIP FORMWORK AND CONCRETE

Hall et al. (1998) worked with FRP SIP open formwork on a hybrid concrete-FRP section. Corrugated FRP sheets can be used as floor panels, which can be used as floor panels integrated with tension reinforcement and as continuous open SIP structural shaping for the concrete slab, as shown in Fig.2.1. Then the cast hybrid beam made of concrete-FRP was screened with a bending of four points. It was discovered at the very original point that there was some horizontal shear slippage between the surface of concrete and FRP. Due to presence of big strain lag between the FRP and surface of concrete, this horizontal shear slippage significantly decreases the member's flexural ability.

Adhesive bonding was implemented in an effort to cope with the above-mentioned issue. This was accomplished by applying adhesive (epoxy mortar) straight to the FRP formwork surface before the concrete was poured. This adhesive was Specially made for bonding with the fresh wet concrete. During favorable bending, the resulting scheme showed monolithic behavior. Fig.2.2 shows the plot for mean shear stress versus slip. The observed failure mode was diagonal tension shear cracking, which happened in the concrete owing to the lack of shear reinforcement. Tension cracking was critical in the lack of the FRP sheet's longitudinal stiffening ribs. Overall, it appears that the idea of applying adhesive to the formwork before pouring concrete has produced beneficial outcomes. From a manufacturing point of view, it was an advantageous method because it reduced the use of mechanical shear studs or the use of aggregate bonding on the formwork surface, because both of them are very time consuming to install than adhesive bonding.

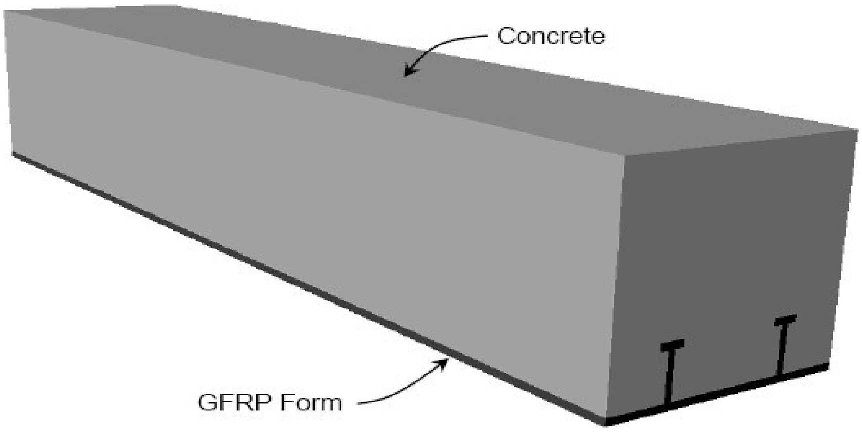


Fig.2.1 Concrete and GFRP Ribbed Sheet Hybrid Section (Hall et al. (1998))

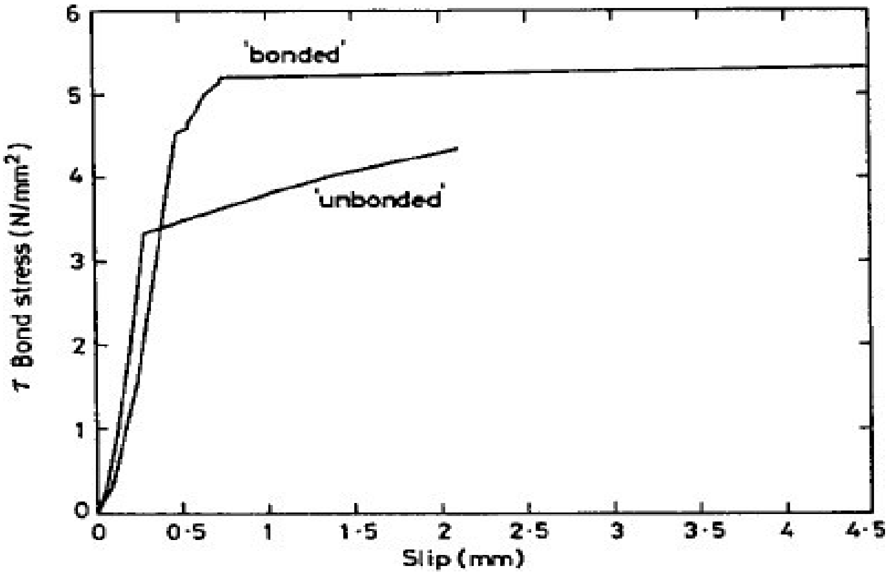


Fig.2.2 Average Bond Stress with Slip *(Hall et al. (1998))*

Dieter et al. (2002) conducted a survey on various FRP formworks and bridge deck FRP reinforcement. The stay-in-place hybrid concrete-FRP open structural formwork and reinforcement of the FRP grid were used. A pultruded FRP sheet with hollow FRP box segments (Fig.2.3) running along the length provides stiffness and is used as tensile reinforcement and plays the function of open structural SIP formwork for the cast concrete slab. For areas where negative bending moments occur, the top longitudinal reinforcement is provided by a bi-direction grid integrated with pultruded FRP components . In order to obtain sufficient bond between the FRP SIP formwork and concrete slab cast over it, it is necessary to roughen the FRP formwork surface before pouring the concrete together with the coating of an epoxy-gravel mixture. This was discovered to have a declining impact on the results of the bond. A very critical slippage was discovered in the locations where the bond mechanism was absent between the FRP surface and the concrete slab. Consequently, the areas where the flexural crack pattern was absent from bonding were very much predominant than the bonding areas.

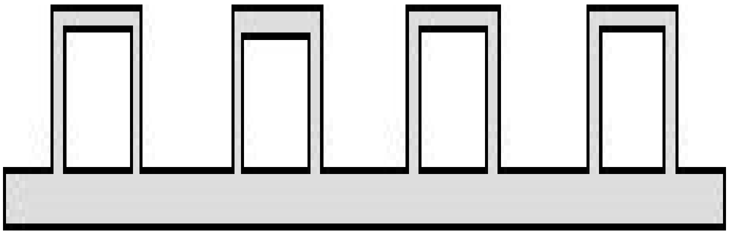


Fig.2.3 Selection of Formwork used **(*Dieter et al. (2002)*)**

Bank et al. (2006) addressed the pultruded polymer strengthened FRP plank which can be used as a formwork and as a reinforcement for a concrete member in the tensile region. The research was affected by the construction of a new bridge being built in FRP planks in Wisconsin as both continuous formwork and as reinforcement. The main requirement was to have a bond between the FRP plank and concrete for the composite action to be achieved between FRP plank and concrete (Fig.2.4). Aggregates bonding was introduced to accomplish this bond at the interface. Two types of aggregates that are sandand gravel have been used. In order to obtain the aggregate, a commercially accessible adhesive was used. Using pultruded FRP plank, concrete beams of various lengths have been cast and limit the use of shear reinforcement in beams. Two control beams were casted. One control beam was without aggregate bonding and the other control beam was cast traditionally using strengthening and FRP plank.

Fig.2.5 indicates the size of strengthened beam samples manufactured by the FRP plank. Appropriate bond has been accomplished between FRP plank and concrete and depends on the beam length, flexural or shear failures that happened during the test. Based on the outcomes, a concrete beam's original cracking moment capacity was improved in the case of coated FRP plank and demonstrated to be an advantage to a bridge deck in terms of serviceability variables. The sand-coated FRP plank specimen showed greater original cracking ability with respect to the gravel-coated FRP plank specimen showing even interface or soft surface for sand-coated specimen. Using aggregate bonding, it was discovered that it is proven to be a system for distributing cracks and transferring bond stress between the plank and the concrete on the ground.

It had been discovered that aggregate bonded FRP plank can also be used to an efficient tension reinforcement and demonstrates very comparable distribution of flexural cracks as shown by inner steel reinforcements. As far as the original cracking moment capability is concerned, the capacity to distribute flexural cracks and ultimate load carrying capacity demonstrates better outcomes than the steel reinforcement of the aggregate bonded FRP plank samples. The samples casted without any surface treatment led in significant slippage during testing between concrete and FRP and have much less load carrying ability. The ultimate capacity of the aggregate coated FRP plank samples was greater with respect to the control samples. Fig.2.6 and Fig.2.7 show the failure mode of all samples. This research demonstrates that the FRP SIP plank can be used as a formwork and has the capacity to be used for concrete beams as a tensile reinforcement.

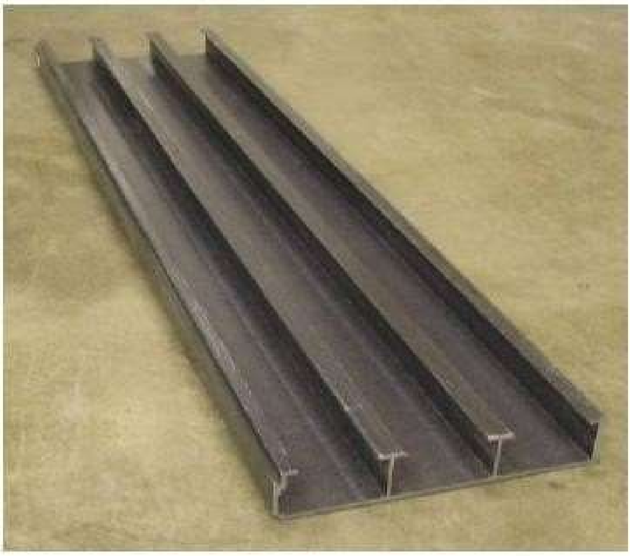


Fig.2.4 12 Inches Wide Pultruded FRP Plank ***(Bank et al. (2006))***

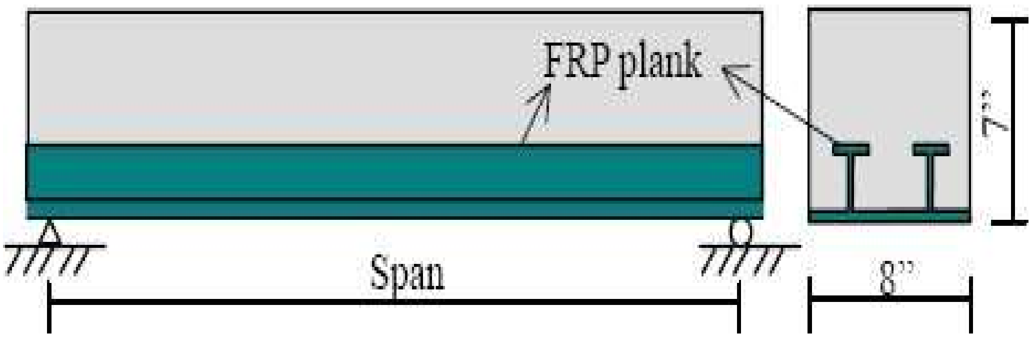


Fig.2.5 Dimension of FRP Plank Reinforced Beam Specimens **(Bank et al. (2006))**

Table 2.1 Dimension of fabricated FRP plank reinforced beam specimens ***(Bank et al. (2006))***

Specimen I.D.	Span	Tensile Reinforcement	Compressive Strength(Psi)
1	3“7”	Gravel coated FRP Plank	3,740
2	3“7”	Sand coated FRP plank	3,740
3	3“7”	Sand coated FRP plank	3,550
C1	3“7”	FRP plank	3,740
4	6“	Sand coated FRP plank	4,650
5	6“	Sand coated FRP plank	4,860
C2	6“	Sand coated FRP plank	4,775


a) Shear failure of specimen 1


b) Shear failure of specimen 2


c) Shear failure of specimen 3


d) Flexural failure of specimen C1

Fig.2.6 Specimens 1-3 and C1 after Test **(*Bank et al., 2006)***


1) Hybrid failure mode of specimen 4


2) Hybrid failure mode of specimen 5


3) Flexural failure of specimen C2

Fig.2.7 Specimens 4-5 and C2 after Test

Fam et al. (2009) provided a survey on the segment of trapezoidal pultruded GFRP used as a concrete girder structure. To guarantee continuity in the transverse direction, the pin-and eye connection was used. The efficiency in positive and negative bending girders with distinct sizes was cast and tested for flexure for the research of distinct bond structures. Fig.2.8 shows the GFRP profile and the various concrete-filled profiles. The bonding technologies used are (a) adhesive bonding to newly cast concrete (b) bonding aggregates and (c) anchoring mechanical shear studs to the GFRP flanges. Steel wire meshes have been welded close to the upper surface of the slab and are primarily intended to control shrinkage crack.

The concrete and GFRP section showed no slippage, but within the concrete layer remaining attached to the plank, delamination happened. The pull-out experiment caused mechanical studs to fail. At the ultimate bond failure, concrete and GFRP accomplished about 47–75 percent of their complete strengths. It has also been shown that the adhesive bonding has shown equal power as that of other technologies and its ease of application.

A "moment-curvature" analytical model was created, validated and used in a continual research, integrating a powerful bond failure criterion. The growing compressive strength of the concrete influenced rigidity or the bond failure load. Flexural strength is improved as far as concrete compression failure is concerned. With the rise in the density of the GFRP flanges the flexural power and stiffness of the specimen improves significantly on the other side there was no possible impact on the load of the bond failure.

The tension region's hollow concrete core had minimal stiffness impact. Because of the hollow concrete core, the void is developed and passes through the lower GFRP flange, which in turn reduces the bond and also results in a 13 percent decrease in strength, but the general strength-to-self weight ratio of voided section is nearly 30 percent higher than the filled section. Fig.2.9 shows the distinct specimens ' load-deflection reactions. Critical values for the shear span-to-depth ratio, cement mortar concrete strength, top GFRP flange width and concrete strength were discovered, after which the necessary flexural failure mode occurred before bond failure.

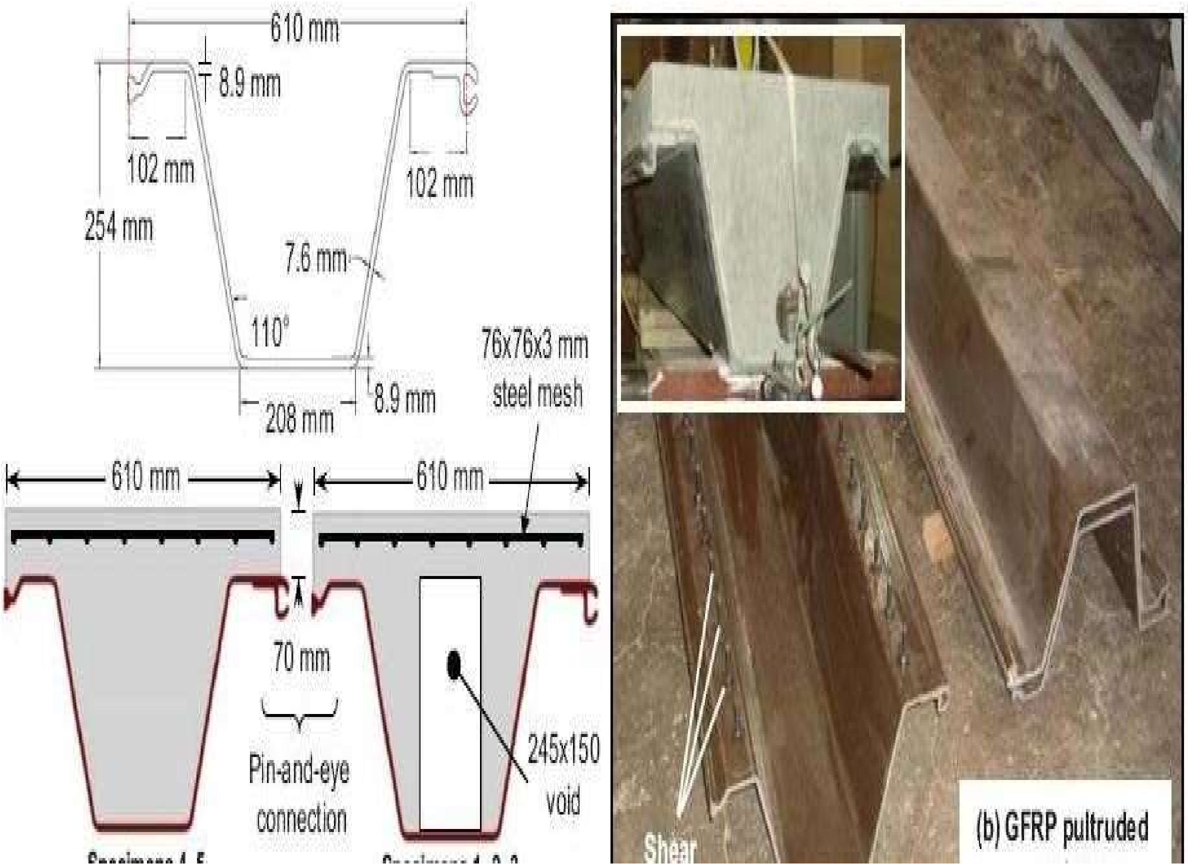


Fig.2.8 GFRP Profile and Concrete Fill Configuration ***(Fam et al. (2009))***

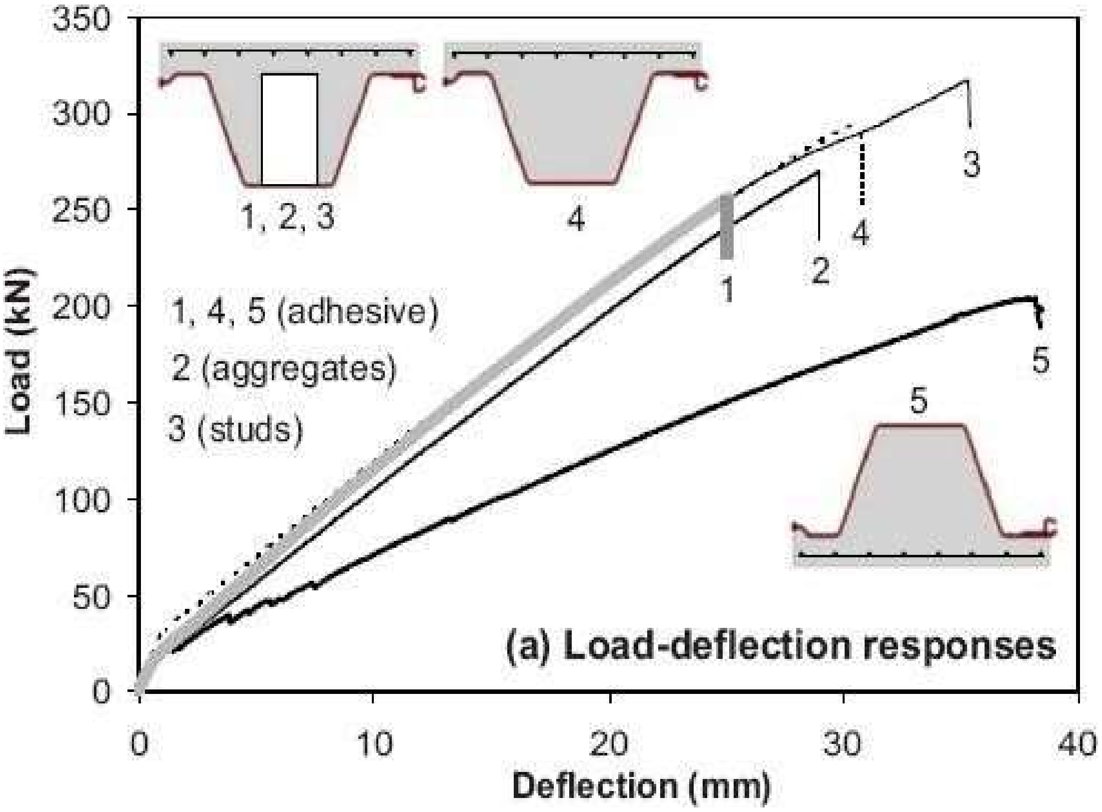


Fig.2.9 Load Deflection Response ***(Fam et al. (2009)***

The use of FRP SIP formwork was studied by **Goyal et al. (2016)** in culverts with three distinct adhesives and two distinct implementation methods, aggregate bonding and adhesive bonding . The FRP which is also used as SIP is also a commercially accessible profile of pultruded GFRP which containing T-shaped rib plates displayed in Fig.2.10. A self-compacting, 50 MPa compressive concrete and specified Mechanical characteristics of adhesives were used . Specimen of concrete with FRP formwork with and without adhesive layer were prepared as shown in Fig.2.11 and put in Universal Testing Machine (UTM) and pulled upwards, leading in FRP tension and concrete compression. The outcome indicates two significant failure modes (a) interface failure (b) concrete failure. Very less control concrete failure load demonstrates the significance of bond therapy for the successful performance of the FRP formwork at the interface between concrete and FRP. The mode of failure and ability of load vary with adhesive use as shown in Table.2.2. Load displacement behavior provided in Fig.2.12 shows that original sample stiffness with the mixed mode type failure (AB, GB) were 2.5 times higher to failure of FRP adhesive interface (AA, GA) samples, but the original stiffness of GC and AC was comparable to the GB and AB respectively. Overall, it appears that the idea of using formwork adhesive before pouring concrete has produced the beneficial outcomes. For the bonding with that cured concrete, most of the adhesives available on the market are produced, whereas for wet concrete with adhesive bonding is to poured overthe adhesive. This essentially changes the polymerization process . Therefore, it is not good enough depending on the data sheet of the manufacturer and the adhesives should be tested specifically for their implementation. As far as manufacturing is concerned, it was a useful method because it eliminated the need for mechanical shear studs or a bonded coarse aggregate coating on the formwork surface, both of which would take much more time to install than an adhesive layer.

Fig.2.10 FRP Plank **(Goyal et al. (2016)**

Table 2.2 Load Capacities and Failure Modes **(Goyal et al. (2016))**

Series	Load capacity (kN)	Standard Deviation	Mode of failure
C	5	0.328	Failure of FRP-concrete interface
AA	33	1.140	Failure of FRP-adhesive interface
GA	19.5	1.843	Failure of FRP-adhesive interface
AB	44	1.702	Failure of FRP-adhesive and Concrete-adhesive mixed
GB	43.6	1.740	Failure of FRP-adhesive and Concrete-adhesive mixed
AC	46.18	1.472	Failure of Concrete
GC	45.2	0.758	Failure of Concrete

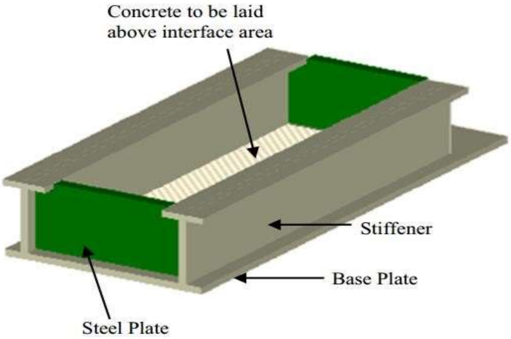
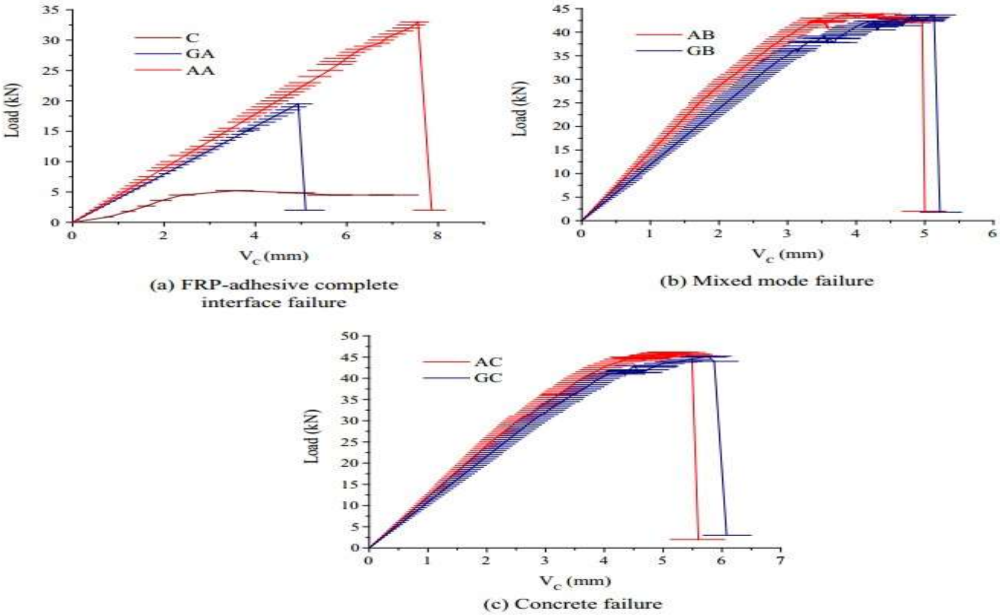


Fig.2.11 FRP Formwork with Bond Coating **(Goyal et al. (2016))**



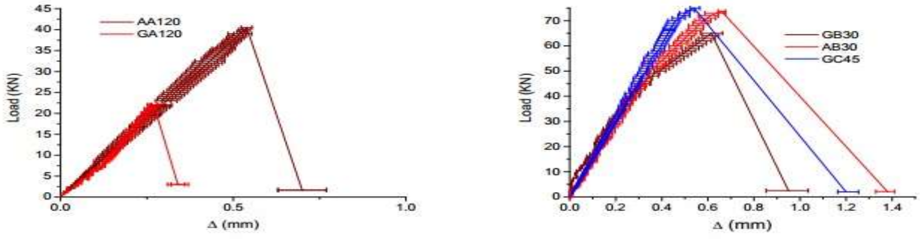
(a) FRP-adhesive complete interface failure

(b) Mixed mode failure

(c) Concrete failure

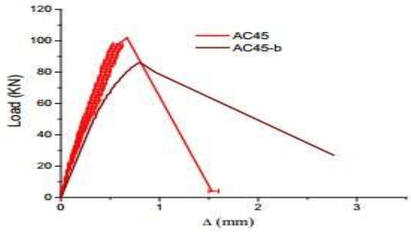
Fig.2.12 Load vs Concrete Displacement for Different Failure Modes ***(Goyal et al. (2016))***

Goyal et al. (2016) explored the bond between the SIP FRP and cast-in-situ concrete with two main goals (a) to know the efficiency of commercially accessible bonding adhesives; and (b) to compare adhesive bonding quality and aggregate bonding performance. Push out experiments are performed to study the bond characteristics. Concrete was loaded on top with standardized compression. Through the bonded FRP-concrete interface the whole force passes as shear. All samples were screened with a load speed of 0.2mm / min in displacement control mode. The outcome shows that adhesive bonding is stronger than aggregate bonding and time-saving and simple to apply. The smallest stiffness was shown by the control sample. The sample of FRP-adhesive interface failure demonstrates twice as much rigidity as control samples. Due to FRP-adhesive interface failure, the concrete-adhesive interface failure specimen accomplished about three times more rigidity than the samples received. The rigidity of the samples with material failure was comparable to that of those with concrete-adhesive interface failure. Visibly, the sort ofadhesive is thought to have an effect on the mode of failure and the stiffness of the specimen. It has also been discovered that the ultimate sample load increased as the length of increased. However, with increasing bond area, the average shear stress reduces as shown in Fig.2.14. Non-uniform distribution of shear stress happening in the bonded region is the primary reason for local failure. Thereafter, owing to the initiation of different failure modes, an increase in the bond area is noted. In addition, a significant reduction in the increase in failure load was seen with the rise in bond length.



(a) FRP-adhesive interface failure

(b) Adhesive-concrete interface failure



(c) Material failure

Fig.2.13 Load-Concrete Displacement Plot for Different Failure Modes ***(Goyal et al. (2016))***

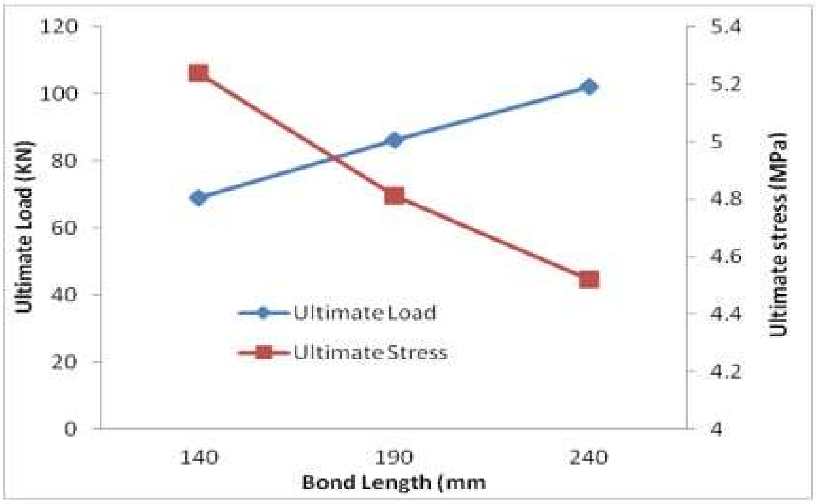


Fig.2.14 Effect of Bond Length on Ultimate Load and Ultimate Stress ***(Goyal et al. (2016))***

2.3 FLEXURAL BEHAVIOUR

In the GFRP SIP formwork for bridge decks, **Fam et al. (2012)** explored the function of various interlocking joints. The GFRP formwork consisted of pin-and-eye corrugated panels as shown in Fig.2.15. All samples under a single load were screened for failure. The link between the supporting girders and deck and their construction information was provided significance in this paper. To check the effectiveness of using GFRP SIP types for an overhanging section, a sample was built and evaluated. The study focused primarily on the interfacial adhesive bonding at concrete and formwork interface and its thickness depending on the orthogonal steel bar mesh at the top and the bottom. The result shows that deflections of all internal deck spans installed with GFRP SIP formwork at service loads show deflection below the span/1,600 limit as per the code. In addition, the GFRP formwork indicates less than 2 percent of the ultimate strain at service loads. The significant failure criteria of all interior span GFRP shaped deck panel was primarily through punching shear that was very comparable to the RC control deck panel. The GFRP formwork web failed due to inclined crack arising from the tearing at supports close the corner between the web and the bottom flange, which was triggered by punching shear and related de-bonding. Without failure and harm, the pin-and-eye connections mounted in transverse direction continued. Between GFRP SIP formwork and girders there was no slip. It has been shown in this paper that adhesive bonding has resulted in considerably enhanced stiffness but very less increase in ultimate strength.

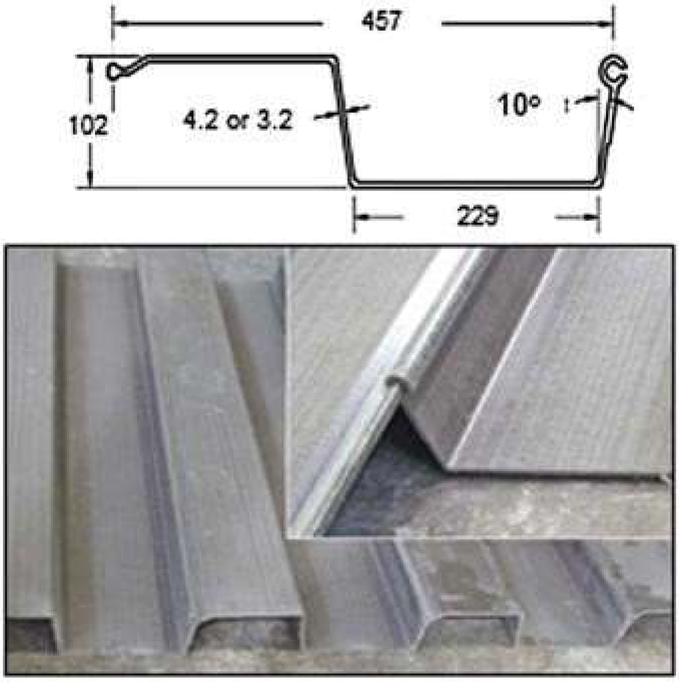


Fig.2.15 Corrugated GFRP Panels with Pin-and-Eye Connections ***(Fam et al. (2012))***

Cheng et al. (2005) researched the conduct of FRP-concrete composites that contains a hybrid modular deck structure and eliminates the use of reinforcement and the combination and performance of the two distinct materials. For this research, a concrete slab is cast over the CFRP slab, which has been strengthened with CFRP, which performs both the function of SIP formwork and the role of flexural reinforcement (Fig.2.16). The panel surface is produced rough by treating it with sand and equipped with shear ribs to enhance the interface link between the cast concrete and the deck panel. The primary objective of thisstudy is to fully comprehend the structural conduct of this composite FRP-concrete deck structure by incorporating analytical simulation and research involving tests on static flexural-shear conduct and fatigue reactions under cyclic loads. Test samples include five 610 mm broad concrete slabs (SF1–SF5) produced without reinforcement and mounted with distinct spacing stiffeners and shear ribs. All test specimens were cast using concrete blocks with strengthening at both ends to create the situation of fixity on the supporting girders . Fig. 2.17 demonstrates that the test specimen was simply supported at one end by a roller with a pin at the other end and loaded at a very slow pace from the top by a double rod hydraulic actuator. The load was transmitted at separate service speeds through an elastomeric loading bearing pad as per the AASHTO wheel load (98 kN), including the 33 percent impact factor. According to AASHTO (2004), a load factor of 1.75 was used for strengthening I design level.

The structural conduct of the first three samples with 305 mm spacing stiffeners in the middle was very comparable. At the mid span near the bottom slab, vertical Flexural crack was observed as quickly as the load reached 98 kN. As to the load further increased, some more cracks were discovered at the interface shear ribs locations and further shifted diagonally up to the load point, as shown in Fig.2.18, owing to the impact of main tensile stress. According to the investigations of this specific paper, it was not only suggested to design rectangular stiffener for carrying construction load, but it is also necessary to consider the flexural strength of FRP-concrete deck system composites.

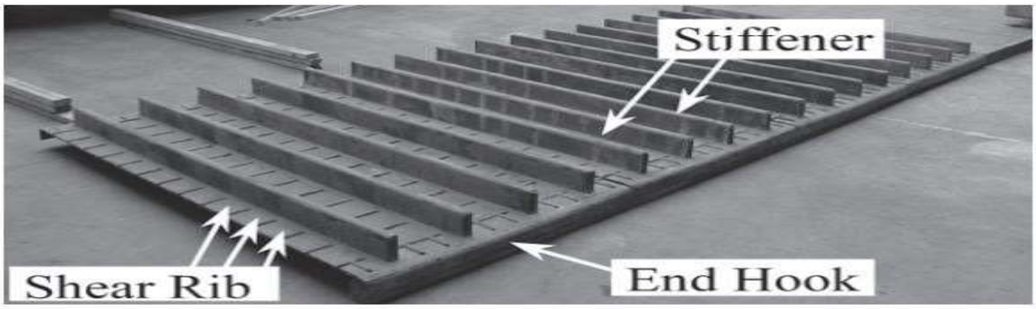
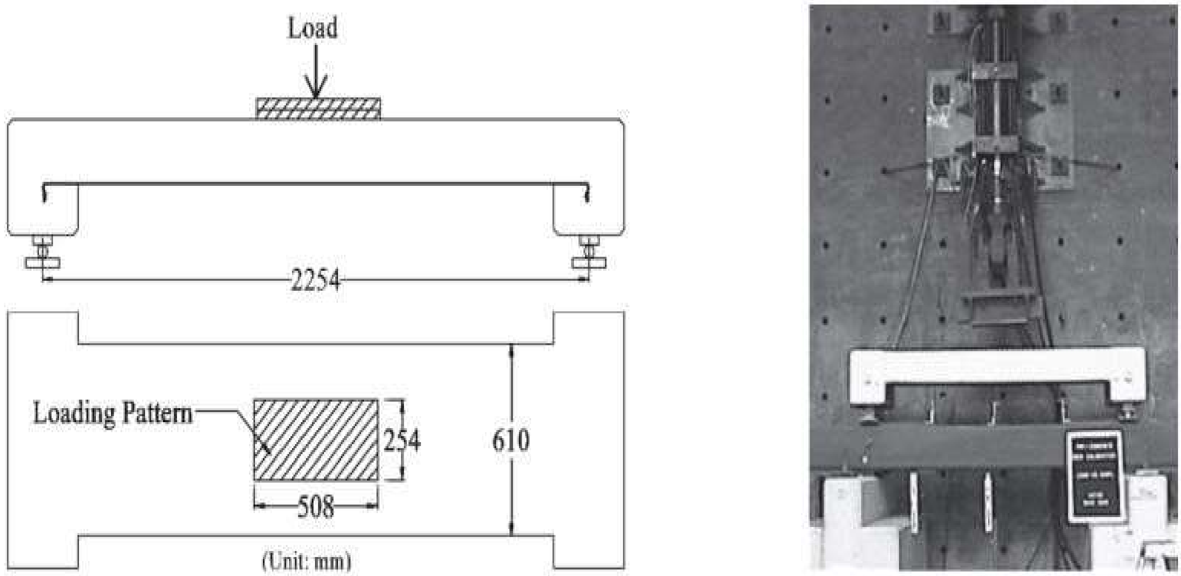


Fig.2.16 Geometry of FRP Composite Deck Panel ***(Cheng et al. (2005))***



(a) (b)

Fig.2.17 (a) Geometry and (b) Configuration of Test Setup **(Cheng et al. (2005))**

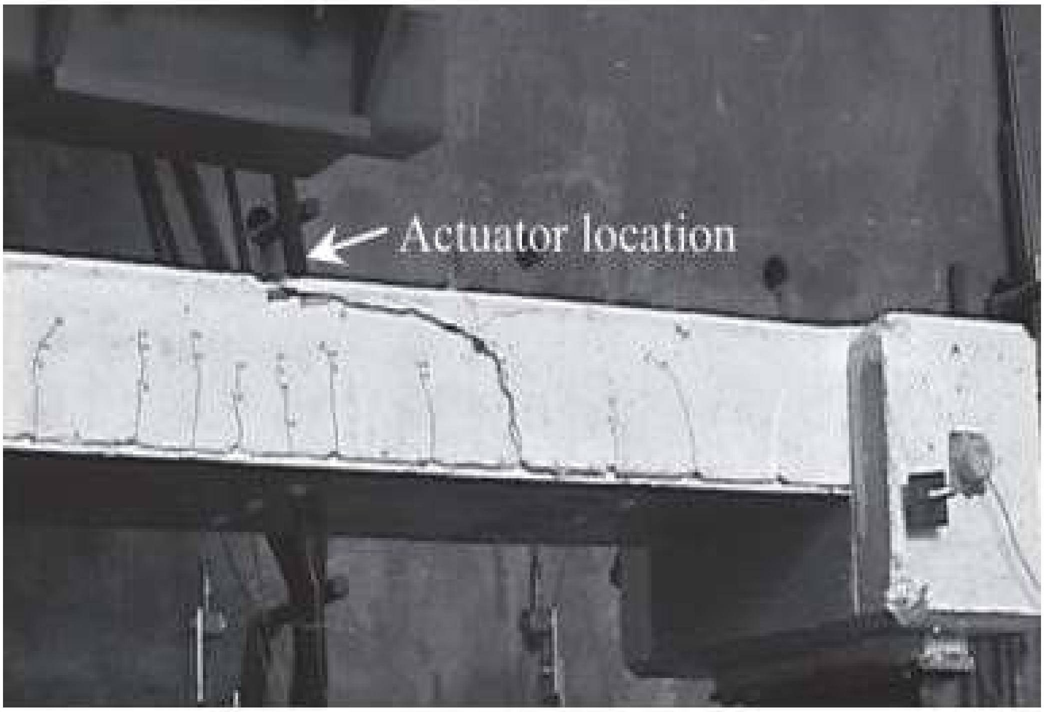


Fig.2.18 Load vs. Displacement Response for SF1, SF2 and SF3 ***(Cheng et al. (2005))***

Honickman et al. (2009) investigated to the bond behaviour in between concrete formwork and GFRP. Testing samples include eight concrete slabs casted using GFRP SIP formwork and tested for understanding and comparing the distinct bonding mechanisms and GFRP reinforcement ratios in flexural bending. This research provides experimental and analytical evaluation of concrete slabs casted as SIP formwork using GFRP planks and also plays the function of stress strengthening. Various bond mechanisms have been researched in this paper as a mechanical and adhesive bond scheme . In order to study the impact of GFRP plate reinforcement ratios, concrete slab thickness was varied. For the purpose of studying distinct bonding processes, sample specimens are cast out of which the first 4 have the size of 1,220 x 400 x 160 mm. The various bonding processes to be studied include: (a) adhesive bonding, (b) aggregate bonding, (c) shear connectors for GFRP and (d) shear connectors for steel. Other sample specimens to be casted were slabs of size 2,440 x 400 mm (96 / 15.7 in.), numbered from 5 to 8 and with different thicknesses from 110 to 210 mm, with distinct reinforcement of GFRP ratios ranging from 8.5 to 4.3 percent, respectively. On the other side, adhesive bonding was implemented in slabs 5 to 7 and aggregate bonding was implemented in Slab 8. On the specimen, four-point bending was done (Fig.2.19). Testing was carried out with span of 1,000 mm on samples 1 to 4 and a steady moment zone of 250 mm and samples 5 to 8 with a span of 2,200 mm with a steady zone of moment of 250 mm. Applied load rate was 1 mm per minute. 100 mm strain transducers and strain gauges were to used to evaluate the deflection at the mid span between concrete and GFRP plate linear potentiometer.

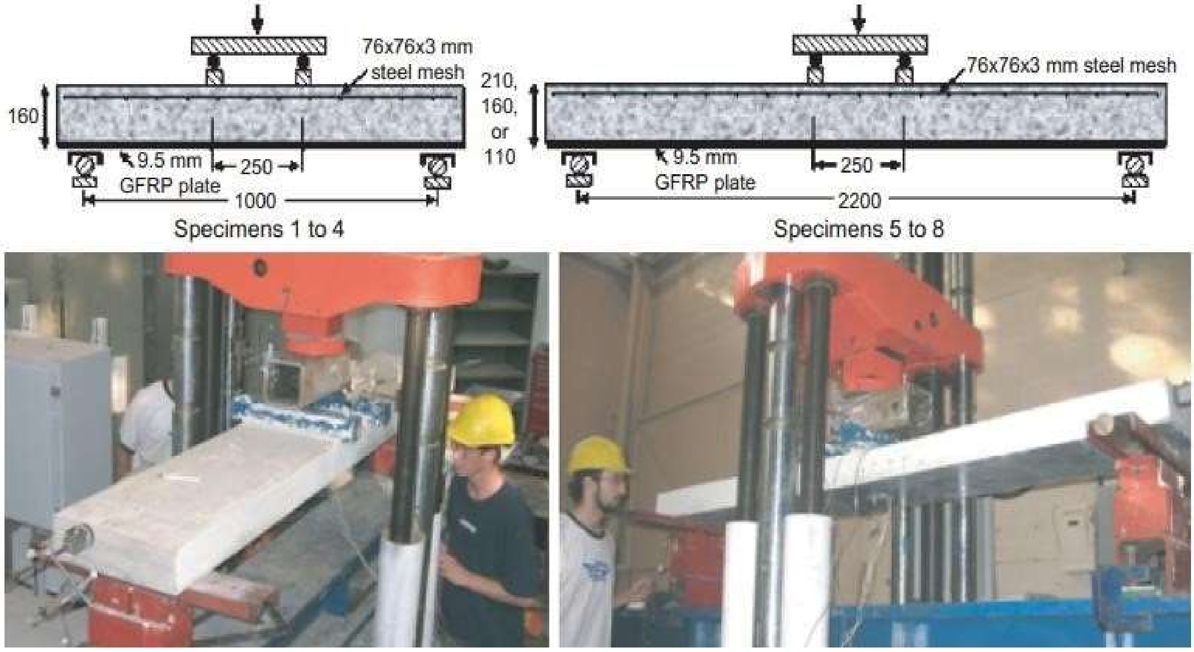
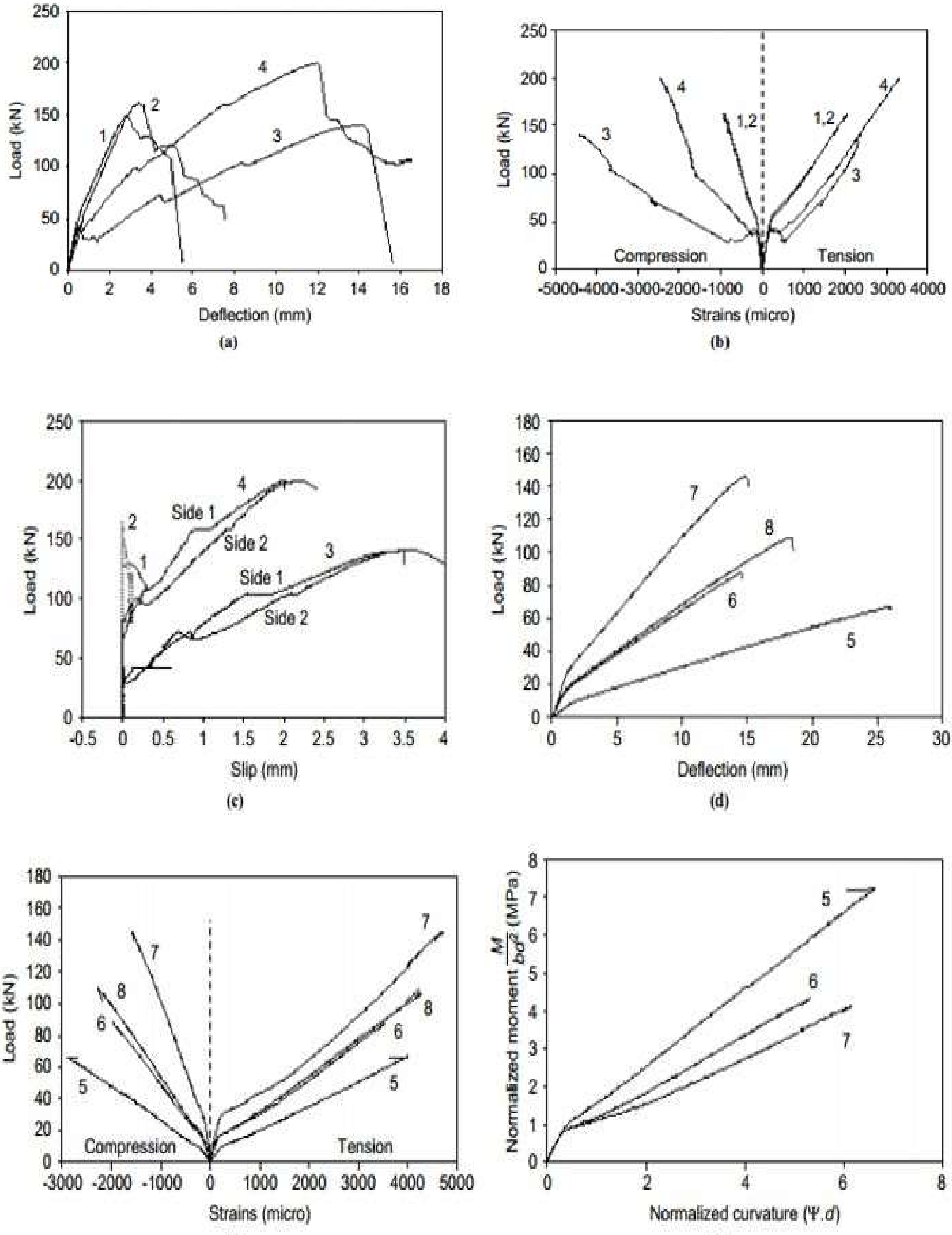


Fig.2.19 Test specimens and experimental setup**. *(Honickman et al. (2009))***

By critically researching the interfacial surfaces following samples 1 and 2 failure, to which it was inferred that no failure happened on the adhesive bond line, whereas failure of bond happened within a thin layer of cement mortar. Fig.2.21 and Fig.2.22 show the various specimens ' failure modes. A layer of cement paste that stayed in touch with the GFRP plate demonstrated this in (Fig.2.23). Specimen 4 demonstrates reduced post-cracking stiffness than Specimens 1 and 2 owing to some slip occurrence, while it indicates greater stiffness than Specimen 3 (Fig.2.20(a)). This was due to the steel studs with greater elasticity modulus compared to the GFRP studs, which decreases slip in turns (Fig. 2.20(c)). Fig.2.20(f) shows that the flexural stiffness of the specimen 5 to 7 is proportional to the reinforcement ratio, which shows that the use of available GFRP slabs as a formwork for that of concrete slabs is very convenient and very effective when adhesive bonding was used, as it resulted in to a substantial increase in slab stiffness with respect to that to the mechanically bonded slabs cast with shear connection. For both flexural and shear cracking requirements, the main reason for failure was due to GFRP plate debonding. The longitudinal strains measured at midspan give an impression that stress failure in the GFRP plate is much less likely. In some of the slabs, concrete compression failure was imminent. Because the increase in the flexural strength of the reinforcement ratio also increases, but its effect on the final moment could not be evaluated as there was no flexural failure but consistent bond failure occurred.



(a) (b) (c) (d) (e) (f)

Fig.2.20 Summary of test Results for Specimens 1 to 4: (*a*) Load–Deflection Responses, (*b*) Load–Strain Responses, and (*c*) Load–Slip Responses; for Specimens 5 to 8: (*d*) Load– Deflection Responses, (*e*) Load–Strain Responses, and (*f*) Load–Slip Responses**. (Honickman et al. (2009))**

Fig.2.21 Failure Modes Specimens 1 to 4 ***(Honickman et al. (2009))***

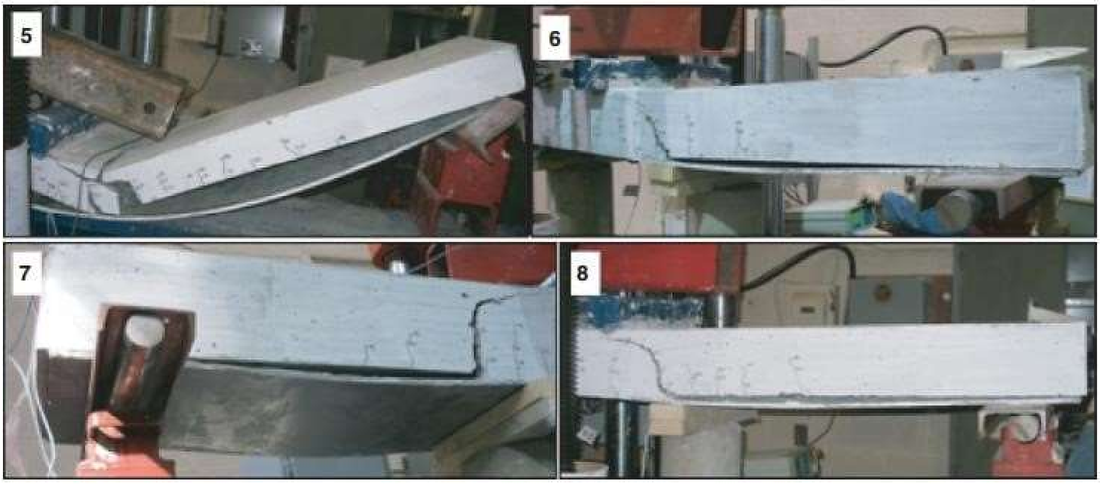


Fig 2.22 Failure Modes of Specimens 5 to 8 ***(Honickman et. al. (2009))***

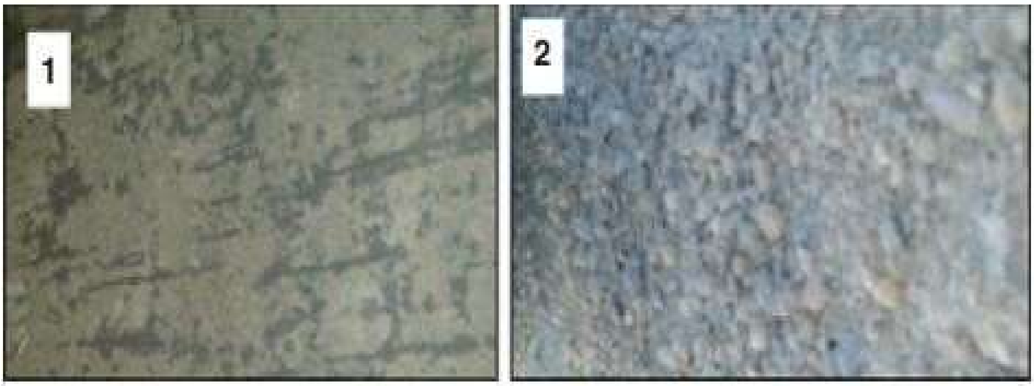


Fig 2.23 Surface Texture after Failure (Specimens 1 and 2)(***Honickman et. al. (2009)***

Orretal et al. (2013) investigated iterative methods for designing concrete beams that are simply supported, flexibly formed. This design and construction techniques have led in material savings of up to 40% using flexible formwork. This article also describes the distinct techniques used by distinct techniques for geometric control in beam construction. This paper also mentions various techniques for anchoring fabric-formed beams. This paper also offers the technique needed to build concrete beams using fabric forwork . The method described in this paper is for a simple beam, from the moment calculation and shear envelopes, through capacity prediction, to the detailed design of the component of reinforced concrete beams in steel.

Goyal et al. (2017) researched the feasibility of the FRP profile both as to stay-in-place formwork (SIP) and as strengthening. There were three phases of experimental investigation on the feasibility of FRP profile as both stay-in-place (SIP) formwork and as reinforcement. To use the FRP profile as SIP formwork at the moment of concrete casting, its deflection should be within permissible boundaries, so sand loading testing was carried out as shown in Fg.2.24. In the second phase, various types of adhesive that were commercially accessible as stated in Table 2.3 were used to verify the adhesive effectiveness in creating contact with concrete and GFRP plank through aggregate and adhesive bonding . Flexural testing was carried out in the third phase to study the function of the GFRP plank as reinforcement. Fig.2.25 demonstrates the tested specimens ' load-deflection plot and load-strain plot. 3 criteria that is. original cracking of load, the crack pattern and the ultimate load, were researched in order to study a function of FRP as reinforcement and the requirement for correct bond system for the FRP-concrete composite action. It was found that the use of GFRP planks as SIP forms for concrete slabs and beams is very useful when correct bonding between concrete and GFRP is carried out using suitable bonding system . Adhesive choice varies significantly with the strength of the FRP–concrete interface bond. Both adhesive type bonding and aggregate provide better bonding between to FRP and concrete, while adhesive type bond provides best outcomes when it comes to ultimate load and of failure mode than aggregate bonding. It can also be concluded that to the use of the FRP plank as SIPformwork and the tensile reinforcement without using any adhesive for bond therapy resulted in a significant slip during testing between concrete and correspondingly less ability. The plank that uses specific adhesive with adequate bonding therapy demonstrates better outcomes as tensile reinforcement. It is therefore appropriate to use as a SIP

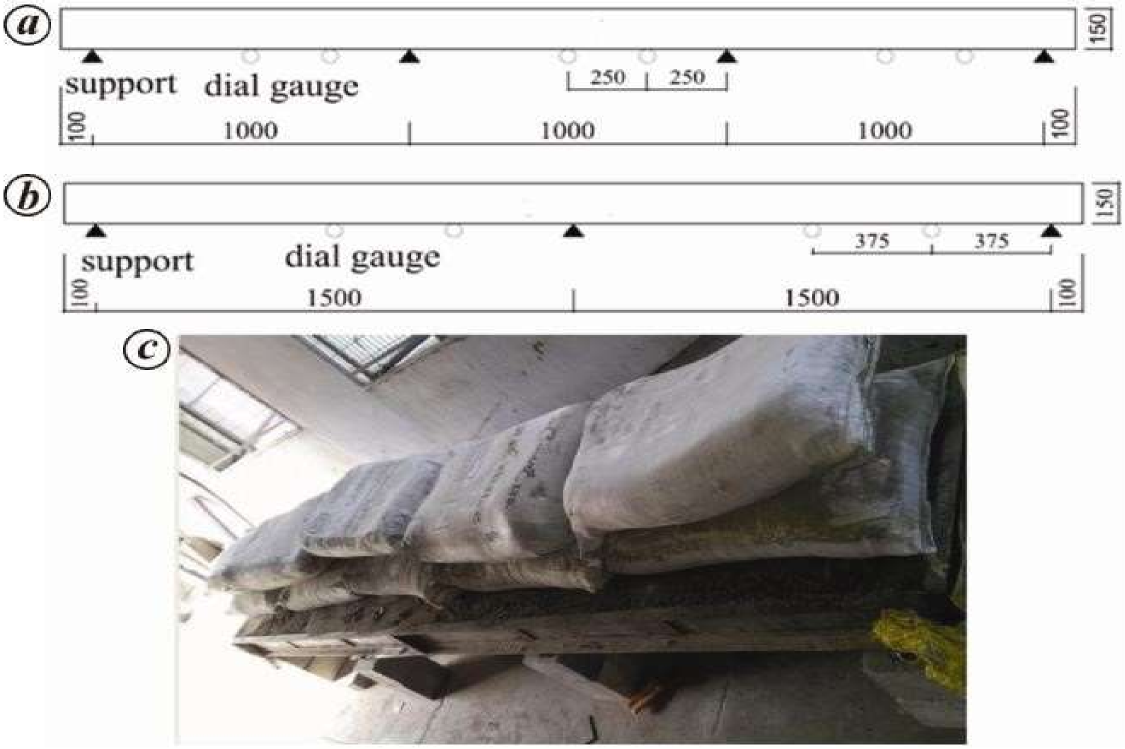


Fig 2.24 Sand-loading test. a, Three-span testing; b, Two-span testing; c, Experimental set-up for three-span testing **(Goyal et al. (2017))**

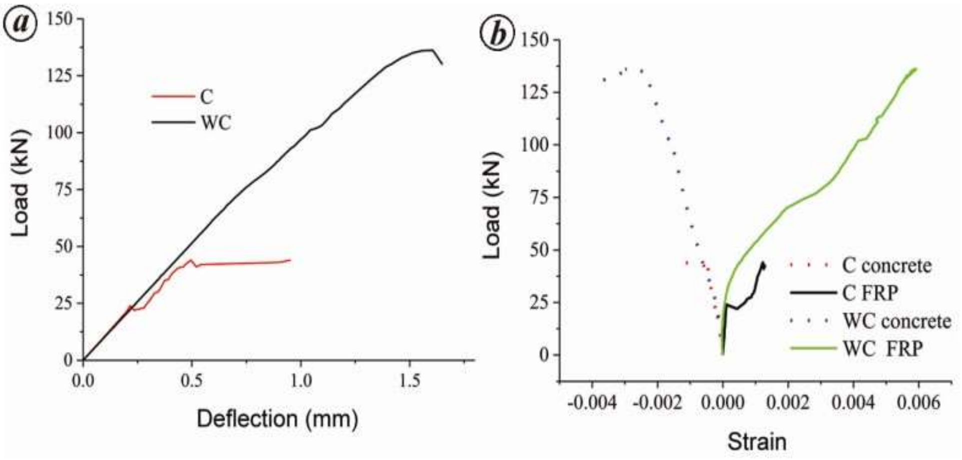


Fig 2.25 Comparison between the Bond Treated and the Untreated Specimens. *a*, Load–Deflection Plot; *b*, Load–Strain Plot. **(Goyal et al. (2017)**

Table 2.3 Specimen Summary and Load Capacity **(Goyal et al. (2017))**

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

2.4 FRP SIP FORMWORK IN BRIDGES

There is now a growing number of FRP SIP formwork field applications, most of which can be defined as demonstration projects. The exception is in the region of bridge decks and girders where activity has been growing over the past few years, driven by the need for lighter weight and a more durable system to offset the rising price of maintaining standard structural concrete in regions of severe climate circumstances or where structural upgrades are needed to satisfy new code demands. Below is provided the study work conducted in the field of structural formwork of FRP SIP for bridge decks and girders.

Berg et al. (2005) defined the use of SIP FRP materials for a deck in concrete highway bridge as reinforcements and formwork. They outlined the building method and supplied the project with a cost analysis. Three types of FRP reinforcement have been combined in this project to strengthen the deck of concrete: FRP stay-in-place (SIP) forms, deformed FRP reinforcement bars (rebars) and a unique manufactured FRP reinforcing panel (Fig.2.26). The scheme was created to decrease the cost of building work to offset the elevated original price of FRP materials compared to standard steel reinforcement. A twin structure with temporary formwork and steel reinforcement was built adjacent to the FRP strengthened deck. The deck panels of the SIP FRP were 2350 mm (7 ft. 10 in.) by 457 mm (1 ft. 6 in.) Eachpanel was spaced 229 mm (9 in.) apart by the two 76 mm (3 in.) square tubular hollow" "cells." The deck panels spanning in between the prestressed concrete girders perpendicularly and in at the girders were discontinuous.

The deck panels were being served as the upper tensile reinforcement in the transverse direction for the deck after a concrete was poured. The FRP bars in between the deck were used to give the girders with adverse moment continuity over the center pier as well as strengthening of temperature and shrinkage elsewhere. The FRP bars have been finished with a texture of fine sand. Prefabricated bi-directional pultruded FRP grid was constructed from 50 mm (2 in.) elevated T-bars spaced at 100 mm (4 in.) in the center and 13 mm (0.5 in.) in the center spaced at 100 mm. The grid was served as the top reinforcement of the concrete deck and caused tensile stress over the girders in the transverse direction of the deck due to adverse bending moment. They were joined between the girders in the positive moment area of the panel. At the ends of the grids, a mechanical splice link (a pultruded coupler) wasthen used to keep them in place during building. Polystyrene haunches were connected to the corners of the concrete girder's top flange with an epoxy adhesive after the concrete girder was positioned. The panels of the FRP deck were then put on the foam. At the ends of the panels, the hollow tubular cells were filled with expandable polyurethane foam to avoid wet concrete from flowing into the cavities and mix water. Then the FRP rebars was put parallel to the concrete girders and they are supported by ongoing plastic chairs that stood above deck panel tubular cells. On top of the rebars, the FRP panel was

then put. The grid T-bars were set perpendicular to the rebars of the FRP (Fig.2.27). Before pouring, the ends of all the FRP materials were sealed with the sameepoxy used to observe the aggregate to the deck panel's horizontal surfaces.

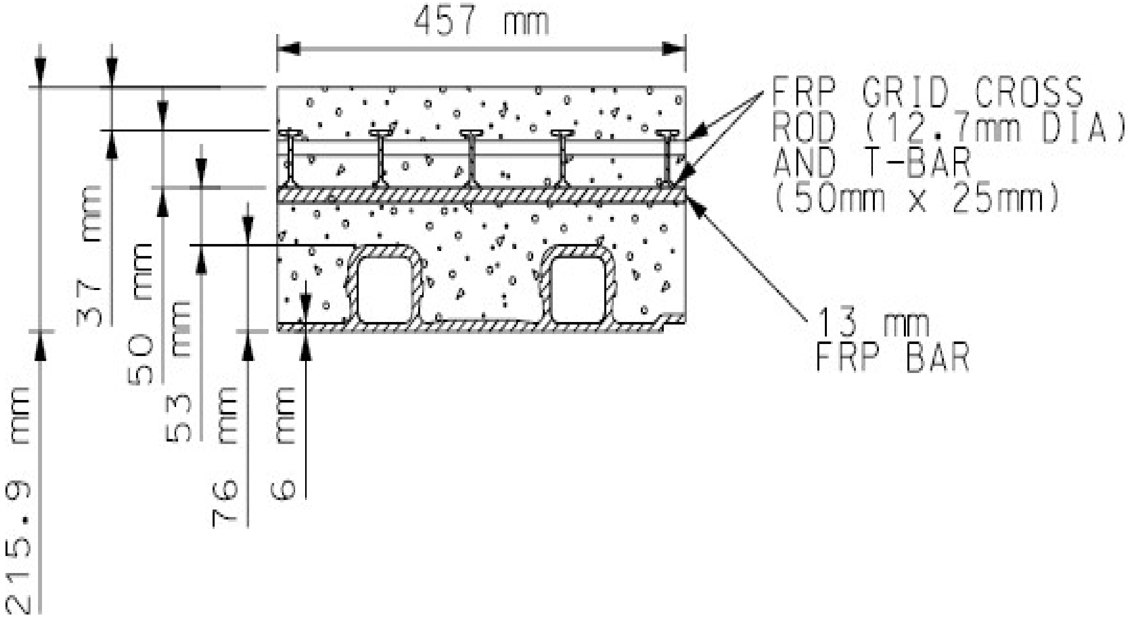


Fig.2.26. FRP reinforcement system **(Berg et al., 2005)**

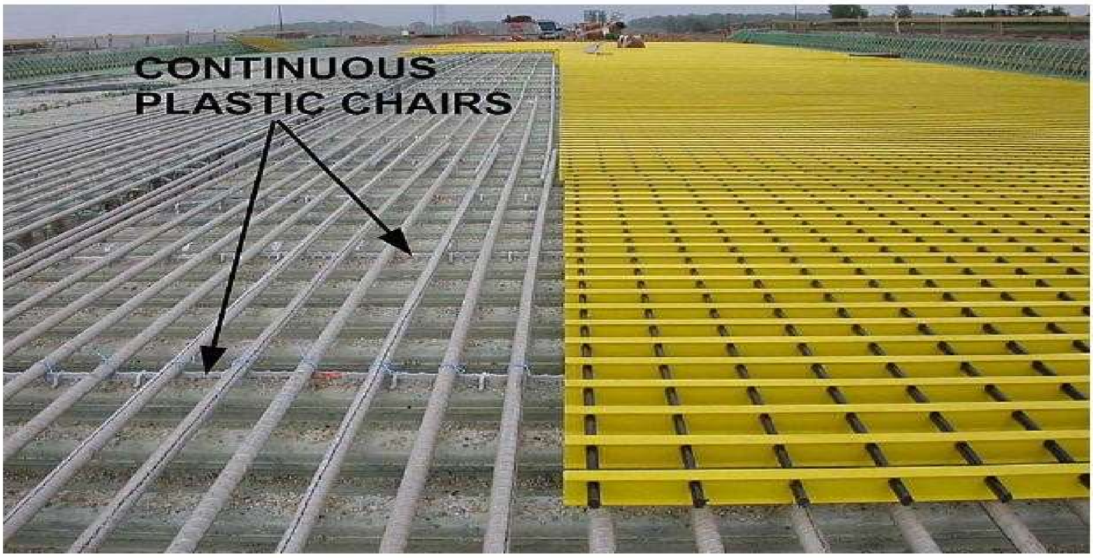


Fig.2.27. FRP SIP deck panels, FRP rebars, and bi-directional FRP grid during placemen **(Berg et al., 2005)**

Hanus et al. (2009) explored a stay-in-place (SIP) structural fiber-reinforced polymer (FRP) type use to build and strengthen deck for the military bridge prototype scheme. The deck is subjected to mixed longitudinal axial load and bending for this implementation. During the building phase, the structural SIP FRP form is connected to the bridge to a deployable truss support scheme (Fig.2.28). The SIP shape is then to be filled withconcrete to form a deck, which, in resisting live loads, also acting as the upper truss chord (Fig.2.29).

In addition, the accelerated construction benefit, SIPforms for a concrete deck was chosen mainly to reduce the bridge system's distribution requirements and use in to theater materials. The structural SIP FRP form was selected for the highest strength-to-weight ratio, which also reduces the system's distribution requirements, and for the proven development techniques for composite action. In this project, FRP SIP consisted of a single grid layer with I bars with three part cross rods and was epoxied to it with 3.18 mm thick pultruded plank (Fig.2.30).

Ten samples were built and tested in three distinct settings (single span, double span, with or without axial load). Several design elements werethen investigated, as well as the effect of adding to the concrete a synthetic short fiber material (FRC) and the details of the assembly. In this dissertation, the maximum permissible deflection limit of L/180 was used.

The experimental results were then analyzed and equated to the equations in the design guide ACI 440 (guide for structural concrete design & construction reinforced with FRP bars). This assessment included the survey of motion of the neutral axis through the elastic state to ultimate failure under favorable moment loading (compression at the top). The downward movement of the N.A was theoretically illustrated and experimentally proven in strengthened parts of the FRP. This behavior impacts the implementation of the equations for serviceability and strength limit states of the ACI design manual. The flexure equation of the ACI 440 design guide for over-reinforced parts, without the longitudinal axial load, was discovered to estimate correctly the ability of the segments strengthened in this research with the concrete FRP SIP form. The design guide for segments strengthened with bars is designed for the ACI 440, but it appears appropriate for segments strengthened with structural FRP SIP shape in relation to over-reinforced flexural failure. The ACI 440 equations were found to accurately predict the flexural and flexural-shear capacities under the combined loads provided that the eccentricity was accounted for in the calculations due to the combined loading.

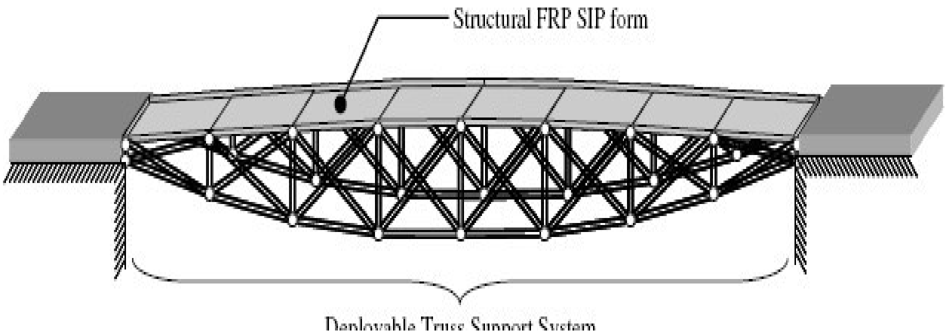


Fig.2.28. Construction stages **(Hanus et al.,2009)**

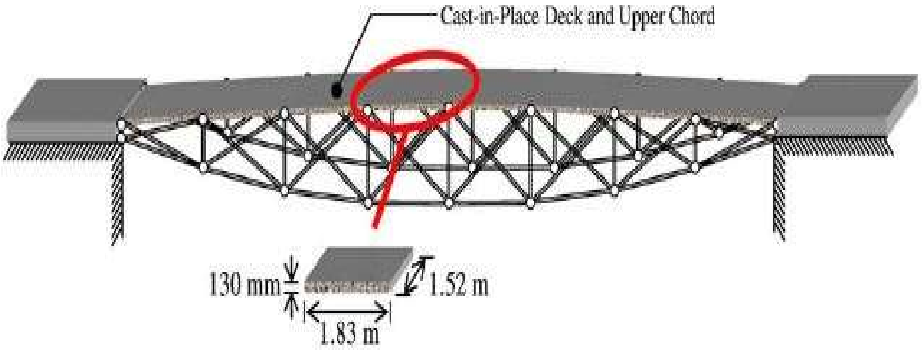


Fig.2.29. Completed stage **(Hanus et al.,2009)**

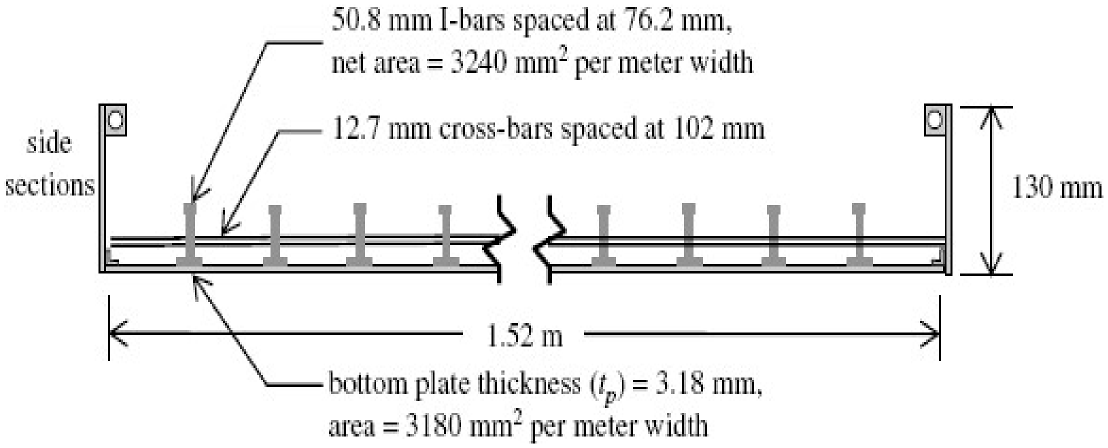


Fig.2.30 Cross-section structural SIP forms for deck component**. (Hanus et al., 2009)**

Seibal et al. (1998) created a modular FRP bridge based on a carbon / glass hybrid material scheme based on hand lay-up and the pultrusion. The beam-and-slab bridge of the hybrid pipe scheme (HTS) suggested the use of the hollow carbon / E-glass hybrid beams linked to the polypropylene fiber reinforced concrete deck system along their tops as is shown in the Fig.2.31. The girders consisted the rectangular segments of hand laid-up or pultruded E-glass / vinyl ester, strengthened with unidirectional carbon fibers along the bottom flange. The pultruded girders were secured with an FRP panel providing the flexural reinforcement of the concrete slab among girders as well as SIP formation of the slab. The panel's end hooks were held by loading polymer concrete in a bottom of the "dovetail" compartments of the longitudinal girder. Also, prefabricated carbon / vinyl ester snap-in stirrups were snapped into the grooves for horizontal shear transfer between the girders and the deck of concrete.

A parametric study of the hybrid pipe bridge system was carried out by assessing the maximum supported span length of the system under a set of permissible service and factored load design requirements. The bridge system being considered consisting of seven cross-spaced HTS girders supporting a 13 m broad surface of road. The results indicated that live load deflection controls the prevalent design of FRP structures.

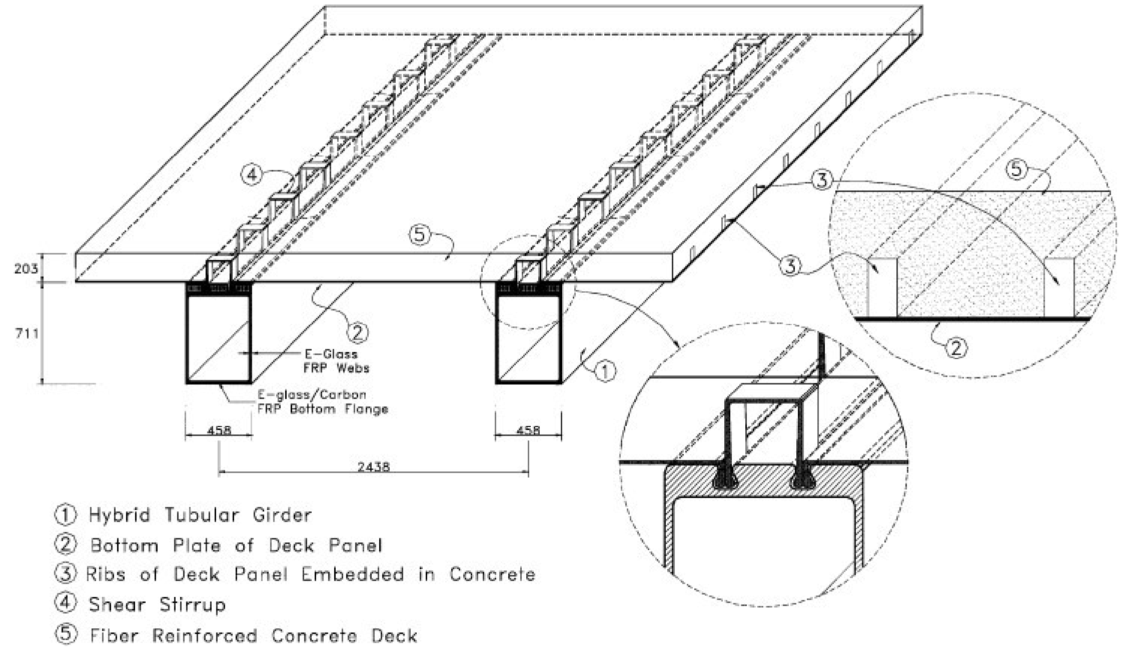


Fig.2.31. Hybrid tube bridge system **(Seibal et al., 1998)**

Matta et al. (2004) revealed on a venture involving the creation and application of a prefabricated SIP GFRP reinforcement system for fast bridge deck construction in Greene County, Missouri, USA, to restore Bridge 1482301. For concept creation, analysis, design, detailing, full-scale lab authentication, project unique provisions development, and construction planning and execution, a substantial joint effort was needed. Associated task was completed through collaboration between Wisconsin-Madison University and Missouri S&T, vendors of FRP reinforcement, Department of Greene County Highway (proprietor), designated contractor and Record Engineer.

Model SIP reinforcement panels were assembled by using off-shelf pultruded GFRP profiles where the transfer of load was achieved mechanically restricting the core concrete within the 3-D grating. The SIPformwork is made up of GFRP epoxy-bonded plates to the strengthening ground coating. The grid form details are shown in Fig. 2.32

The use of big and lightweight panels (23.7 kg / m2) was designed to facilitate rapid and easy assembly, labor-intensive configuration, eliminating time-consuming and elimination of plywood forms and in-situ bar binding.

Laboratory testing of subassemblies and deck panel samples with full-scale overhang validated the post-deck connection and deck design. The findings substantiated the results of the model and verified significant safety margins for error with respect to the required quality requirements for the appropriate code. The series of ultimate capability experiments on the deck plate samples showed that the critical failure mode was punching shear. Accelerated cyclic fatigue performance on a slab specimen showed no apparent adverse effect of fatigue on the FRP reinforced bridge deck's ultimate strength and overall performance after 2,000,000 load cycles.

It was planned to build with the contractorto reduce time. Instead, the 2-3 weeks the job was completed in five days, same contractor built the steel reinforced concrete bridges. Six workers installed a total of eighteen panels in 6 hrs during the initial day, on the girder bridge covering with the length of 44 m of slab. The next day was to dedicate to mount the rail post cages on the deck panels, for expansion joints preparing the formwork, drip edges and chamfers, and finishing machine setting. The deck was then cast and finished on third operating day. Before forming and casting on the fourth and fifth day morning, the deck panel cages were to mounted on to top of post boxes. The project has proven to be a technology which connects the toughness of FRP internal concrete reinforcement with an important advantages of constructability of using advanced lightweight composite structures built in an advanced, embedded SIP form.

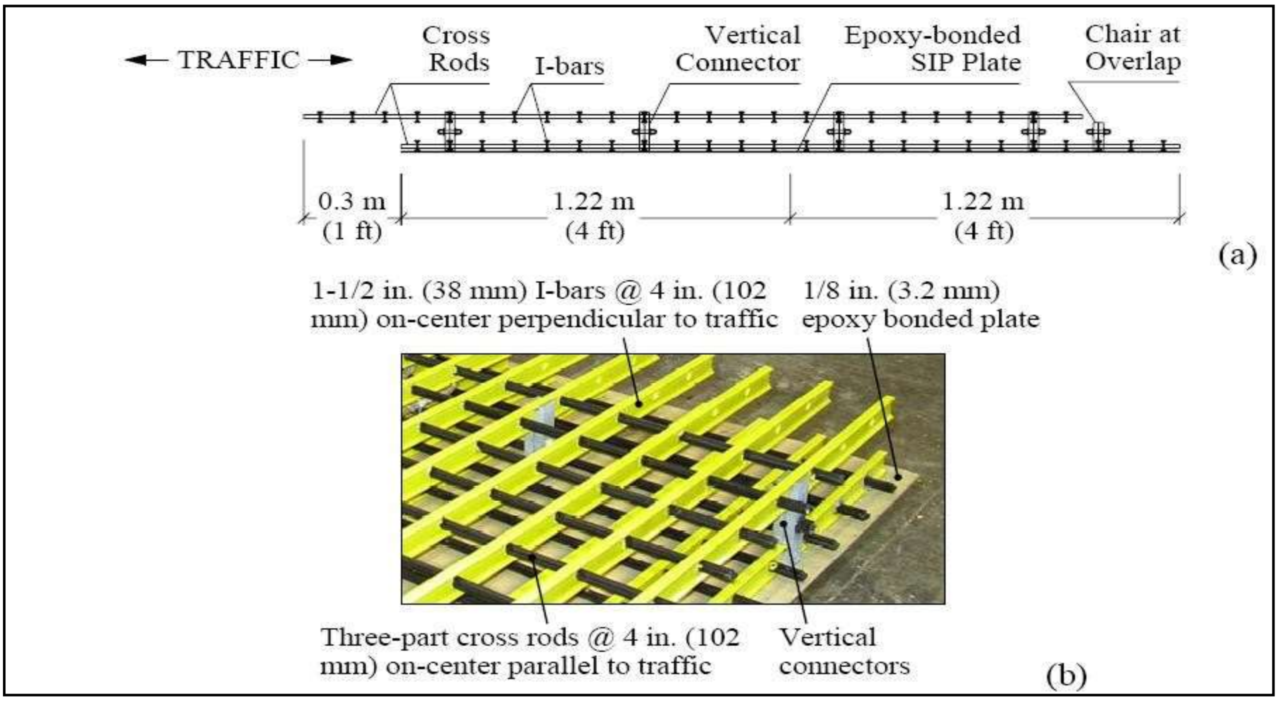


Fig.2.32. Gridform reinforcement panels: longitudinal section (a) and close-up (b) **(Matta et al., 2004)**

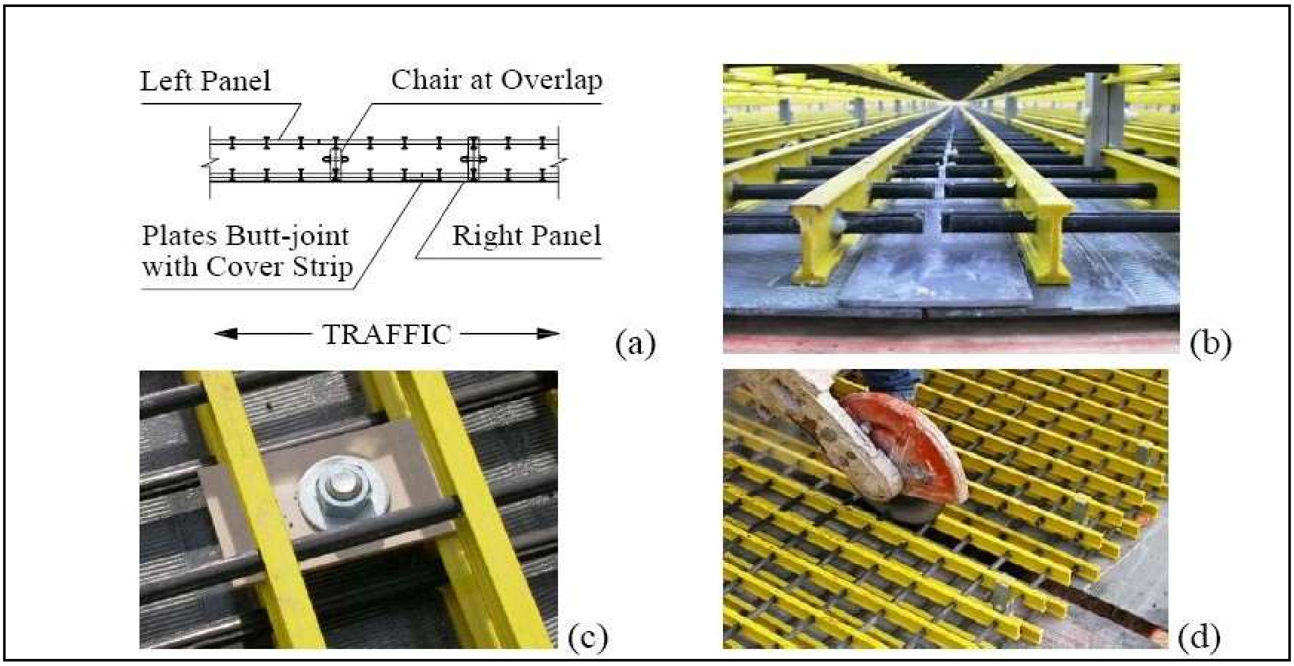


Fig.2.33.Gridform detailing: panel-to-panel overlap connection (a, b); anchoring to girder (c); and cutting of end panels at expansion joint (d). **(Matta et al., 2004)**

Bank et al. (2006) described cost-effective SIP formwork system for bridge deck with an combined modular 3-D polymer reinforcement cage (FRP). At the University of Wisconsin – Madison, which was integrated with reinforcing for decks in concrete road bridges, a cost-effective SIP FRP formwork system was developed and evaluated. Three kinds of bridge decks have been evaluated in this studies: 1) CDS system-SIP forms separated from top layer reinforcement grating (Fig.2.34). 2) SafPlank –consists of one-layer grating panels separated from the top grating layer (Fig.2.35). 3) Grid form-it comprises of two layers of grating separated from each other (Fig.2.36).

All these systems have been shown to provide secure assistance for highway bridge design loads. Fig.2.37 Shows all three kinds of formwork load deflection behaviour. Because of the material costs and the opportunities for quick construction, the Gridform system is presently the most effective choice. Lab screening of full-scale beam and panel samples showed that the Gridform systemmeets the demands of the strength and deflection code; the strength was more than five times the need and rigidity is more than four times the suggested rigidity. Gridform's benefits over standard steel reinforcement is that it is corrosion resistance and the ability to quickly build due to the system's modular nature. Gridform method was implemented efficiently in Greene County, Missouri to replace the superstructure of a slab on the girder bridge, where 3 days were taken to construct deck.

Fig.2.34. Installation of the CDS deck panels

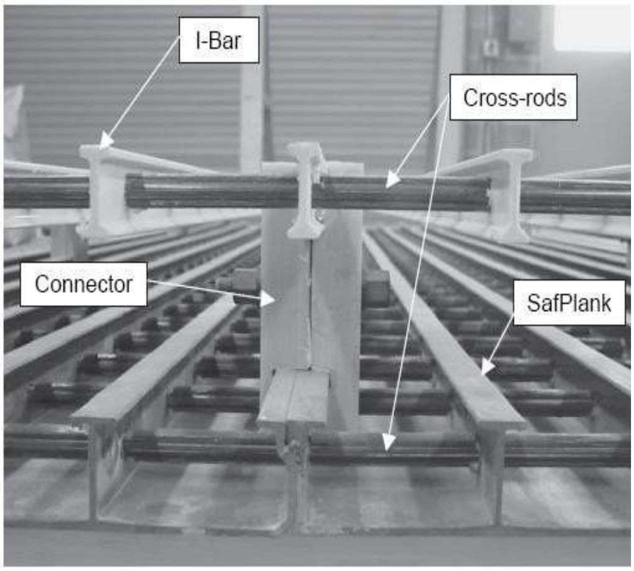


Fig.2.35. SafPlank panel

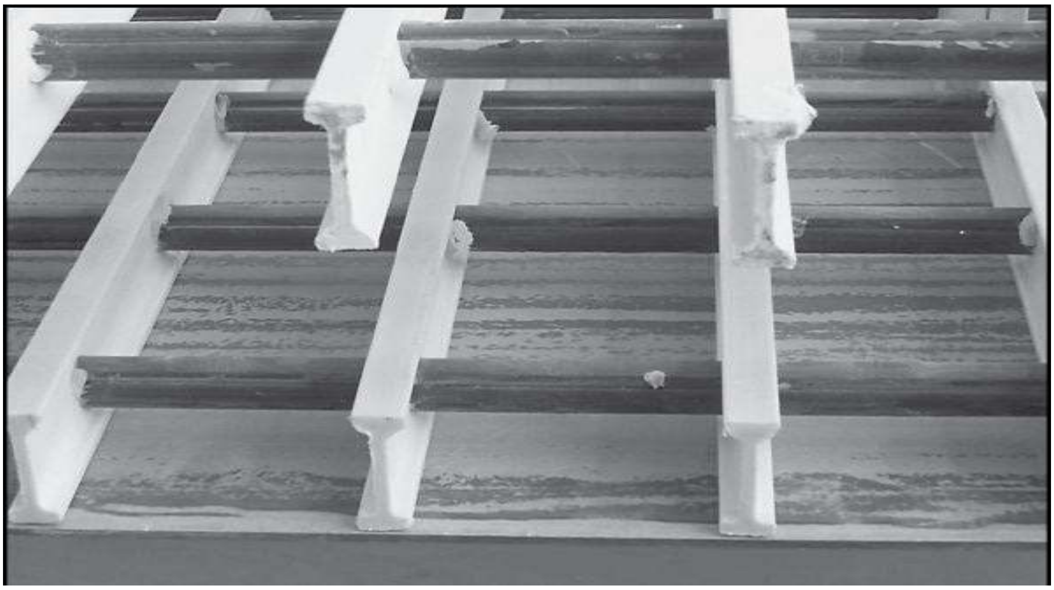


Fig.2.36. Gridform reinforcement detail **(Bank et al., 2006)**

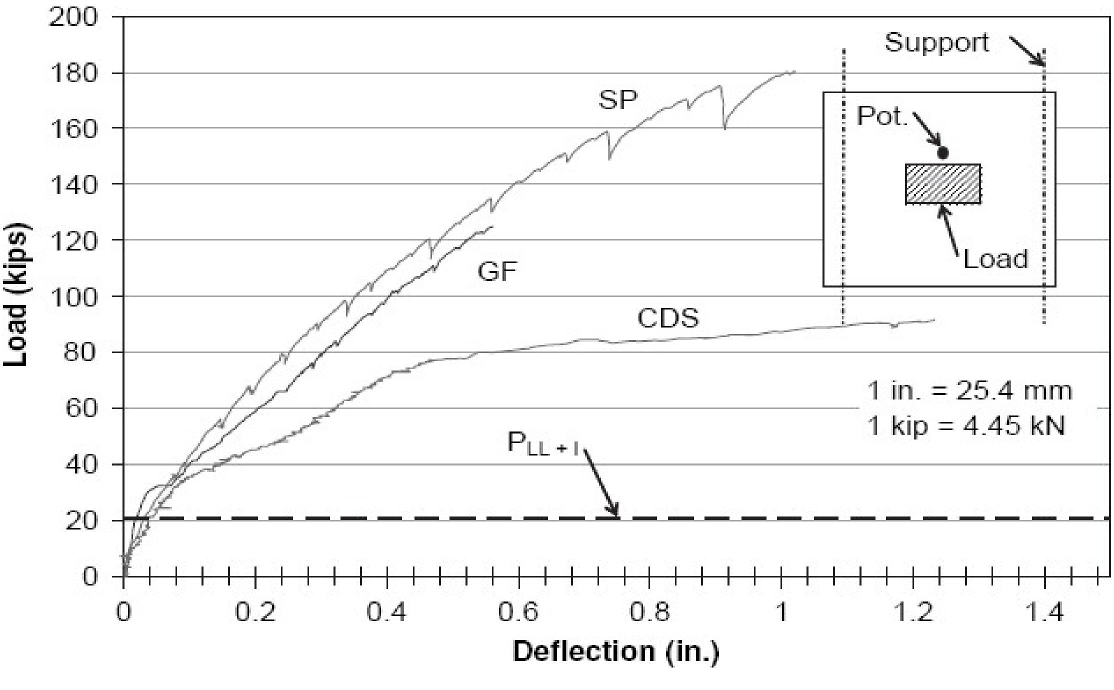


Fig.2.37 Load and the deflection behaviour for panel specimens**.(Bank et al.,2006*)***

2.5 Splicing of FRP SIP Structural Forms

Emir et al. (2014) experimental research focused on the design and the spacing of the splices of SIP FRP forms used in decks of concrete bridges. Typically, as shown in Fig 2.38, the panels of FRP that span the distance between limited size girders and are therefore joined by overlap. Overall 23 additional lap splice tensile tests addressed numerous attachment processes including adhesive bolts of numerous spacing and diameter. 7-scaled bridge deck structures were to built with the FRP panels of varying widths, some of with connected splices and also some with no bond at all in the area of overlap. Research has shown that using narrow FRP sheets of small width-to-deck thickness (b / t) ratio significantly reduces the deck capacity when no splice bond is supplied as narrow panels can force the punching shear gap to stop at a steeper angle at a splice, thereby reducing the punching shear capacity. The b / t=1.9 deck showed a decreased capacity of 24 percent compared to b / t=7.2. The final load of error ranged within 5.7 to 8.8 times to the respective load of service. Bonded-splice decks have no impact on plate width strength. The ideal splice was spaced at 1.8 times the length of the overlap by combining adhesive and fasteners dia equal to the plate thickness for a 4.3 times the plate thickness overlap splice.Bonded-splice decks have no effect on the strength of the plate width. Ultimate failure load varied within 5.7 to 8.8 times to the corresponding service load. The ideal splice was spaced to 1.8 times to the length of overlap by combining adhesive and the fasteners of diameter equal to the thickness of the plate for an overlap splice of 4.3 times the thickness of the plate. It created 68 percent of plate tensile strength, while fasteners alone, depending on their spacing and diameter, produced only 14–45 percent strength.

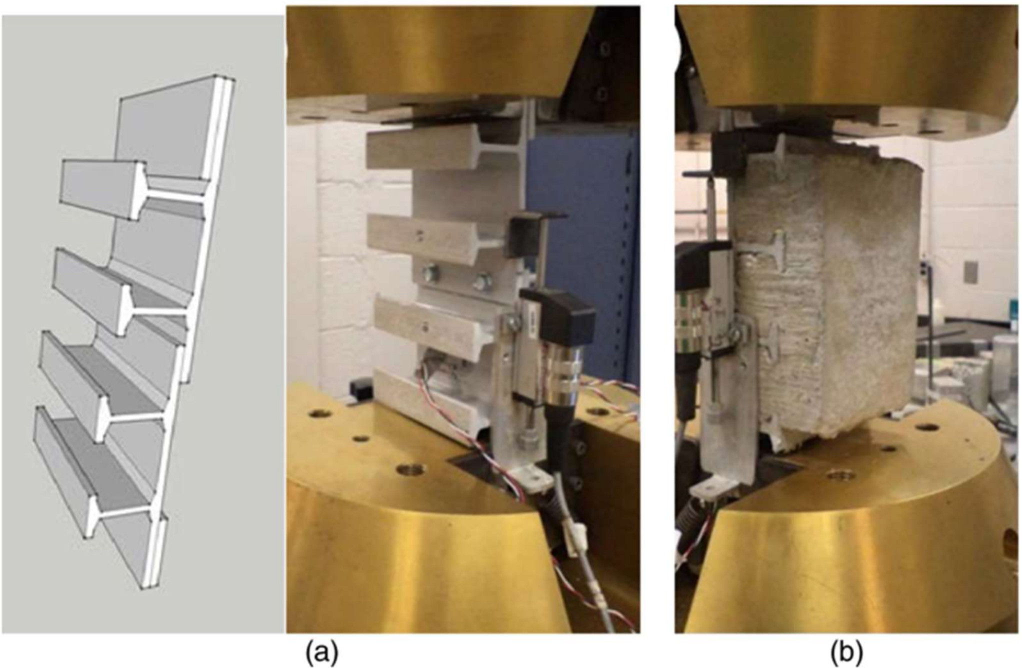

(a) (b)

Fig 2.38 Tension splice test (a) without (b) with concrete infill

Fam et al. (2013) explored the structural FRP SIP system for decks in concrete bridges. The panel consists of composite FRP panels stretching within girders and is acting both as continuous formwork, reinforcement of the bottom slab. The experiment on a scale of 1:2.75 consisted of the ten bridge panel segments and to examine various serious parameters, specifically: varying deck sample size (w) relative to length (s) and variable concrete strength, interface bond situation and deck load location. The deck performance has been shown to approach the realperformance built as the width (w) increases with respect to the span (s). The aspect ratio (w / s) higher than 1.6 was discovered to reflect efficiency properly and at reduced aspect ratios to prevent overly conservative outcomes. Variable concrete resistance from to 17 MPa to 42 MPa in the same decks led in a 20 percent increase in ability but did not affect rigidity. Applying FRP-concrete surface adhesive connection to produce 30% and 73% composite piece improved deck strength and original rigidity. Loading decks with that of adhesive bond directly to above the splice of the FRP led in a 20 percent decrease in power relative to insert between splices halfway. This is the reverse pattern of non-adhesive bonding decks.

CHAPTER 3 EXPERIMENTAL PROGRAM

3.1 GENERAL

In this chapter, details of preliminary casting and flexural testing of beams and one-way concrete slabs casted using GFRP SIP stay-in-place formwork is discussed which performs the role of permanent formwork and tensile reinforcement.

The casting and testing are done in two phases: -

I. Casting and testing of FRP Flats
II. Casting and testing of FRP SIP Beams & slabs

3.2 COUPON TENSION TEST

In order to check which epoxy is best suited as adhesive for making the butt joint between FRP’s, two FRP flats of size (222 mm x 65 mm) having butt joint was prepared. Two different epoxies were used for casting. The epoxies used are Araldite and Ark336. The size of cover plate of Butt joint is 65 x 65 mm. The curing period was 7 days.

Fig 3.1 FRP Flats having Butt Joint

3.3 BEAMS & SLAB CASTING

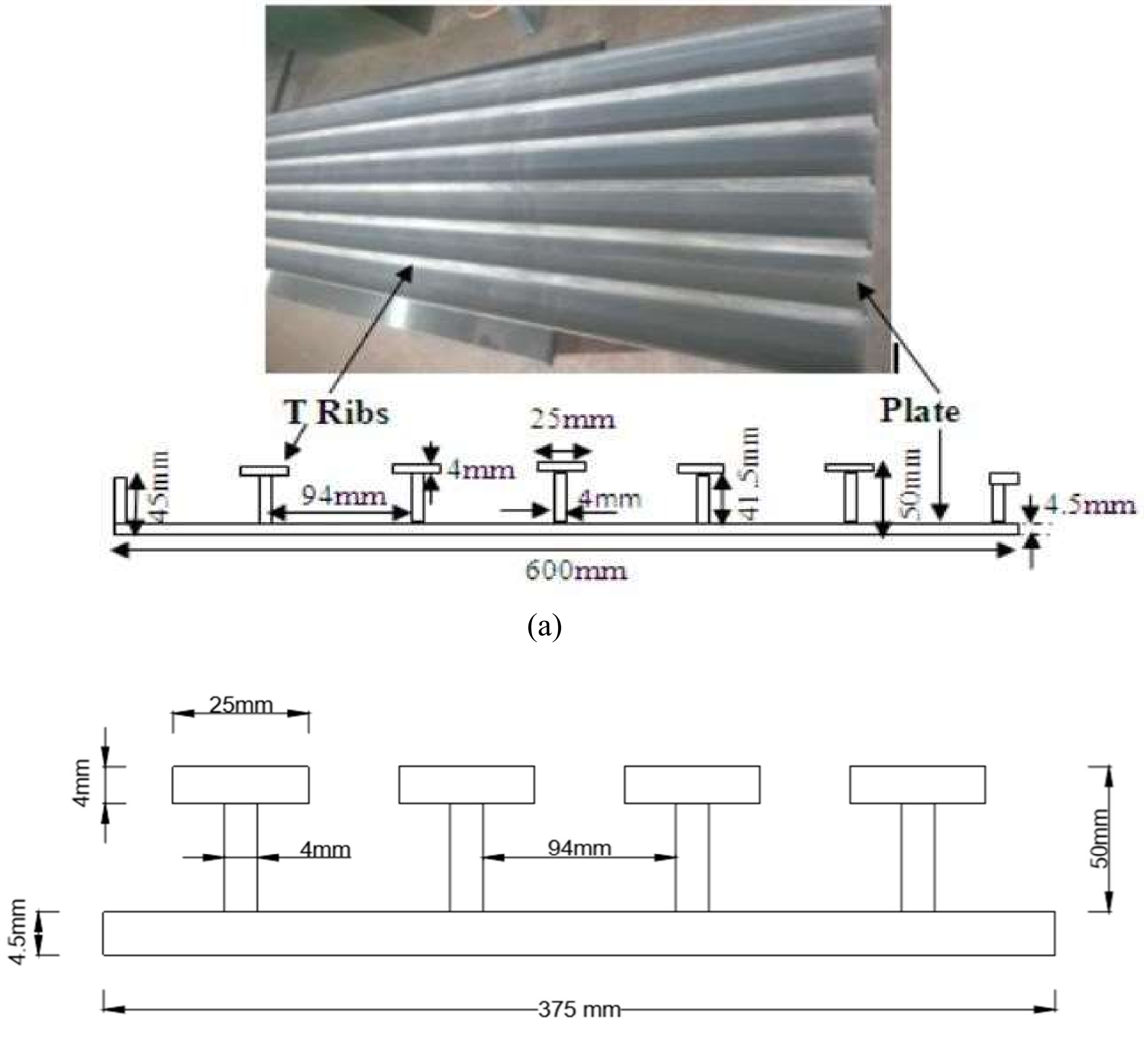
The details for FRP SIP formwork for casting is presented below.

3.3.1 Materials Used

The major materials used for FRP SIP formwork construction are GFRP planks, adhesive and concrete. The properties of all these materials have been discussed in the following section.

- **GFRP Plank** - GFRP formwork was used as the permanent formwork for casting of the concrete. Actual width of the plank available was 600mm as shown in Fig.3.2(a). Total

length of the formwork used was 3.2m and width of around 0.375m. There were three T stiffners running along the length of the plank that plays the of reinforcement. Other specifications of the plank are mentioned in Fig.3.2(b). Properties of GFRP plank are mentioned in Table 3.1.



(b)

Fig 3.2 (a) GFRP Plank Available (b)Dimensions of the Used GFRP Plank

Table 3.1 Properties of the GFRP Profile **(Ircon Jodhpur)**

	Thickness(mm)	Young's modulus (GPa)		Tensile strength (MPa)		Volume fraction
		Average	Std. Dev.	Average	Std. Dev.	
Plate	4.5	27.9	2.55	375.5	5.86	0.35
Stiffeners	4	23.8	2.2	352.3	5.45	0.3

- **Concrete**- For casting of beams and slabs concrete of grade M-40 was used as per the IS codal provisions. The design mix proportions was 1:0.43:1.5:0.94 with 0.015 water reducing admixture. Portland Pozzolana cement is used for preparing concrete. Aggregates of size 10mm having Specific Gravity of 2.62 is used. Specific gravity of the sand which was used 2.65 and it belonged to zone II. Also super plasticizer called Complast 430 was used with a dosage of 0.015.
- **Type of adhesive used**- Adhesive used was Sikadur 31 for bonding between concrete and GFRP and Ark 336 for making Butt Joint. The mechanical properties specified by the manufacturer are presented in Table 3.2.

Table 3.2 Mechanical Properties of the Adhesive **(Sika India Pvt Ltd)**

Properties	**Adhesive (Sikadur 31)**
Pot life	45 minutes at 25°C
Viscosity	Viscous thixotropic
E modulus	5 GPa
Elongation at break	0.4%
Tensile strength	15 MPa
Flexural strength	30 MPa
Bond strength	8-10 Pa

- **Formwork** - For the casting of the beams, formwork of beam having size 150mm x 150mm x 700mm is used and for slabs steel side forms were used as shown in Fig.3.3 These side forms were placed around the GFRP plank for casting of concrete.

Fig.3.3 Steel Side Form

3.3.2 Casting Set-up

For the casting of the slabs it was required to put the plank along with the steel side formwork on a raised platform. Therefore, a platform of cubes was created to achieve the height of 300mm from the ground after which the steel rods were placed over the cubes at a distance of 100 mm from the ends over which the plank was placed. The front view of the test set-up is shown in the Fig.3.4.

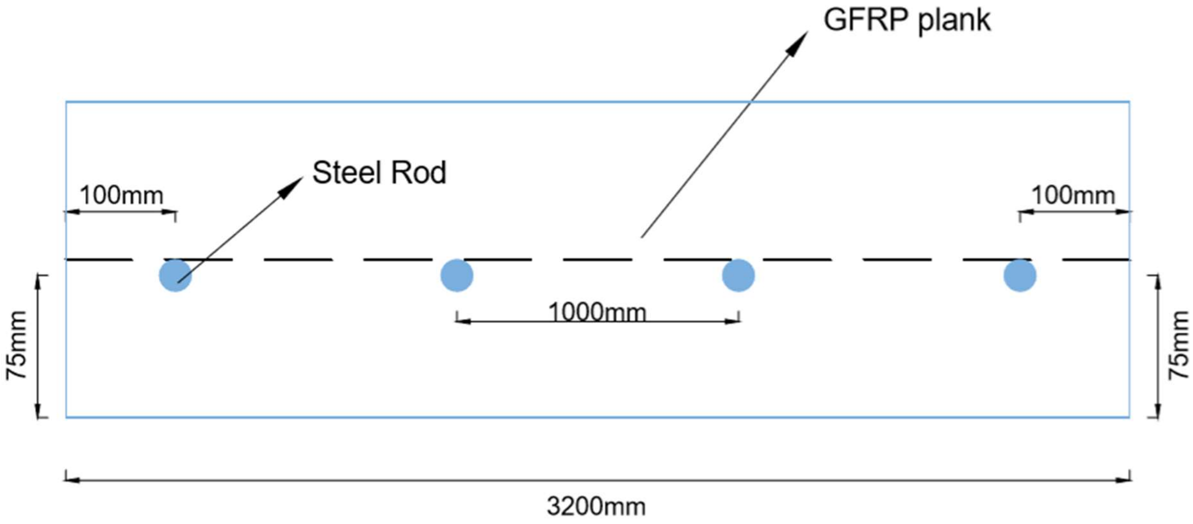


Fig.3.4 Position of Rods for Support (front view)

3.3.3 Beam and Slab Fabrication

Five beams having size (150 x 150 x 700 mm) & two slabs having size (375 x 150 x 3200 mm) were casted with different configurations. The test matrix for the casted specimens is shown in Table 3.3.

Table 3.3 Test Matrix

S.No.	Specimen	Description
1	Beam without joint (Control Beam)	BC
2	Beam having longitudinal joint with bolt	BLB_0
3	Beam having transverse joint with bolt and adhesive	BTB_0A
4	Beam having transverse joint with bolt	BTB_0
5	Beam having longitudinal joint with adhesive	BLA
6	Slab having longitudinal joint with adhesive	SLA

7	Slab having longitudinal joint with bolt	SLB_0

3.3.4. Casting of Beams

For the casting of beams, firstly plank was cut as per the specified dimensions of 700mm in length and 150mm in width. The required section of the plank consists of two T-ribs running along the length of the plank.

For one beam namely BC full Plank length was used without any cut referred as Control Beam .

Two planks for two beams namely BLB_0 and BLA were cut into two halves longitudinally. For Specimen BLB_0 as shown in Fig 3.5, Single cover Butt joint was made of size 700 x 60mm by using 6mm dia bolts 3 on each side. For Specimen BLA, Single cover Butt joint was made of size 700 x 60mm by using only adhesive Ark 336.

Two planks for other two beams namely BTB_0A and BTB_0 were cut into two halves transversely . For Specimen BTB_0A as shown in Fig 3.6, Single cover Butt joint was made of size 100 x 60mm by using adhesive Ark 336 and bolts of dia 6mm 2 on each side. For Specimen BTB_0 as shown in Fig 3.7 ,Single cover Butt joint was made of size 100 x 60mm by using only bolts of dia 6mm 2 on each side.

Each plank joint made by using adhesive was then allowed to cure for almost 7 days .After that adhesive (Sikadur-31) is applied over the base plate and also on the top flanges of the T- section of the plank. There was no adhesive appliedon the vertical ribs of the T- section. After the application of the adhesive , concreting was done.

Fig 3.5 Specimen BLB_0

Fig 3.6 Specimen BTB_0A

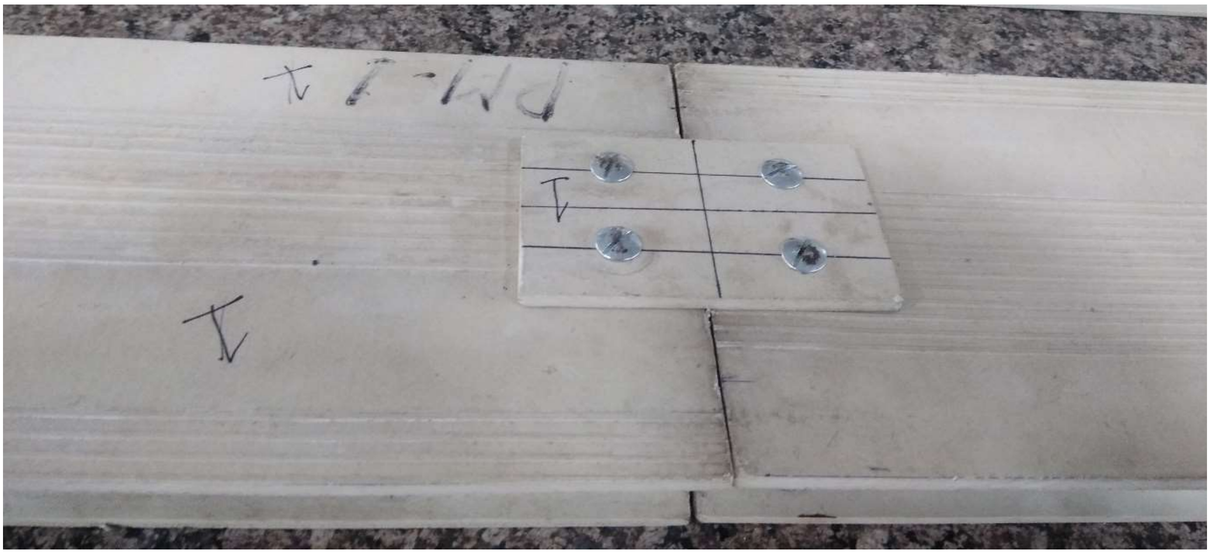


Fig 3.7 Specimen BTB_0

3.3.5 Casting of Slabs

For the casting of slab , cut the plank as per the dimension of the slab to be casted. The required dimension of the plank was 3.2 m in length and 375mm in width. The required section of the plank consists of 4 T ribs running along the length of the plank. For specimen

SLA , Single cover Butt joint was made of size 3.2 x 0.375m by using only adhesive Ark 336. Then curing is done for 7 days. After that adhesive (Sikadur-31) is applied over the base plate and also on the top flanges of the T- section of the plank as shown in the Fig.3.8. There was no adhesive applied on the vertical ribs of the T- section. Now the plank was placed over the raised platform of height around 300 mm with rods acting as a support at the ends. After this the sideforms of height 150 mm were put around the GFRP plank.

Fig.3.8 Adhesive Bonded GFRP Plank

After the application of the adhesive Sikadur-31 the concrete was poured within 30 minutes. To measure the deflection in the slab 3 dial gauges were placed below the slab out of which 1 was placed at the center and other two were placed at a distance of 0.75 m to the right of the center and 0.75 m to the left of the center respectively. Casting of the slab was done using concrete of 28 days compressive strength of 40 MPa. During pouring of concrete the weight of concrete in one container was measured which comes out to be 25 kg and after pouring of every 4 container of concrete that is around 100 kg, concrete was spread evenly and reading in the dial gauge were noted. The same procedure was repeated till the concrete fills up to the height of the side form. Casted specimen SLA is shown in Fig.3.9

Fig.3.9 Casted Specimen SLA

3.4 FLEXURAL TESTING OF BEAMS AND SLABS

The beams and slabs were tested in two point flexural loading. The deflection at mid span in case of beams and deflection at mid span and at quarter span in case of slabs was measured using dial gauges of 0.001 mm level.

For testing of beams, the beam was placed over the two I sections which were at a distance of 600 mm apart. Universal Testing Machine was used to apply the load. One LVDT and One dial gauge were used to measure the deflections during flexural testing of the beam. Load Vs deflection curves were plotted till failure of beams.

To perform the flexural test on the slabs, the slab was placed over the two I sections which were at a distance of 3m apart and two-point loading was applied. Three LVDTs were used to measure the deflection during the flexure testing of the slab. One LVDT was placed at the centre and other two were placed at a distance of 750mm from the ends. Load Vs deflection curves were plotted to represent the results.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 GENERAL

This chapter presents the results and outcomes of the testing that has been performed on the different beam and slab specimens to test the efficiency of joining different planks of FRP SIP formwork. Prepared GFRP-beams and concrete slabs were tested in flexural load.

4.2 COUPON TENSION TEST

Direct tension test was done to check the suitability of adhesive for making the butt joint between different FRP SIP planks. Tensile test was done on Universal Testing Machine having capacity of 600kN. Butt joint using adhesive (Ark 336) reported the tensile strength of 15MPa while butt joint made using adhesive (Araldite) reported the tensile strength of 5MPa.

In the Butt joint made using adhesive (Ark 336) the FRP cover plate was failed in tension as shown in Fig 4.1. In case of joint made using adhesive (Araldite), the joint failed due to slipping of one of the main plates and the cover plate remained attached to the main plate as shown in Fig 4.2 .The failure is here due to shear failure of the joint.

Fig 4.1 Failure of FRP cover plate

Fig 4.2 Failure of joint after slipping of cover plate

From the pilot testing of coupons, it was decided to choose Ark 336 as an adhesive for further investigations of splices in FRP SIP. This adhesive will be used for comparing the performance of various kind of joints under flexural loading of beams and slabs.

4.3 BEAM RESULTS

4.3.1 CONTROL BEAM (BC)

The specimen BC (150mm x 150mm x 700mm) with supports separated by 600mm apart was tested under two-point loading test on Universal Testing Machine. As the load increased cracks started appearing under the point load at 45^0. Fig.4.4 shows the cracked beam which failed at an ultimate load of 74 kN and at ultimate deflection of 5.48mm at center as shown in Fig.4.3. Following observations are made in the control beam specimen:-

- In the control beam the failure mode observed was shear failure in concrete.
- No debonding failure of FRP from concrete was observed.

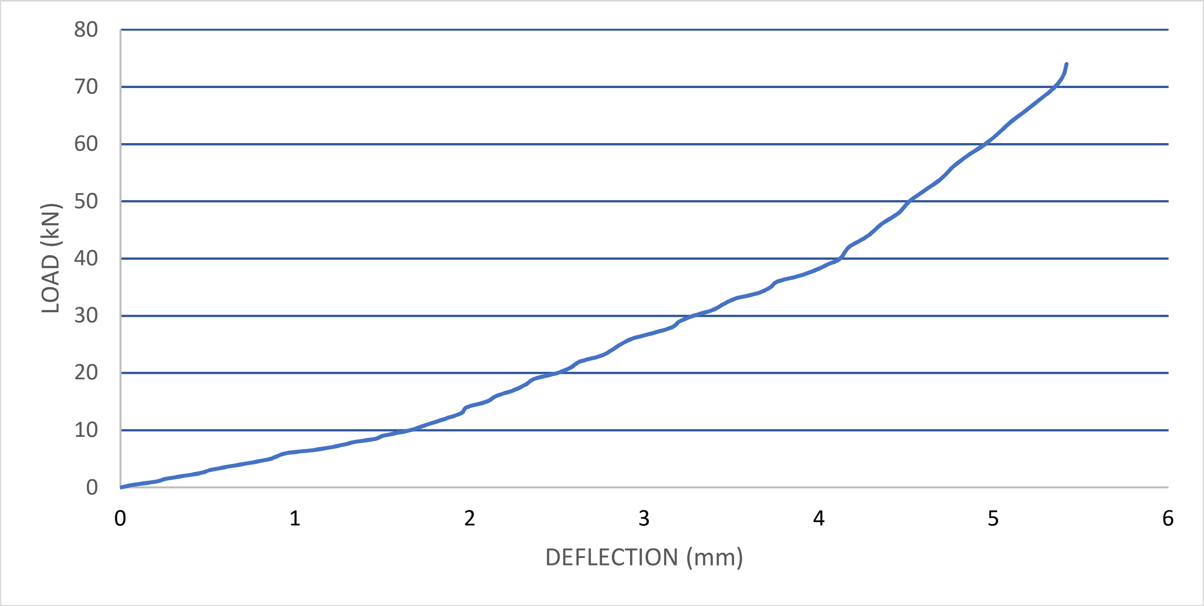


Fig 4.3 Load Vs Deflection plot of Control Specimen BC

Fig 4.4 Shear failure in Control Beam

No debonding of FRP from concrete

Fig 4.5 Condition of joint at failure in specimen BC

4.3.2 LONGITUDINAL JOINT

4.3.2.1 SPECIMEN BLB_0 WITH BOLTS

The specimen BLB_O (150mm x 150mm x 700mm) with supports separated by 600 mm apart was tested in two-point loading test on Universal Testing Machine. Fig.4.6 shows the cracks that occurred in the beam under the point load at 45^0 from top. The beam failed at an ultimate load of 78 kN. The total deflection achieved at ultimate load was of about 2.64mm at center as shown in Fig.4.7. Following observations are made in the beam specimen with FRP planks longitudinally joined with bolts:-

- The failure mode was shear failure in concrete .
- The butt joint sustained no damage due to loading as shown in Fig 4.8.
- No debonding or delamination of FRP from concrete was observed.

Fig 4.6 Shear failure in concrete (BLB$_0$)

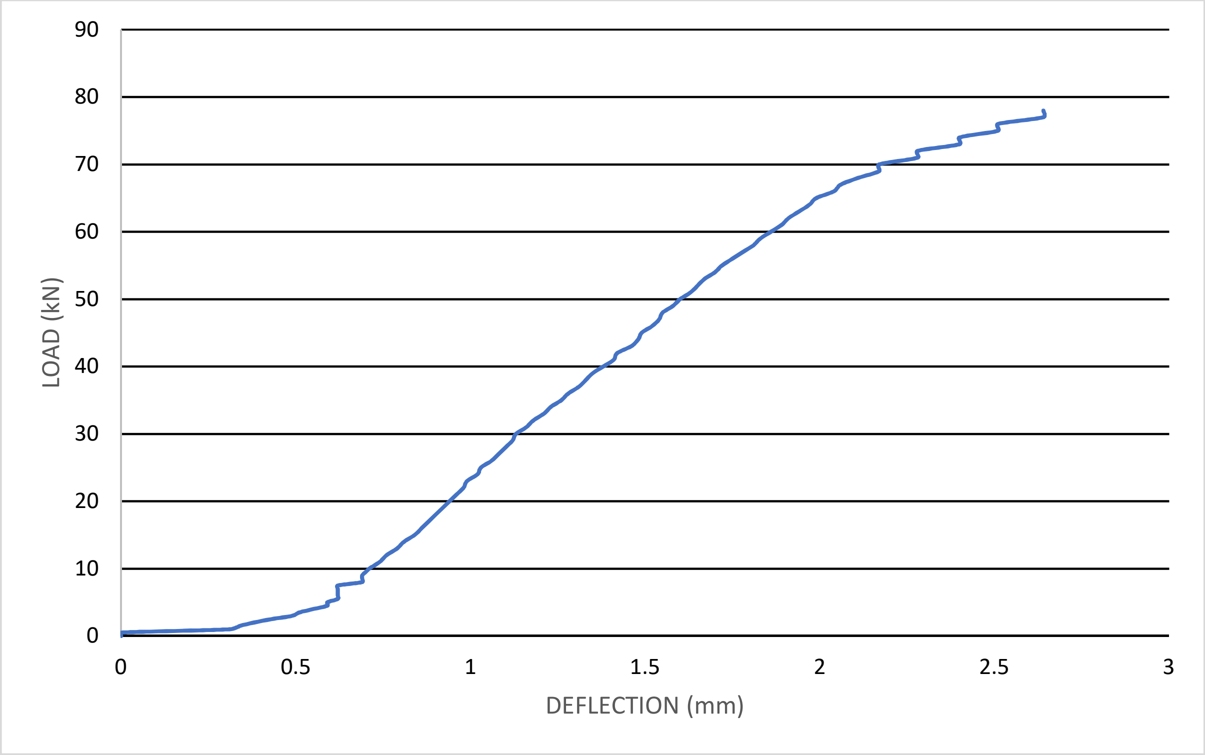


Fig 4.7 Load Vs Deflection plot of specimen BLB$_0$

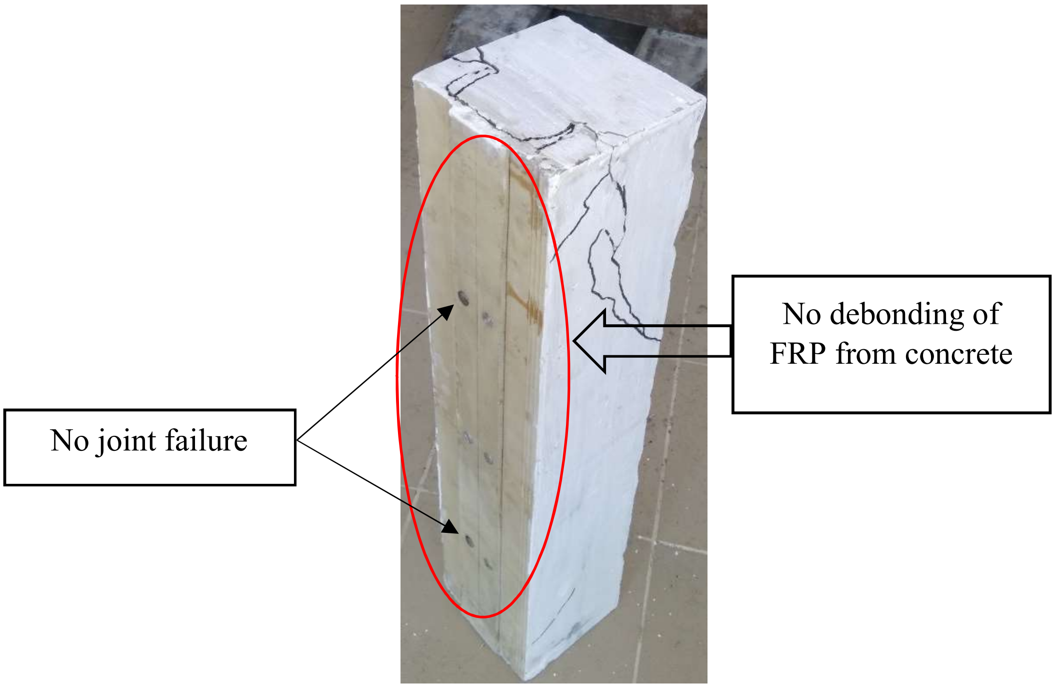


Fig 4.8 Condition of joint at failure in specimen BLB$_0$

Hence, it can be concluded that the failure in the FRP planks used as SIP with a longitudinal joint failed by concrete crushing. There was no failure observed in butt joint.

4.3.2.2 SPECIMEN BLA WITH ADHESIVE

The specimen BLA (150mm x 150mm x 700mm) with supports separated by 600mm was tested in two-point loading test on Universal Testing Machine. Fig.4.10 shows the cracks that occurred in the beam under the point load at 45^0 from top. The beam failed at an ultimate load of 79 kN .The deflection achieved at ultimate load was of about 5.78mm at center as shown in Fig.4.9. Following observations are made in the beam specimen with FRP planks longitudinally joined with adhesive:-

- The failure was observed in concrete as shear failure.
- The adhesively jointed butt joint did not fail under loading.
- No debonding or delamination of FRP from concrete was observed.

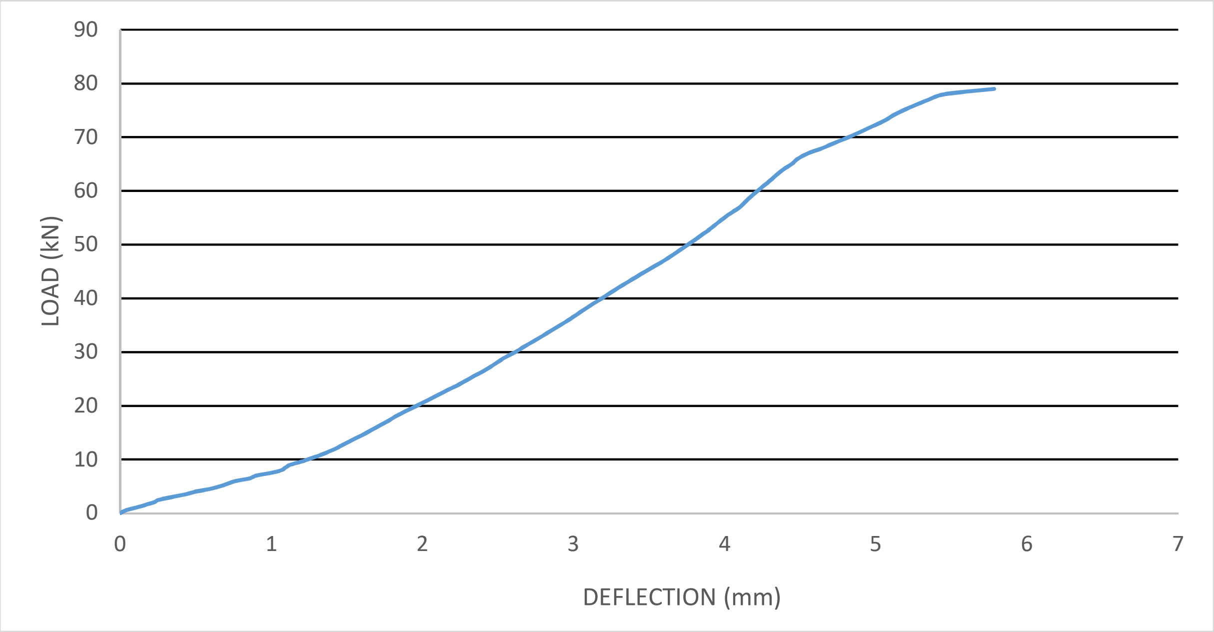


Fig 4.9 Load vs Deflection plot of specimen BLA

Fig 4.10 Shear cracks on specimen BLA

Hence ,the failure observed is in the concrete by crushing rather than the joint/bond between FRP and concrete.

Table 4.1 Overall results of longitudinal beam specimens

SPECIMEN	**BC**	**BLB$_0$**	**BLA**
Load (kN)	74	78	79
Deflection (mm)	5.48	2.64	5.78

Table 4.1 shows the comparison of performance of longitudinally jointed FRP SIP planks under flexural loading. It is observed that beam joined longitudinally with adhesive (BLA) reported 6.75% larger strength than the Control Beam (BC) .The beam joined longitudinally with bolts (BLB$_0$) also reported 5.4% larger strength than the Control Beam (BC).

Also, longitudinally joined bolted FRP beam (BLB$_0$) sustained less deflection of 51.82% in comparison to Control Beam (BC) which points towards the effect of providing joint in the FRP planks with bolts. Beam joined longitudinally with adhesive (BLA) sustained minor increase in deflection of 5.4% in comparison to Control Beam (BC) pointing towards better flexibility offered by adhesively jointed planks.

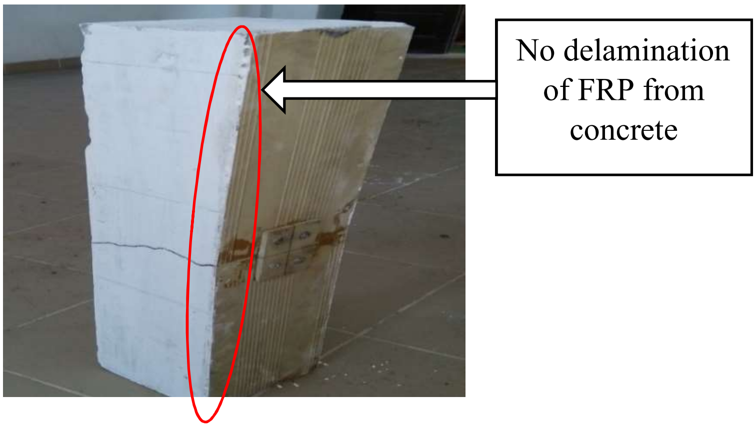
4.3.3 TRANSVERSE JOINT

4.3.3.1 SPECIMEN BTAB$_0$ WITH ADHESIVE AND BOLTS

The specimen BTAB$_O$ (150mm x 150mm x 700mm) with supports separated by 600mm apart was tested in two-point loading test on Universal Testing Machine. Fig**.**4.11 shows the cracks that occurred in the beam at midspan perpendicular to the longitudinal axis of beam .The beam failed at an ultimate load of 21 kN. The deflection achieved at ultimate load was of about 1.79 mm at center as shown in Fig.4.12. Following observations are made in the beam specimen with FRP planks longitudinally joined with bolts and adhesive:-

- The failure mode was flexure failure.
- The butt joint sustained no damage due to loading as shown in Fig 4.11

- No delamination or debonding of FRP from concrete was observed.



No delamination of FRP from concrete

Fig 4.11 Flexure cracks on specimen BTAB$_0$

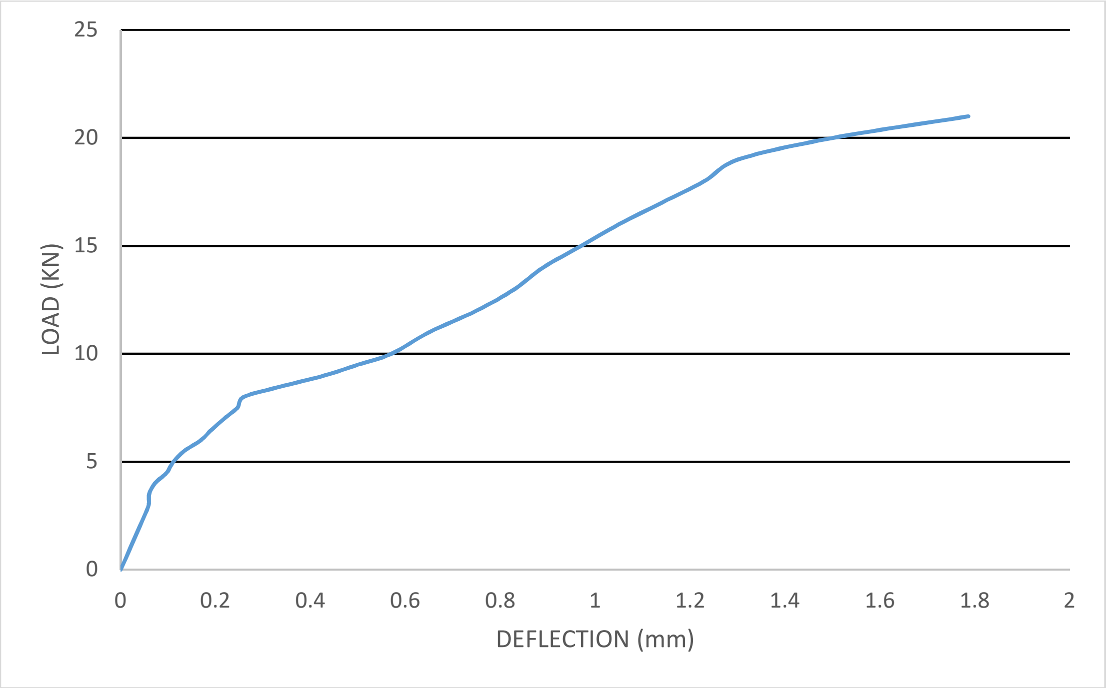


Fig 4.12 Load Vs Deflection plot of specimen BTAB$_0$

Hence , it can be concluded that the beam with FRP plank used as SIP with a transverse joint failed in flexure. There was no failure observed in the butt joint. This joint is not effective.

4.3.3.2 SPECIMEN BTB$_0$ WITH BOLTS

The specimen BTBO (150mm x 150mm x 700mm) with supports separated by 600mm apart was tested in two-point loading test on Universal Testing Machine. Fig.4.13 shows the cracks that occurred in the beam at mid span perpendicular to the longitudinal axis of the beam. The beam failed at an ultimate load of 17 kN. The deflection achieved at ultimate load was of about 3.92mm at center as shown in Fig.4.14. Following observations are made in the beam specimen with FRP planks transversely jointed with bolts:-

- The failure mode was flexure failure.
- The butt joint sustained no damage during loading as shown in Fig 4.13.
- No debonding or delamination of FRP from concrete was observed.

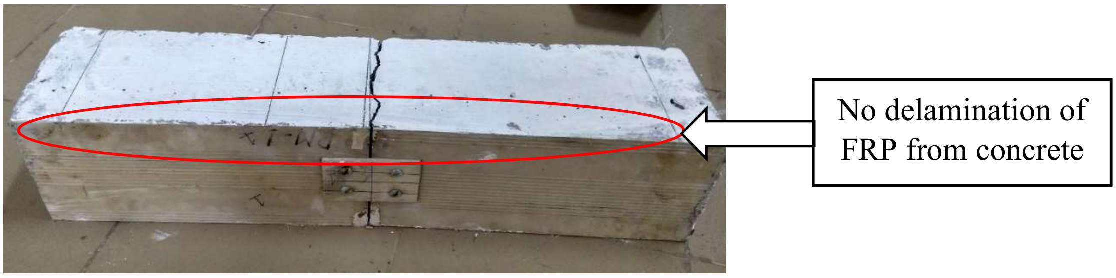


Fig 4.13 Flexure cracks on specimen BTB_0

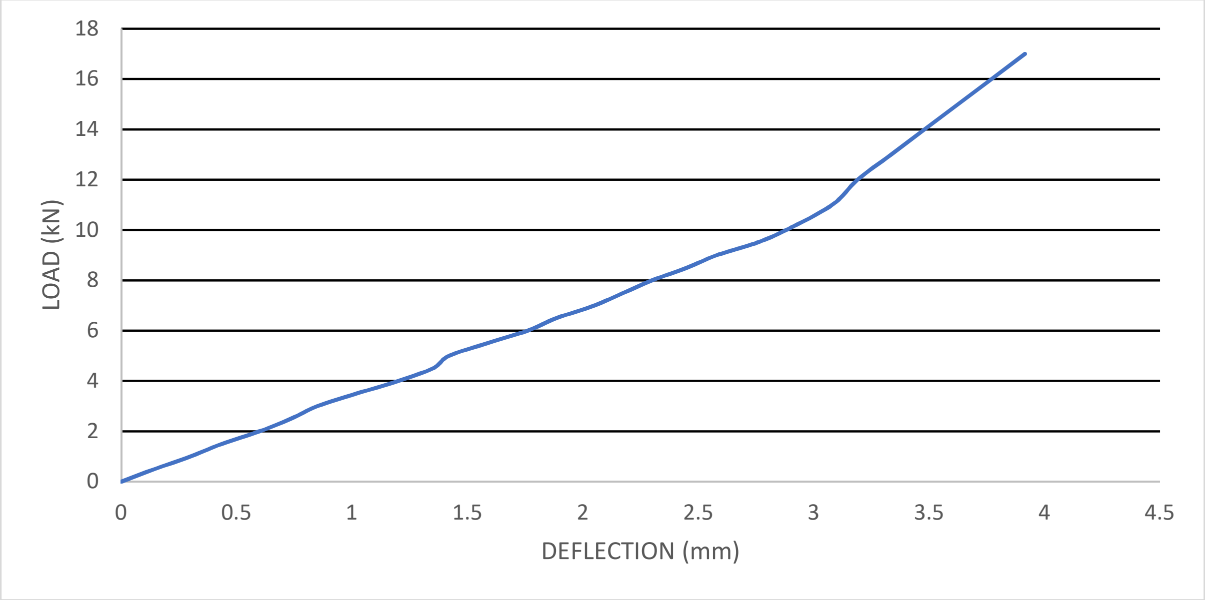


Fig 4.14 Load Vs Deflection plot of specimen BTB_0

Table 4.2 Overall results of transverse beam specimens

SPECIMEN	BC	$BTAB_0$	BTB_0
Load (kN)	74	21	17
Deflection (mm)	5.48	1.79	3.92

Table 4.2 shows the comparison of performance of transversely jointed FRP SIP planks under flexural loading. It is observed that beam joined transversely with adhesive and bolts ($BTAB_0$) reported 71.62% lesser strength than the Control Beam (BC). The beam joined transversely with bolts (BTB_0) reported 77% lesser strength than the Control Beam (BC).

Also, transversely joined bolted FRP beam ($BTAB_0$) sustained 67.33% less deflection in comparison to Control Beam (BC) .Beam joined transversely with bolts (BTB_0) sustained 28.46% less deflection in comparison to the Control Beam (BC).

Hence, it is concluded that transversely joined planks perform very poor in comparison to longitudinal as well as control beam. Therefore, testing of FRP planks in slab has been done only with longitudinal joint

4.4 SLAB RESULTS

The Control FRP slab specimen were tested by Goyal (2018). The Slab was failed at an ultimate load of 113kN. The deflection at mid-span and quarter-span was 47mm and 36mm respectively.

4.4.1 SPECIMEN SLA

The specimen SLA (3200mm x 375mm x 150mm) with supports separated by 3m apart was tested in two-point loading test on loading frame. Fig.4.15 shows the cracks that occurred in the slab under the point load at 45^0 from top .The slab failed at an ultimate load of 120 kN. The deflection achieved at ultimate load was of about 46.57 mm at mid-span and 36.5 mm at quarter-span as shown in Fig.4.16 and Fig.4.17 respectively. Following observations are made in the slab specimen with FRP planks longitudinally joined with adhesive:-

- The failure mode was shear failure in concrete.
- No debonding or delamination of FRP from concrete was observed .
- The butt joint sustained no damage during loading as shown in Fig 4.18

Fig 4.15 Shear cracks on specimen SLA

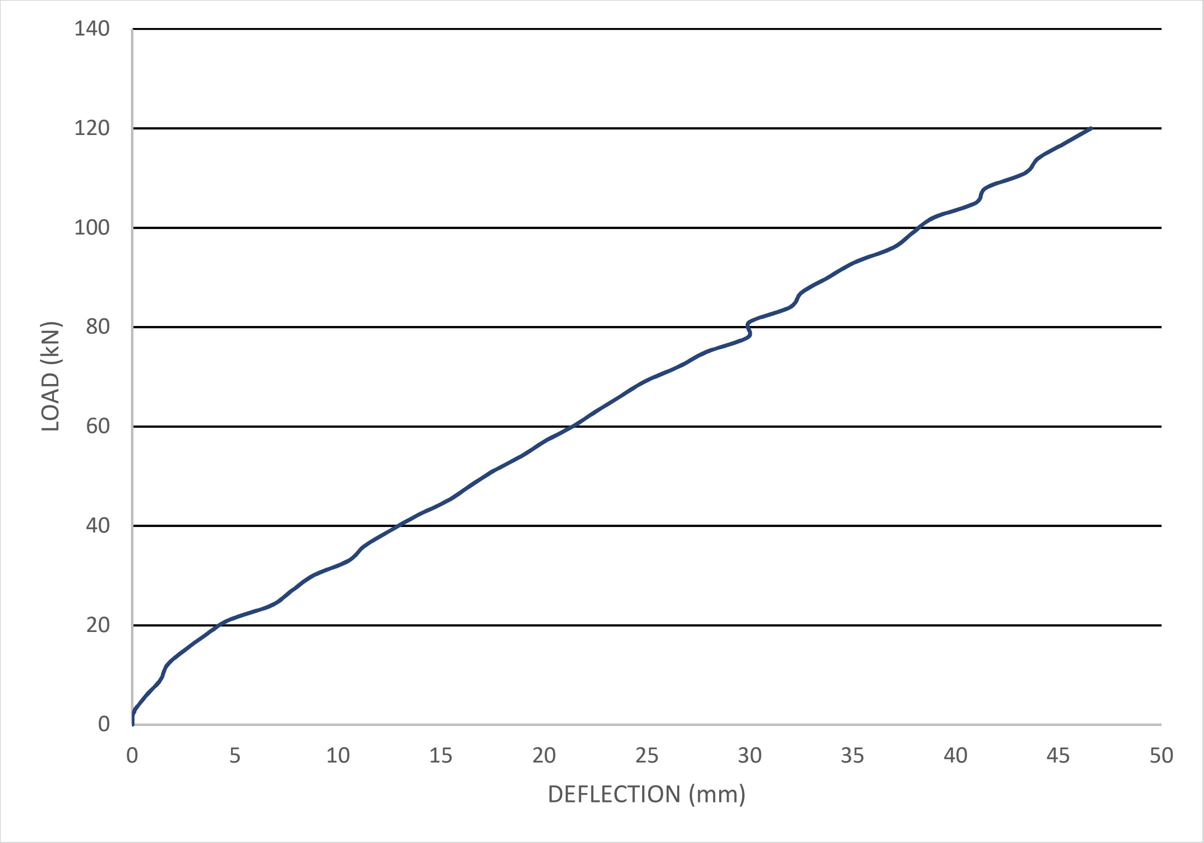


Fig 4.16 Load Vs Deflection plot of specimen SLA at mid-span

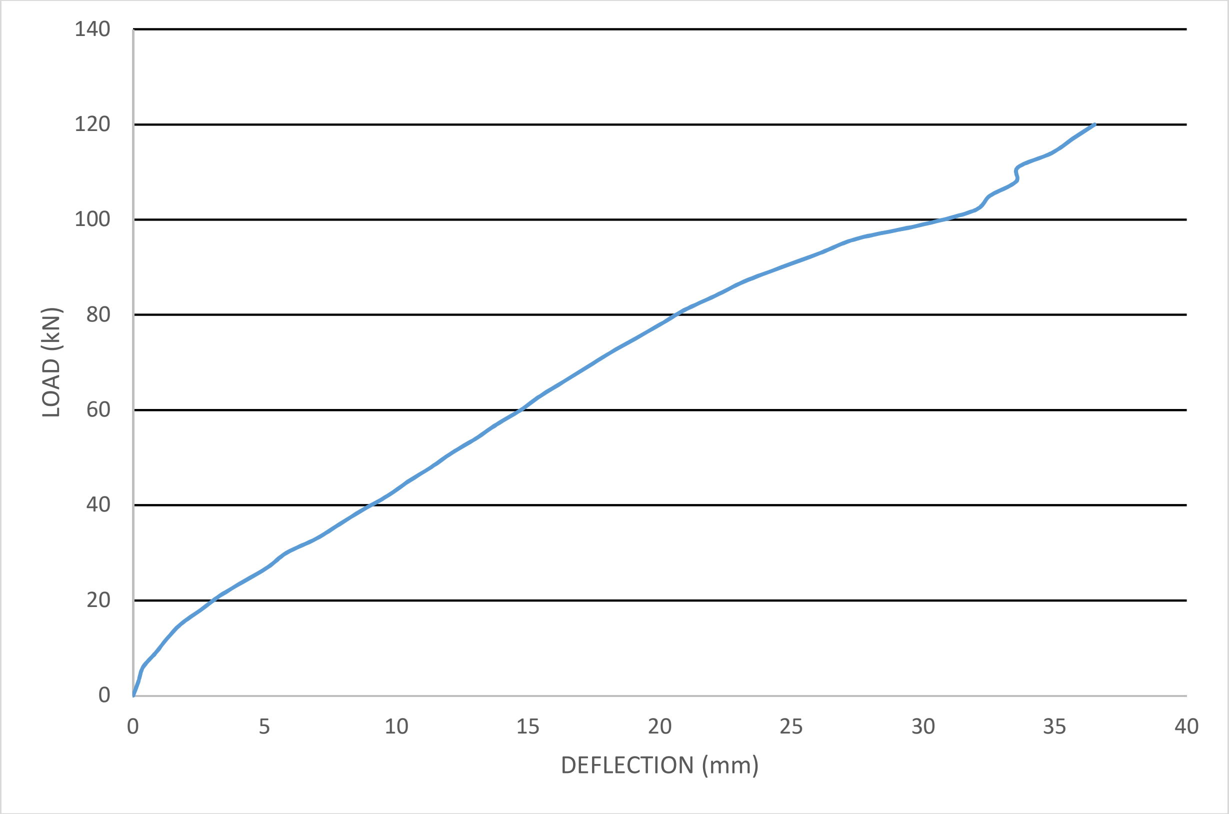
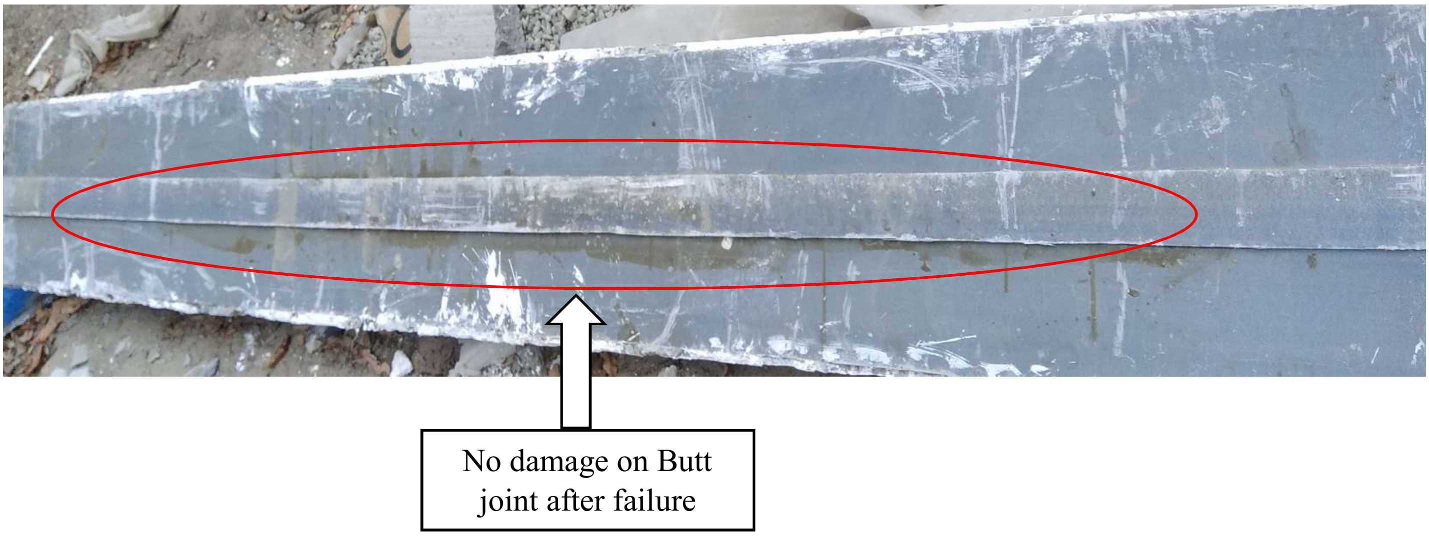


Fig 4.17 Load Vs Deflection plot of specimen SLA at quarter span



No damage on Butt joint after failure

Fig 4.18 Condition of joint at failure in specimen SLA

Hence, it can be concluded that the slab with FRP planks used as SIP with a longitudinal joint failed by concrete crushing. There was no failure observed in the butt joint.

4.4.2 SPECIMEN SLB_0

The specimen SLB_0 (3200mm x 375mm x 150mm) with supports separated by 3m apart was tested in two-point loading test on loading frame .Fig.4.19 shows the cracks that occurred in the slab under the point load at 45^0 from top. The slab failed at an ultimate load of 114 kN. The deflection achieved at ultimate load was of about 58 mm at mid-span and 38.95 mm at quarter-span as shown in Fig.4.20 and Fig.4.21 respectively. Following observations are made in the slab specimen with FRP planks longitudinally joined with bolts:-

- The failure mode was shear failure in concrete.
- The butt joint sustained no damage during loading as shown in Fig 4.22
- No delamination of debonding of FRP from concrete was observed.

Fig 4.19 Crack pattern of Specimen SLB_O after final stage

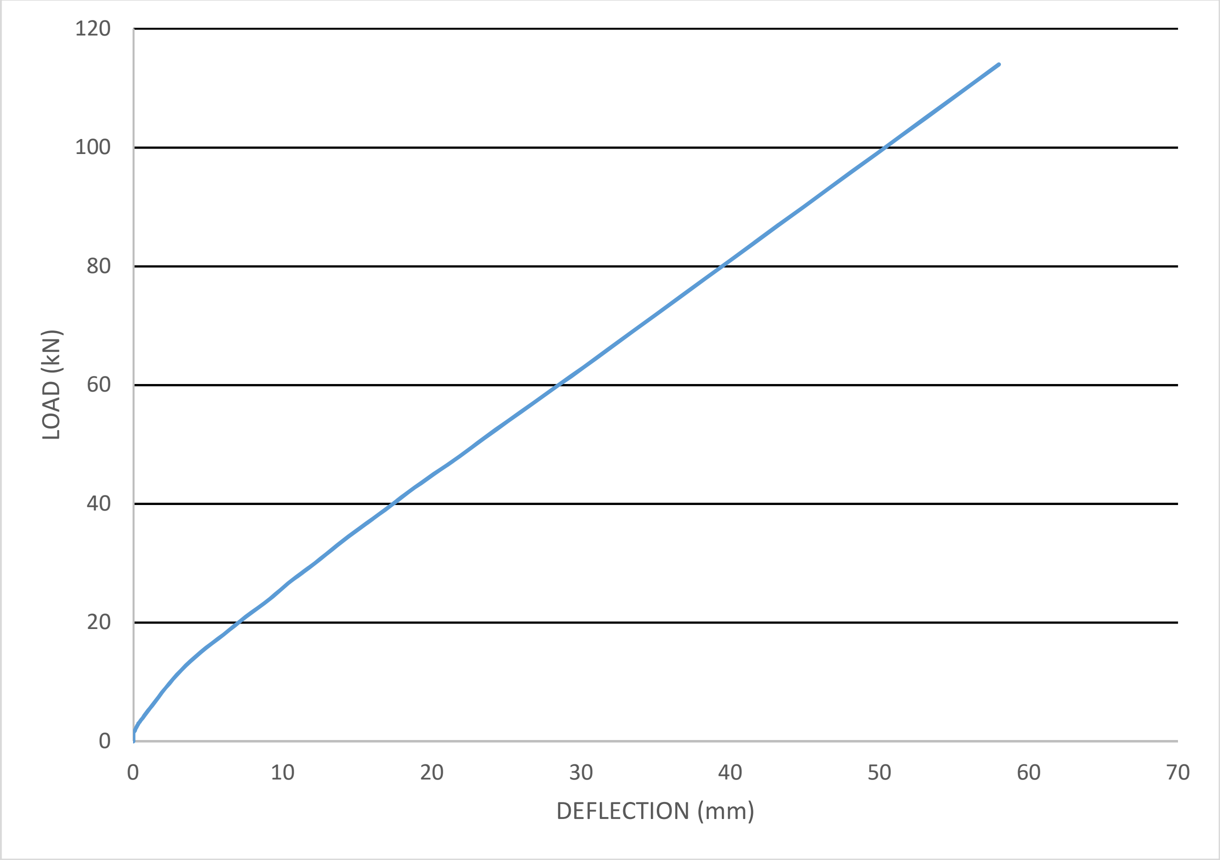


Fig 4.20 Load Vs Deflection plot of Specimen SLB_O at Mid Span

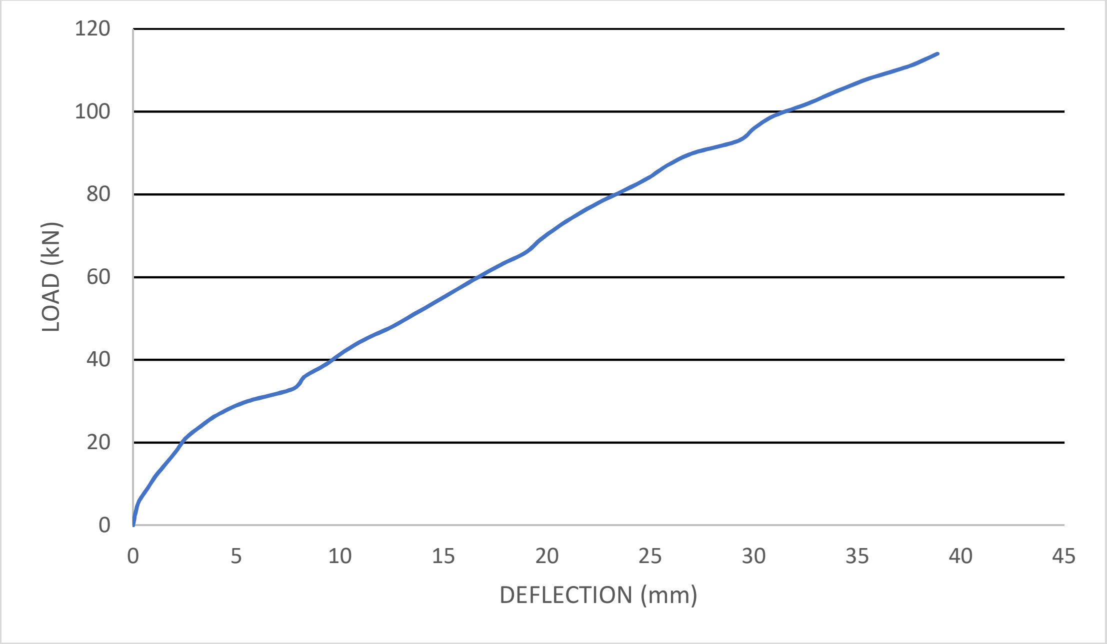


Fig 4.21 Load Vs Deflection plot of Specimen SLB$_O$ at Quarter Span

No damage to butt joint after failure of slab

Fig 4.22 Condition of joint after failure of specimen SLB$_0$

Hence, it can be concluded that the slab with FRP planks used as SIP with a longitudinal joint failed by concrete crushing. There was no failure observed in the butt joint.

Table 4.3 Overall results of Slab specimens

SPECIMEN	**SC**	**SLA**	**SLB_0**
Load (kN)	113	120	114
Deflection (mm) at mid-span	47	46.57	58
Deflection (mm) at quarter-span	36	36.5	38.95

Table 4.3 shows the comparison of performance of longitudinal jointed FRP SIP planks under flexural loading. It is observed that slab joined longitudinally with adhesive (SLA) reported 6.19% larger strength than the Control Slab (SC) .The slab joined longitudinally with bolts (SLB_0) reported very minor increase in strength of 0.88% than the Control Slab (SC).

Also, slab joined longitudinally with adhesive (SLA) sustained 0.91% less mid-span deflection in comparison to Control Slab (SC) and the slab joined longitudinally with bolts (SLB_0) sustained 23.40% more deflection in comparison to Control Slab (SC).

Also, slab joined longitudinally with adhesive (SLA) sustained minor increase in quarter-span deflection of 1.39% in comparison to Control Slab (SC) and the slab joined longitudinally with bolts (SLB_0) sustained 8.19% more quarter-span deflection in comparison to Control Slab (SC).

CHAPTER 5 : CONCLUSION

6.1 GENERAL

In this study GFRP planks having Butt Joint with different configurations were tested for their role as flexible SIP formwork for beams and slabs. Flexural performance of GFRP concrete beams and slabs was investigated using two point loading test. Comparison was made between flexural performance of beams and slabs with control beam and slab. For achieving composite behavior between GFRP plank and cast-in-place concrete, Sikadur-31 adhesive is being applied on GFRP plank.

6.2 CONCLUSIONS

1. In all specimens of beams and slabs, no debonding or delamination of FRP from concrete was observed.
2. FRP planks used as SIP with a longitudinal joint failed by concrete crushing. There was no failure observed in butt joint.
3. From Coupon tension test, it was concluded that strength of Ark 336 adhesive is 3 times that of Araldite adhesive. Hence Ark 336 is better adhesive.
4. The Longitudinal butt joint made by using adhesive has more strength as compared to butt joint made by using bolt and Control Beam.
5. The transverse butt joint made by using bolts as well by using bolts and adhesive has very low strength as compared to the Control Beam.
6. Slabs having longitudinal butt joint using adhesive has more joint strength as compared to that using bolts as well as Control Slab.

6.3 SCOPE FOR FUTURE WORK

The work can be extended as follows:

1. The use of GFRP as a flexible formwork is new to the construction industry. Structural members with different configuration can be casted.
2. Concept of flexible formwork can be extended to the use of different type of formwork which can provide liberty to cast structural members of different configuration like fabric formwork.
3. Some technological advances can be made to allow its failure to be ductile rather than brittle.

4. The primary issue with using FRPs is the fire issue. It is therefore necessary to investigate the efficiency of the suggested system under fire

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