Thesis Report
On

PULTRUDED GFRP STAY IN PLACE FORMWORK AS BEAMS

A Thesis submitted in the partial fulfilment of
Requirement for the award of the degree of

MASTER OF ENGINEERING
IN
STRUCTURES

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CERTIFICATE

This is to certify that the seminar report titled, **"PULTRUDED GFRP STAY-IN-PLACE FORMWORK AS BEAMS"**, being submitted by **Mr. Sumit Pathania**, in partial fulfilment of the requirement for the award of degree of **MASTER OF ENGINEERING IN STRUCTURES (M.E)** in the **Department of Civil Engineering, Thapar University, Patiala,** is an authentic record of student's on work carried out under our her under our guidance and supervision.

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PLACE

ABSTRACT

Commercially available Fiber Reinforced Polymer (FRP) off the shelf structural shapes have great potential as stay in place forms for concrete structures. This system simplifies and accelerates construction, and the non corrosive FRP forms can fully or partially replace steel rebar reinforcement. This report has described structurally integrated stay in place (SIP) FRP forms including their advantages and limitations. It provides a thorough review of the basic principles and research findings to date on stay in place FRP forms for concrete structures.

Open forms which are used for flexural members like beams, slabs, bridge decks etc. have been discussed in this report. Open forms are particularly well suited for applications where positive bending is involved. This is because the inherent location of the formwork, at the bottom of the member, allows it to provide tensile reinforcement for resisting positive moments. This resistance, however, can only occur if sufficient shear connection exists between the concrete and the formwork.

Literature review about open formwork addresses FRP profiles that have potential as structural forms, various bond mechanisms and flexural members that have been developed and studied is presented. It has also described various concerns that are related with open stay-in-place formwork. Implementation of the technology in the field is focused through examples of field applications on the advantage offered by these materials over conventional materials of construction.

So my thesis work was motivated by desire of using FRP SIP formwork in multi-storey buildings as beams. The experimental work performed by using FRP SIP formwork gave me an idea that these can be successfully implemented in residential and commercial structures.

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Chapter 1

Introduction

1.1 GENERAL

Conventional reinforced concrete structures are fabricated by casting concrete in temporary forms that are usually made from wood or steel. The forms are often held in place by temporary shoring or scaffolding structures. Upon hardening of the concrete, the forms and shoring are removed, revealing the concrete structure within. Stay-in-place formwork is a system that is not intended to be removed upon hardening of concrete for one or more reasons, often related to the speed and ease of construction. Open forms are particularly well suited for applications where positive bending is involved. This is because the inherent location of the formwork, at the bottom of the member, allows it to provide tensile reinforcement for resisting positive moments. This resistance, however, can only occur if sufficient shear connection exists between the concrete and the formwork. The elimination of conventional rebar cages can significantly simplify the engineering and detailing process, as well as saving a great deal of time and effort during construction. It can also help to improve the longevity of the system by eliminating steel reinforcements that are susceptible to corrosion. They often utilize fiber reinforced polymer (FRP) materials. Due to low track record of application of FRP in structure, compared to steel, their long term durability is yet to be confirmed. Since this type of formwork is typically mass produced using FRP pultrusion in factories, it is ready to be used immediately when it arrives at the construction site. It is also relatively light weight, so forms can be shipped, maneuvered, and installed by a few workers without the aid of heavy machinery. Since these forms have excellent stiffness and dimensional stability, the need for scaffolding or shoring is greatly reduced or eliminated completely. In this case, the FRP formwork can simply be rested on supports at either end of the span, and then the concrete can be poured onto the formwork. In essence, the resultant member is a concrete/FRP hybrid member in which each of these materials is utilized efficiently; the FRP resists tension, and the concrete primarily resists compression. While the initial cost of FRP stay-in-place forms is likely greater than that of conventional concrete forms fabricated from wood or steel, this additional cost would be offset by improved ease and speed of erection, and reduced life-cycle costs of the overall structure due to superior longevity and durability.

1.2 MOTIVATION

Fiber-reinforced polymer (FRP) composites have found increased application in bridge structures over recent years. Applications for strengthening and repair are already well established. A growing number of new bridges are constructed hybrid-FRP structures, in which FRPs are combined with traditional materials such as concrete. This is predominantly due to the advantageous properties of FRP composites, such as low self-weight, high strength, high degree of free formability, and substantial resistance to corrosion and fatigue. Furthermore, construction details can be designed much more simply than in the case of concrete decks. The water proofing layer and associated complicated parapet detailing are not necessary.

The application of such hybrid-FRP structures is still in bridge area only and very less application in commercial multistory buildings. So the thesis work was motivated to check whether such hybrid FRP structures can be brought into buildings or not. Another thing to check is whether the pultruded FRP sections commercially available have the strength capacity, shape to be used as beams. In addition to strength capacity, such sections can reduce the cost and speed of construction as compared with regular wooden formwork.

1.3 OBJECTIVES

The main objective for this research project was to examine that the feasibility of using FRP sections as beams. Another objective was to check that the commercially available sections are fit for beam formwork. Due to the non-standardized properties (i.e. fiber volume, type of layer and adhesive) of pultruded FRP sections and lack of available literature the main means chosen to show the feasibility was through laboratory testing. In order to meet these objectives the following project tasks were defined:

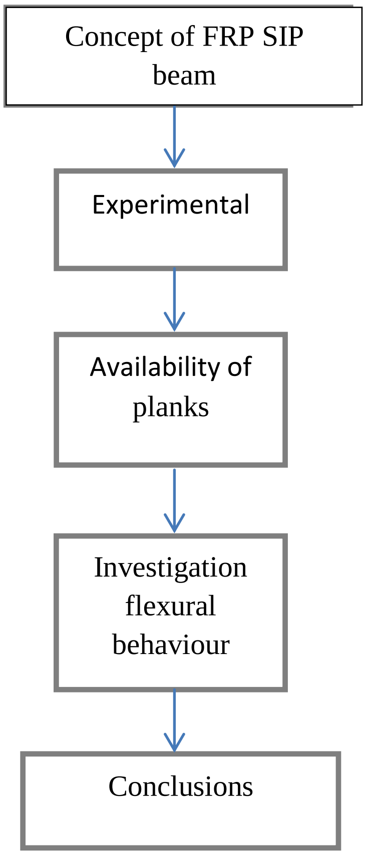
- Determining the various pultruded FRP shapes available and matching these with the various beam applications.
- Investigating different combinations possible for beam systems using different FRP SIP formwork.
- Examining the non-structural performance i.e. deflection under the sand loading of FRP SIP formwork.
- Examining the deflection at various points in GFRP SIP formwork caused by wet concrete loading during casting of beams with different GFRP SIP formworks.
- Examining the behavior of hybrid FRP concrete single span slab systems under flexural loading.
- Measure strain and deflection under expected loading conditions.
- Examining various failure modes of the slab.

1.4 SCOPE OF WORK

The scope of this study includes experimental investigations and analytical models of the behavior of flexural concrete members reinforced with GFRP stay-in-place structural open formwork.

The experimental investigation was intended to assess the feasibility of using commercially available, mass produced, pultruded GFRP sections as stay-in-place structural open forms for concrete beams. Four one-way slabs were constructed and tested under one point loading. These tests were used to quantify the performance of the concrete/GFRP hybrid system.

1.5OUTLINE OF THESIS



The contents of thesis are outlined below:-

Chapter 2: A brief introduction to FRP and SIP formwork.

Chapter 3: A brief review of literature pertaining to the topics studied in this investigation

Chapter 4: A introduction to methods and materials involved

Chapter 5: A manuscript that experimentally and analytically investigates concrete beam specimens using different cross sections

Chapter 6: Several results and conclusions that were drawn from this investigation.

References

Chapter 2

Fiber Reinforced Polymer As

Stay In Place Formwork

2.1 GENERAL

As a manufacturing techniques improve, the application of FRP materials become more diverse. Recently the FRP materials have been used as a construction material either strengthening deteriorated structures or replacing the ordinary steel bar. The fact of the matter is that many engineers consider FRP as one of the most innovative material that may overcome the inherited deficiency of reinforcing concrete structures by steel bars. That is the ability of steel to corrode in the presence of water and oxygen. In comparison with steel, FRP have higher resistance to corrosion, higher tensile capacity and lower weight. They are also non-conductive for electricity and non-magnetic. Even though the application of fiber reinforced polymer (FRP) as a concrete reinforcement becomes more common with various advantages, one of the inherent shortcomings may include its brittleness and on-site fabrication and handling. Unfortunately, FRP materials do not have a yield plateau, a characteristics that may limit the use of FRP in many civil works.

2.2 FIBER REINFORCED POLYMER (FRP)

2.2.1 Definition

Fiber-reinforced polymers (FRPs) consist of load-bearing fibers embedded in a polymer matrix and the reason for using reinforced polymers is to obtain maximum advantage from the reinforcement fibers. The reinforcement fibers usually dominate the mechanical properties, especially the tensile strength and stiffness of the composite. The volume fraction of fibers determines dimensional stability and resistance to creep under load.

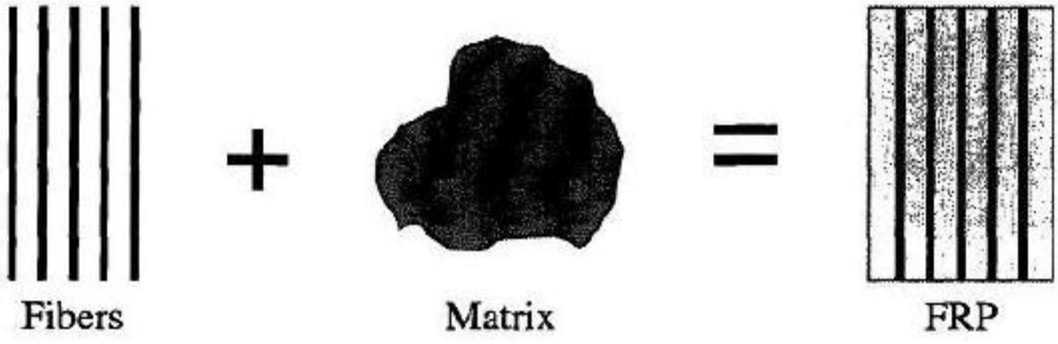


Fig. 2.1 Sketch of FRP

2.2.2 FRP material properties

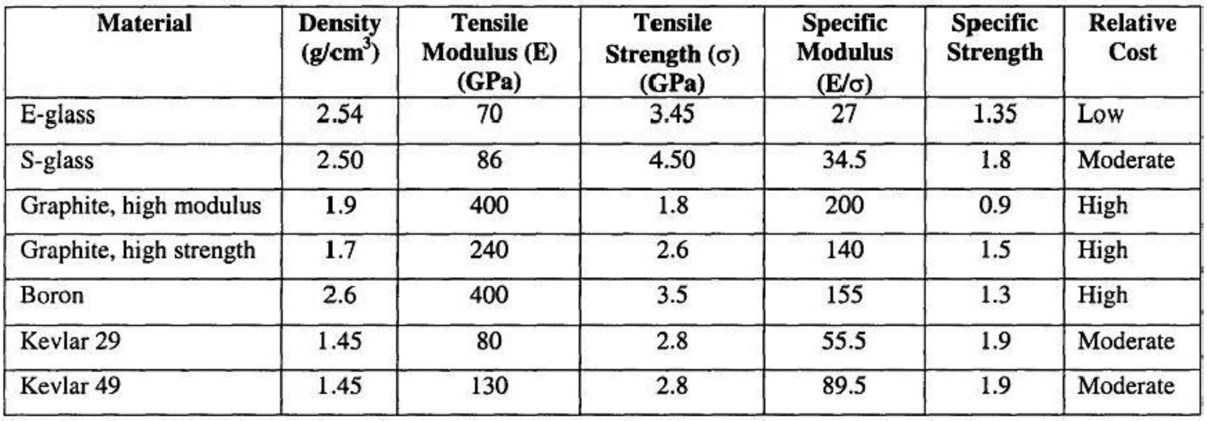
Physical and durability-related properties

FRPs can be optimally engineered to meet customer requirements. Different compositions lead to different properties and a wide range of desirable properties is achievable. The physical durability-related properties, such as density, electrical conductivity, resistance to UV light and temperature, and resistance to chemical effects are dependent on both the fibers and polymers. However, glass fibers are sensitive to humidity and alkaline environments while aramid fibers, unsaturated polyester and vinyl ester are sensitive to UV light. Only carbon fibers are generally considered to be stable in most environmental conditions.

Mechanical properties

The range of FRP mechanical properties is depends to a great extent on the type of fibers used (glass, aramid or carbon); fiber volume fraction, fiber orientation (unidirectional, bidirectional aligned or randomly orientated) and manufacturing method (ranging from manual to fully automated) and quality control. A further influence on the material properties of the FRP can have the choice of the adequate polymer resin. Typical properties of FRPs for different compositions of fibers and resins are shown in Table 2.1.

Table 2.1 Typical properties of fibers



Material	Density (g/cm^3)	Tensile Modulus (E) (GPa)	Tensile Strength (σ) (GPa)	Specific Modulus (E/σ)	Specific Strength	Relative Cost
E-glass	2.54	70	3.45	27	1.35	Low
S-glass	2.50	86	4.50	34.5	1.8	Moderate
Graphite, high modulus	1.9	400	1.8	200	0.9	High
Graphite, high strength	1.7	240	2.6	140	1.5	High
Boron	2.6	400	3.5	155	1.3	High
Kevlar 29	1.45	80	2.8	55.5	1.9	Moderate
Kevlar 49	1.45	130	2.8	89.5	1.9	Moderate

2.3 USE OF FRP IN CIVIL ENGINEERING STRUCTURES

Strengthening

The aim of strengthening existing structures is to repair structural deterioration and/or to increase the load-bearing capacity of structures. In both cases, existing structures are reinforced using tensile elements. The first method used for strengthening concrete was the bonding of steel plates to the reinforced concrete structure, but in recent years the steel plates have been replaced by FRP plates or sheets. The use of FRPs provides the advantages of easy installation, the high strength-to-weight ratio and high corrosion resistance. The primary strengthening components used are strips, sheet elements, prestressing rods and external cables.

FRP cables and reinforcements for concrete structures

FRP cables are advantageously used in bridge engineering due to their high strength-to-weight ratio and corrosion resistance. Typical applications are suspension and stay cable bridges, pre-stressed tendons for concrete structures and external reinforcement for beams. The high strength-to-weight ratio is Favorable for stay cable bridges, since the maximum span of the bridge is limited by the dead weight of the cables. Using high strength steel, the theoretical limit of the span is approximately 5000 m, whereas the span can be doubled by using aramid cables. (*Hollaway, L. C.; Head, P. R.: Advanced Polymer Composites and Polymers in the Civil Infrastructure*).

Another application of FRPs is as reinforcement in reinforced concretes. FRP reinforcements include textiles, rebars, internal tendons and short fibers. Apart from the high strength-to-weight ratio, the advantages of using FRP reinforcement instead of steel are the high corrosion resistance and low electrical conductivity.

All-composite new structures, Stay In Place Formwork

All-composite new structures, especially bridge superstructures, are constructed exclusively with FRP materials, while the abutments and piers are usually composed of traditional materials. Furthermore, FRP bridge decks for rapid deck installation were developed, offering simpler construction than concrete decks; for example, the waterproofing layer and associated complicated parapet detailing were no longer necessary.

In new hybrid bridge structures, FRP materials are combined with concrete. FRP permanent participating formwork is defined as a Stay-In-Place (SIP) system which remains structurally integrated with the concrete and provide structural strength to the overall system. Thus, the FRP not only acts as self-supporting formwork during construction, but remains in place to act as external, but durable, structural reinforcement. The combined structural system makes best use of both FRP and concrete materials, whilst having the potential of simplify the construction process by eliminating internal reinforcements and temporary support, in additional to their corrosion resistance and increase in on site safety. This type of formwork is not removed after the concrete has been cast. With the use of permanent formwork construction speed increases as time for the stripping of the forms is saved. It also results in the saving of labour cost. SIP formwork can be used to improve the constructability and durability of concrete that it encloses. The formwork components are assembled on site, braced and then concrete is poured. After the concrete has gained sufficient strength the bracing is removed and SIP form remains providing exterior shells. It has been found that most of the accidents during construction phase happen while removing the formwork. With the use of SIP formwork these accidents can be prevented. Thus the use of SIP formwork results in fast, economical and safe construction.

Stay-in-place (SIP) formwork can further be classified into two categories:

1. Structural SIP formwork – These forms part of the structural system that acts compositely with the framing system to resist the in-service live loads as well as wet concrete during casting. In other words they act as reinforcement after the concrete has hardened and as formwork during the plastic stage of concrete.
2. Non-structural SIP formwork – These are designed to resist only the loads from the wet concrete and construction live loads until the concrete has hardened.

Structural stay in place are more economical then non-structural stay in place forms due to the integration of the formwork with reinforcing system which also reduces the amount of material that needs to be installed.

SIP formwork can be made up of:

1) Steel
2) Reinforced concrete
3) Fiber reinforced polymers

2.4 TYPES OF FRP SIP FORMS

Broadly FRP forms are classified into two main categories:

1. Closed forms – It is in the form of circular, rectangular and square tubes. Fig.2.1. (d, e, f, g) represents different configurations of closed formwork.
2. Open forms – It is in the form of open square or trapezoidal FRP boxes or thin plates of FRP either alone or with pultruded T or I ribs. Fig.4.1. (a, b, c) and Fig.2.2. Represents FRP open formwork.

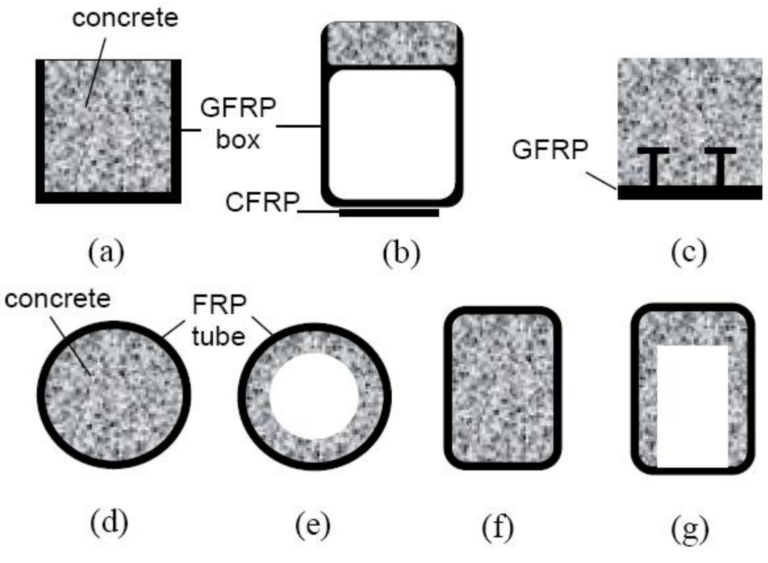


Fig.2.2 Different configurations of FRP structural forms for concrete members (ACI 440-XR)

2.5 OPEN SIP FRP FORMS

The term open form refers to forms that do not completely enclose the concrete within. This type of formwork is essentially a basin into which the concrete is poured. Stay-in-place open structural forms are particularly well suited for applications where positive bending is present. This is because the inherent location of the formwork (at the bottom of the member) allows it to provide tensile reinforcement for resisting positive bending moments. As a result, the majority of research performed on this topic has been related to slabs and beams.

Open formwork can be in the form of open box (Fig.2.2a). This type of formwork is mainly used in girders and beams. It can also be in the of hollow FRP box with a layer of CFRP at the tension side and concrete at the compression side (Fig. 2.2b). It is mainly used in bridge girders. It can be in the form of flat FRP plate or in the form of FRP plate (Fig.2.3 a) which is pultruded together with I or T shape ribs (Fig.2.2c, 2.3 b, c). When such formworks are used after placing all the plates vertical boundaries are attached at the exterior side and then concrete is poured in. The ribs can be of FRP or any other conventional material. Open FRP forms can also be trapezoidal in shape and can be produced as sheet pile section (Fig. 2.3e). It can be pultruded sheet which is stiffened by hollow FRP boxes (Fig.2.3 d).

Since open forms have excellent stiffness and dimensional stability, the need for scaffolding or shoring is greatly reduced or eliminated completely. In this case, the FRP formwork can simply be rested on supports at either end of the span, and then the concrete can be poured onto the formwork. For successful working of FRP stay in place open formwork both FRP and concrete has to work compositely. FRP resist tension and concrete primarily resist compression.

Till now there has been no widespread use of open formwork. Only few demonstration projects have been done till now with the exception of their use in bridge decks which has gained some popularity and now developed countries like USA and Canada are opting this material for bridge deck construction. This is due to the fact that construction involving FRP SIP formwork is much faster than the construction with conventional formwork. With this traffic delays are avoided and less inconvenience is caused to the public. Life of decks is more when FRP SIP formwork is used and reduces the maintenance cost. Live load carrying capacity is increased with the use of FRP deck panels.

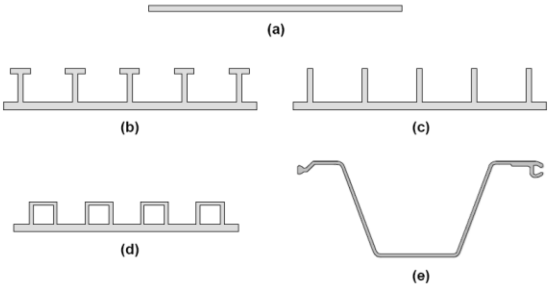


Fig.2.3 Some commonly available FRP sections (Honickman, 2008)

2.6 ADVANTAGES OF FRP SIP SYSTEM

The most common characteristics of the integrated systems are as follows:

1. The FRP shape acts as a permanent form for the concrete; hence, it will save the cost of formwork involved in conventional cast-in-place or precast industries;
2. Main reinforcement for concrete is provided externally by the FRP shape, even though additional reinforcement of other materials, such as steel, may be provided internally.
3. Depending on the nature of loading, the capacity and performance of the system may depend on the composite action between the concrete and FRP shape.
4. The system lends itself to optimization based on material properties of each component. The hybrid system provides the designers with several flexible parameters that can be controlled to achieve optimum design.
5. The contained concrete, in the case of CFFT, is protected from intrusion of moisture with corrosive agents that could otherwise deteriorate the concrete core.

Chapter 3

Literature review on Open Formwork Systems

3.1 GENERAL

This chapter generally reviews research that has been performed on stay-in-place open structural formwork for reinforced concrete flexural members. In particular, the chapter addresses FRP profiles that have potential as structural forms, various bond mechanisms, and flexural members that have been developed and studied. The literature on some concerns regarding FRP Open SIP mentioned earlier is now presented. These concerns are

- Bond mechanism interface
- Ductility of composite
- Splicing of FRP

3.2 BOND MECHANISMS BETWEEN CONCRETE AND STRUCTURAL FORMS

In order to ensure that stay-in-place open structural forms contribute as tension reinforcement in flexure, it is crucial that an adequate shear connection exists between the concrete and the form. Following studies have been carried out to study the effect of various types of bond mechanisms on the composite action of FRP SIP and concrete..

Hall and Mottram (1998) worked on a hybrid concrete-FRP section incorporating FRP stay-in-place open structural form. Ribbed FRP sheets produced as floor panels, provided tensile reinforcement, and behaved as permanent stay-in-place open structural formwork for the concrete slab overlay, as shown in Fig.3.1. The resultant concrete-FRP hybrid beams were tested in four-point bending. Initially, it was found that a significant amount of horizontal shear slippage occurred between the concrete and the FRP formwork. This severely limited the flexural capacity of the member since a large strain lag existed between the concrete and FRP.

In an attempt to combat the aforementioned problem, adhesive bonding was used. This was accomplished by applying adhesive (epoxy mortar) directly to the surface of the FRP formwork immediately prior to pouring concrete. This adhesive was specially formulated for bonding to fresh wet concrete. The resultant system behaved monolithically during positive bending. Plot of mean shear stress versus slip is shown in Fig.3.2. The observed mode of failure was diagonal tension shear cracking in the concrete, which can likely be attributed to the absence of shear reinforcement within the concrete, and the fact that the beams were designed to be over-reinforced. Tension cracking of concrete was severe in the vicinity of the longitudinal stiffening ribs of the FRP sheet. Overall, the concept of applying adhesive to the formwork prior to pouring concrete appears to have yielded positive results. It was an advantageous technique from a fabrication standpoint because it eliminated the need for mechanical shear studs or a bonded coarse aggregate coating on the surface of the formwork, both of which would be far more time consuming to install than an adhesive coating.

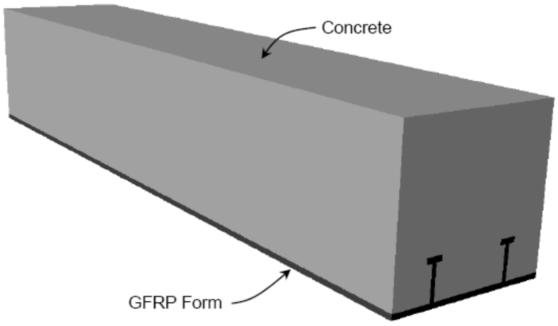


Fig. 3.1 Concrete and GFRP ribbed sheet hybrid section (Hall and Mottram, 1998)

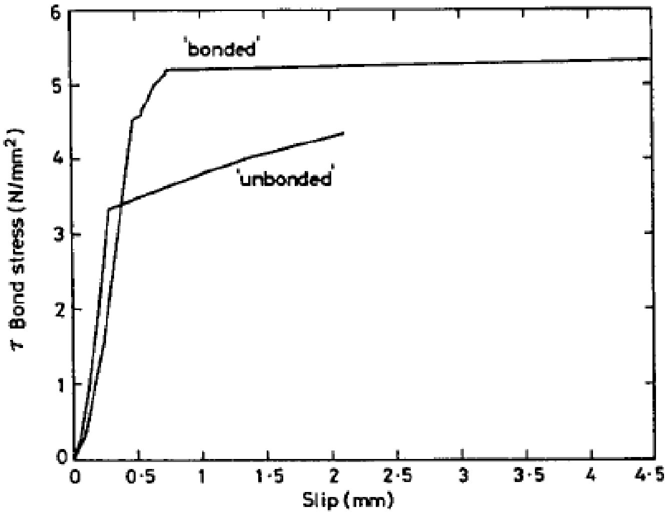


Fig. 3.2 Average Bond Stress with Slip (Hall and Mottram, 1998)

Dieter et al. (2002) carried out study on a hybrid concrete-FRP stay-in-place open structural formwork and FRP grid reinforcement for bridge deck applications. A pultruded FRP sheet stiffened by hollow FRP box sections (Fig.3.3) provided tensile reinforcement, and functioned as stay-in-place structural open formwork for the concrete slab overlay. A bi-direction grid composed of pultruded FRP elements provided the upper longitudinal and transverse reinforcement for regions of negative bending moments. In order to generate sufficient shear bond between the FRP stay-in-place form and the concrete slab overlay, the surface of the FRP form was roughened prior to pouring the concrete by coating it with a mixture of epoxy and gravel. Due to the complex geometry of the formwork, this mechanism was only applied to horizontal surfaces. This was found to have a detrimental effect on the bond performance. In regions where the bond mechanism was absent, severe slippage occurred between the form and the concrete overlay. As a result, the flexural crack pattern in the concrete over unbonded regions was considerably more pronounced than it was in bonded regions.

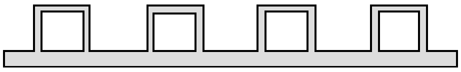


Fig. 3.3 Selection of formwork used (Dieter et al., 2002)

Work of ***Hall and Mottram (1998) & Dieter et.al (2002)*** clearly shows that the bonding between concrete and form is required for composite action and efficiency. Now this bonding action can be achieved by following methods:-

- Bonding by sand.
- Bonding by aggregates.
- Bonding by studs/penetrating rods.
- Bonding by wet adhesive.

Bank et al. (2007) described about the pultruded fiber reinforced polymer (FRP) plank which was used as both the formwork and the tensile reinforcement for a concrete structural member. The study was motivated by the desire to use the FRP plank as a stay-in-place form and reinforcement for a new bridge that was being designed in Wisconsin. For the FRP plank and the concrete to act as a "composite" structural member a satisfactory bond at the interface between the smooth surface of the pultruded plank (Fig.3.4) and the concrete was to be developed. To achieve this interface, stone aggregates of different sizes were bonded to the surface of the pultruded FRP plank. Two kinds of aggregates gravel and sand were bonded to the pultruded FRP plank using a commercially available epoxy system. Concrete beams of different lengths were fabricated using a commercially available pultruded FRP plank. No additional flexural or shear reinforcement was provided in the beams. Two of the beams were used as control specimens. One control beam did not have any aggregate bonded to the FRP plank and the other control had internal steel reinforcing bars instead of the FRP plank. Table 3.1 shows the dimensions of the entire fabricated FRP plank specimen.

The beams were loaded by central patch load to their ultimate capacity. Fig.3.5 shows dimensions of the fabricated beam surface. Depending on the length of the beam, shear or flexural failures occurred, which demonstrated satisfactory bond between the FRP plank and the concrete. Results indicated that coated FRP plank can produce an increase in the initial cracking moment capacity of a concrete beam, which may be a serviceability benefit for a reinforced concrete section, particularly a bridge deck. The beams with the sand coated FRP plank showed higher initial cracking capacity than the specimen with the gravel coated FRP plank indicating that sand coating provided a more even interface than the gravel in the interface region. It was shown that aggregate coating provided a mechanism to distribute the cracks and to transfer bond stresses at the interface between the FRP plank and the concrete.

It was demonstrated that the aggregate coated FRP plank can serve as an effective tensile reinforcement and can distribute flexural cracks in a similar manner to internal steel reinforcements. The aggregate coated FRP plank beams performed as well or better than the steel reinforcement in terms of initial cracking moment capacity, ability to distribute flexural cracks and ultimate load carrying capacity. The use of the FRP plank without the surface treatment as a tensile reinforcement showed the significant slip between concrete and considerably less capacity during test. The ultimate capacity of the aggregate coated FRP plank specimens was higher than that of the control specimens. Fig.3.6 and 3.7 shows the failure mode of all the specimens. This study demonstrated that the FRP plank has the potential to serve as formwork and as tensile reinforcement for appropriately sized concrete beams.

Fig. 3.4 12 inches wide pultruded FRP plank (Bank et al., 2007)

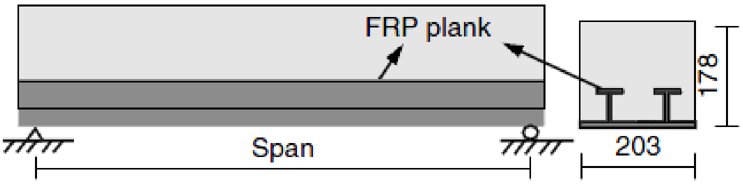


Fig. 3.5 Dimension of fabricated FRP plank reinforced beam specimens (Bank et al., 2007)

Table 3.1 Details of the fabricated beams (Bank et al., 2007)

Specimen I.D.	Span (m)	Tensile Reinforcement	Compressive Strength(MPa)
1	1.09	Gravel coated FRP plank	25.8
2	1.09	Sand coated FRP plank	25.8
3	1.09	Sand coated FRP plank	24.5
C1	1.09	FRP plank	25.8
4	1.83	Sand coated FRP plank	32.1
5	1.83	Sand coated FRP plank	33.5
C2	1.83	Steel reinforced 3D10	32.9

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. 3.6 Specimens 1-3 and C1 after test (Bank et al., 2007)

1) Hybrid failure mode of specimen 4

2) Hybrid failure mode of specimen 5

3) Flexural failure of specimen C2

Fig. 3.7 Specimens 4-5 and C2 after test (Bank et al., 2007)

Bank et al. (2010) tests were motivated by the desire to use alternative formwork systems for long span bridges, on which makes the use of conventional plywood forming and timber joists becomes uneconomical due to the labor required to set-up and strip the forms. In this application, however, the pultruded plank did not only serve as a permanent form, but was also required to control longitudinal flexural cracking in the unreinforced decks. Tests were conducted to investigate the load transfer mechanism between the FRP plank and the concrete to determine if the pultruded FRP plank could serve to control the longitudinal cracking in the deck. Their study describes the use of the pultruded plank as a permanent, or stay-in-place, formwork system for concrete highway bridge decks having a depth of 200 mm.

Since the pultruded FRP plank has a smooth surface it was clear that the plank would not be able to control the flexural cracking unless some bond stress could be developed between the concrete and the pultruded plank. To investigate this, a number of tests were conducted in which the inside surface of the pultruded planks was treated with epoxy bonded aggregates of two different types; gravel and sand. Simply-supported concrete beams with no internal reinforcement were fabricated using the pultruded plank as a form.

In addition, control beam was tested one with no bond treatment on the FRP planks. Results of the tests are described briefly in what follows. Fig.3.9 shows the crack pattern at failure of the beam that had no bond treatment while Fig. 3.10 shows the crack pattern at failure for a beam that had sand aggregate bonded to the inner surface prior to the concrete casting. Fig. 3.11 shows the load–deflection plots for the bond treated (Specimens 1–3) and the untreated (Specimen C1) beams. From the crack pattern shown Fig. 3.10 it can be seen that the beam with the bond treatment between the FRP plank and concrete developed significant shear force transfer at the plank/concrete interface which led to the beam failing in shear with multiple flexural cracks. On the other hand, the beam without the bond treatment failed in flexure with one large crack developing at the center of the beam, which is undesirable. From the data shown in Fig. 3.11 it is seen that the bond treated beams (Specimens 1–3) develop much higher loads than the untreated beam (Specimen C1) and that the behavior of these beams is linear after concrete cracking until the ultimate shear failure.

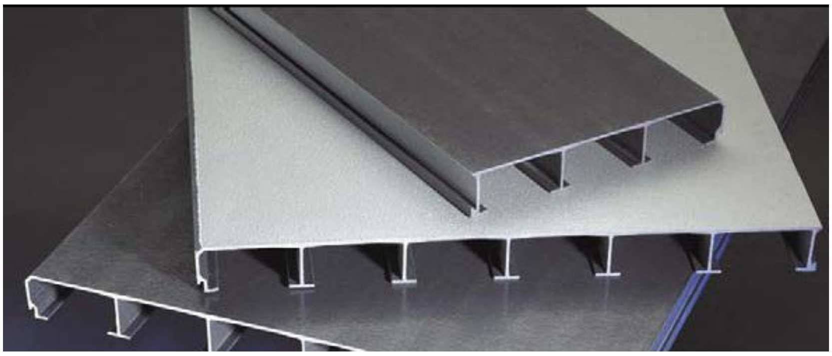


Fig. 3.8 Typical FRP pultruded planks (Bank et al., 2010)

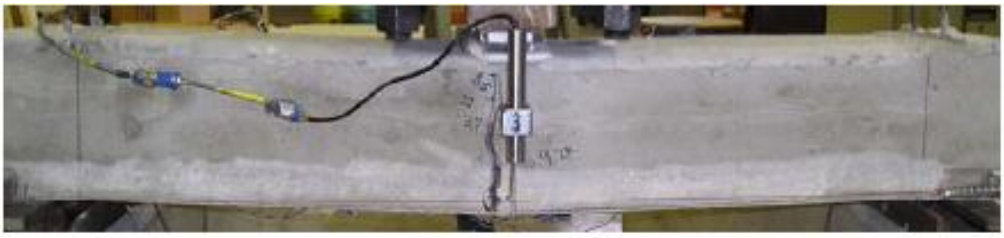


Fig. 3.9 Crack pattern in beam with FRP form and no bond treatment (Bank et al., 2010)

Fig. 3.10 Crack pattern in beam with FRP form and sand aggregate bonded (Bank et al., 2010)

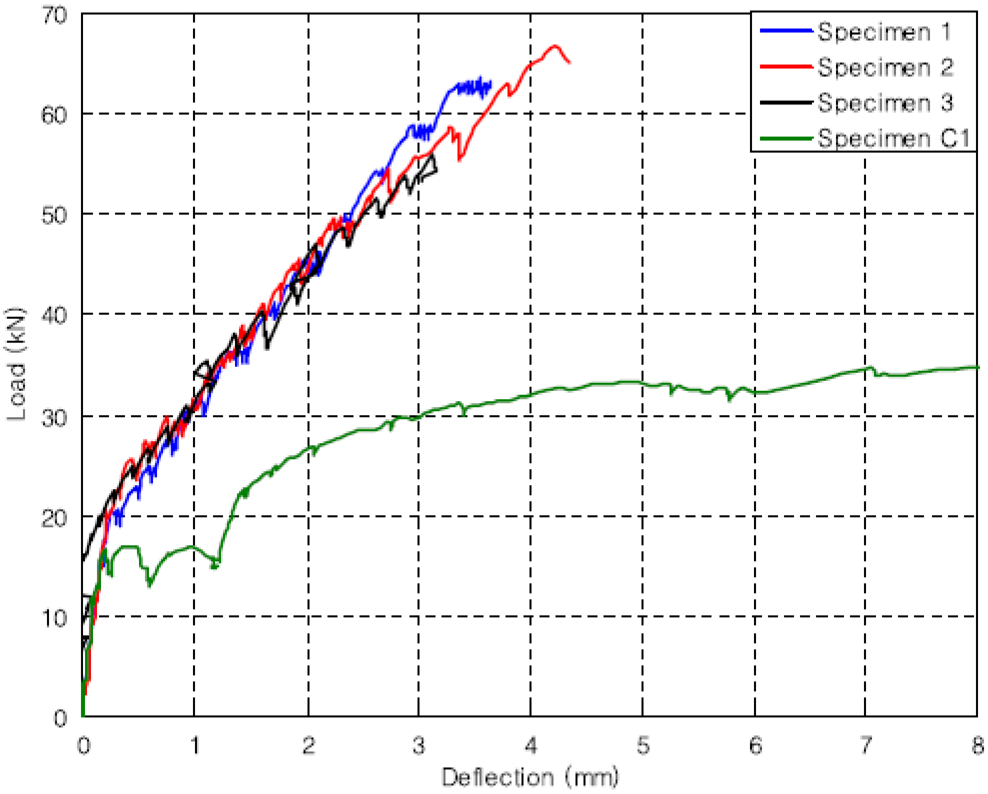


Fig. 3.11 Crack pattern in beam with FRP form with sand epoxied bond treatment (Bank et al. 2010)

Honickman (2008) investigated glass fiber-reinforced polymer (GFRP) off-the-shelf structural shape as stay-in-place open structural forms for concrete structures, including bridge decks and girders. In this study, eight concrete slabs were constructed using flat pultruded GFRP plates (Fig.3.12), and nine girders were constructed using trapezoidal pultruded GFRP sheet pile sections (Fig.3.13) as stay-in-place structural forms. No tension steel reinforcement was used. All specimens were tested in four-point monotonic uniaxial bending. Table 3.2 and Table 3.4 shows summary of test matrix for slabs and girders respectively.

Bond systems in case of plates included fresh concrete adhesively bonded to the plate, coarse aggregates bonded to the plate prior to casting, and GFRP and steel mechanical shear connectors. The performance of these bond systems was objectively assessed and the failure modes were examined. It was found that the most effective bond system, in terms of structural performance and ease and speed of fabrication, was the wet adhesive bonding of fresh concrete to the GFRP plate. The adhesive bonding methods led to a significantly higher stiffness, than that of the mechanically bonded slabs using shear connectors (Fig.3.14). This was attributed to a complete bond throughout loading in the former, until failure occurred suddenly by debonding; whereas in the latter, progressive slip between the GFRP plate and concrete occurred. He observed that failure was typically due to debonding of the GFRP plate, after flexural or shear cracking in the concrete. The measured low longitudinal strains at mid span suggested that tension failure of the GFRP plate was very unlikely in this system. Compression failure of concrete was imminent in some of the slabs. Table 3.3 gives the summary of test results for slabs.

Four adhesive and mechanical bond mechanisms were explored to accomplish composite action in girders. Mechanism M1 involved a liquid epoxy adhesive applied directly to the surface of the GFRP form immediately prior to pouring the concrete. Mechanism M2 involved applying a rough layer to the surface of the GFRP sections in order to create mechanical interlock between the concrete and the GFRP. This was accomplished by applying a thick mortar-like adhesive to the surface of the GFRP sections, and then applying a layer of 4 to 9mm diameter silica pebble aggregates onto the adhesive. Mechanism M3 utilized shear studs. These studs were created by drilling holes through the upper flat surfaces (flanges) of the GFRP sections, passing threaded steel rods through these holes, and then fastening the rods in place with a nut on either side of the GFRP section. Mechanism M4 was similar to mechanism M3 with the addition of heads on the studs.

It was found that similar to the slabs, girders incorporating either adhesive to wet concrete bond or bonded aggregates systems failed by debonding at the concrete/GFRP interface, within a thin layer of cement paste. A thin layer of mortar remained adhered to the GFRP section after failure. The concrete compressive strain and GFRP tensile strain were well below their ultimate values. The specimen incorporating headed shear studs combined with the adhesive bond system was able to achieve flexural failure by concrete crushing, which occurred at a 45% higher load than that reached by specimens incorporating only the adhesive bond system. The specimen incorporating non-headed studs in addition to the adhesive bond system achieved only a modest increase, 24% in strength, over the specimens incorporating only the adhesive bond system. In this case, failure occurred when the studs pulled out prematurely from the concrete slab. Similar to the slabs, in all adhesively bonded and bonded aggregate girders, excellent monolithic composite action was observed prior to the sudden debonding failure. This was evident by the consistent lack of slip between the concrete and the GFRP throughout the loading history. Summary of test results for girders is presented in Table 3.5.

Fig. 3.12 Flat pultruded FRP plates for slabs (Honickman, 2008)

Fig. 3.13 Trapezoidal pultruded GFRP section used for girders (Honickman, 2008)

Table 3.2 Summary of test matrix for slabs (Honickman, 2008)

Spec. ID	Length (mm)	Span L (mm)	Shear span a (mm)	Width B (mm)	GFRP plate thickness t (mm)	Total thickness (Rounded) h (mm)	Effective depth d (mm)	a / d	Reinf. ratio ρ (%age)	Bond mechanism
1	1220	1000	375	400	9.5	160	157	2.4	5.7	Concrete cast on wet adhesive
2										Adhesively bonded coarse aggregate
3										GFRP shear connectors
4										Steel shear connectors
5	2440	2200	975			110	106	9.2	8.5	Concrete cast on wet adhesive
6						160	157	6.2	5.7	
7						210	208	4.7	4.3	
8						160	157	6.2	5.7	Adhesively bonded coarse aggregate

Table 3.3 Summary of test results for slabs (Honickman. 2008)

Spec ID	Peak Load	Peak Moment	Strain at peak load		Load at first slip (KN)	Slip at peak load	Failure mode
			Top (Micro)	Bottom (Micro)			
1	149	27-9	-837	1825	149	0	Concrete Shear-bond failure
2	162	30.3	-907	2349	162	0	Concrete Shear-bond failure
3	140	26.2	-4410	2036	43	3.6	shear failure of GFRP studs
4	200	37.5	-2454	3313	66	2.2	Excessive slip of steel studs
5	67	32.5	-2908	3990	67	0	Bond failure
6	87	42.6	-1962	3520	87	0	Bond failure
7	145	70.8	-1585	4693	145	0	Bond failure
8	109	53.2	-2269	4236	109	0	Bond failure

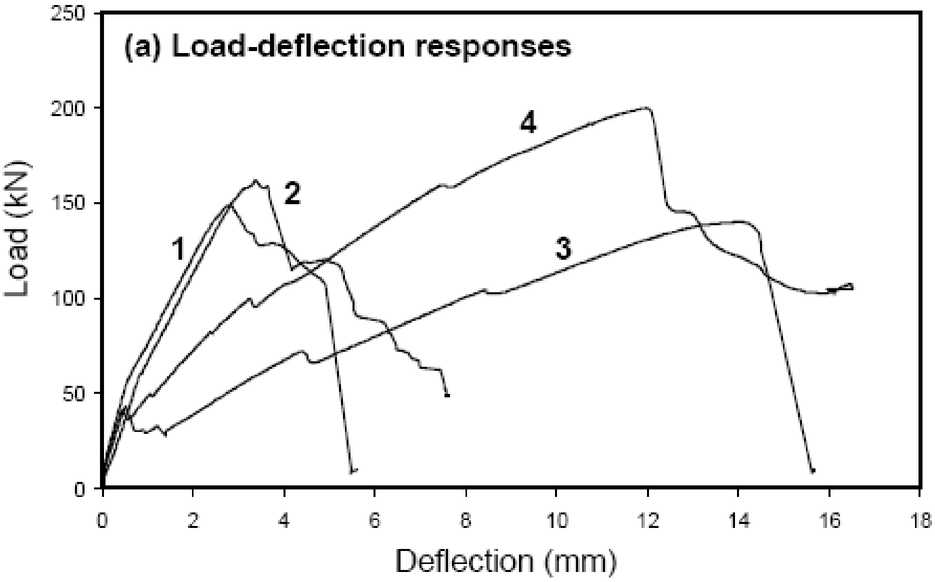


Fig. 3.14 Test results of slabs 1 to 4 (Honickman, 2008)

Table 3.4 Summary of test matrix for girders (Honickman, 2008)

	Type	Bond Mechanisms	Concrete fill	Bending orientation
1	1	M1	Voided Concrete	Positive
2	1	M2	Voided Concrete	Positive
3	1	M1 & M3	Voided Concrete	Positive
4	2	M1	Completely Filled	Positive
5	2	M1	Completely Filled	Negative
6	3	M1	Slab on Box Girder	Positive
7	3	M1 & M4	Slab on Box Girder	Positive
8	3	M1& M4	Slab on Box Girder	Negative
9	3	M3	None	Positive (a) & Negative (b)

Table 3.5 Summary of test results for girders (Honickman, 2008)

Girder	Peak load(KN)	Load at initial bond slip (KN)	Mode of failure
1	250.0	250.0	Bond failure of concrete/GFRP interface
2	269.5	269.5	Bond failure of concrete/GFRP interface
3	317.0	317.0	Vertical pull-out of non headed sheet shear studs
4	294.0	294.0	Bond failure of concrete/GFRP interface
5	204.2	204.2	Lateral opening of GFRP sheet pile section
6	285.0	244.7	Bond failure at concrete/GFRP interface
7	430.0	230.5	Delamination and crushing of concrete slab
8	227.0	47.0	Local buckling and crushing of GFRP section
9a	230.7	NA	Buckling of upper compression flange of GFRP box section

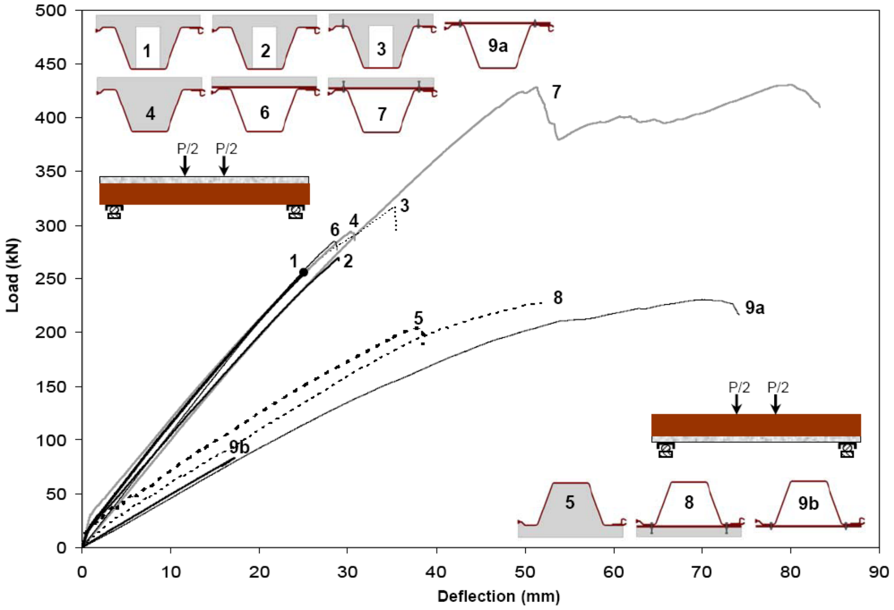


Fig.3.15. Load-deflection responses of girder specimens (Honickman, 2008)

Gai et al. (2009) research was done in view to find more robust mechanical interlock at the interface between concrete and FRP as failure of conventional adhesive bonds is brittle and failure may occur without any warning. To achieve such a robust bond, mechanical FRP shear connectors running in both the longitudinal and transverse directions were investigated. Pultruded GFRP grid and moulded GFRP grating were selected to fulfill the requirement on confining the concrete in both directions. A moulded GFRP grating is fabricated using a square mesh pattern of fibers in bidirectional bundles which is laid down and then submerged in resin contained in a mould. A pultruded grid is fabricated by penetrating through the webs of a series of longitudinal pultruded I-sections with transverse GFRP rods to form a bidirectional grid. Sanded coated GFRP rods were also introduced into the moulded GFRP grating to act as a shear-key between the grating and concrete. The feasibility of using pultruded GFRP grid and moulded GFRP grating as mechanical shear connectors was investigated experimentally via a series of push-out tests.

The grid specimen is shown in Fig. 3.16 and grating specimen is shown in Fig. 3.17 material properties of FRP used are shown in table. Further 10mm diameter sand coated GFRP rods in the out of plane direction to act as shear connectors. Their research clearly signify that addition of shear connectors provide more gradual shear failure.

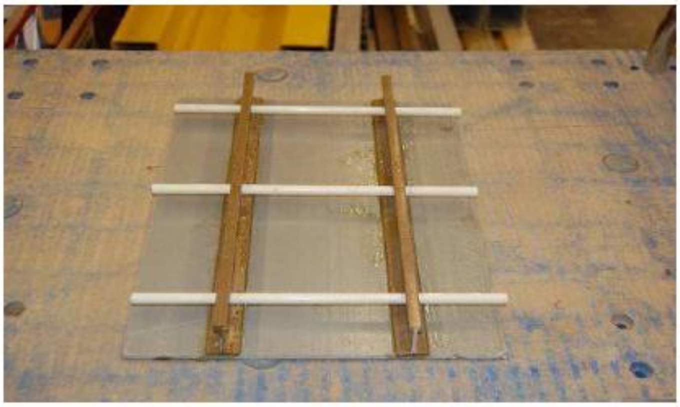


Fig. 3.16 Fabrication of the grid specimen (Gai et al., 2009)

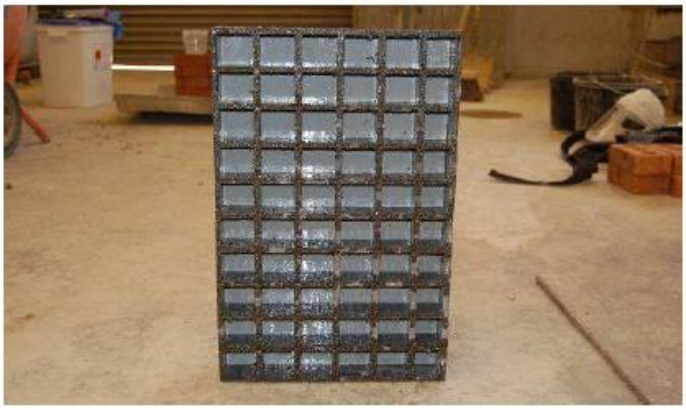
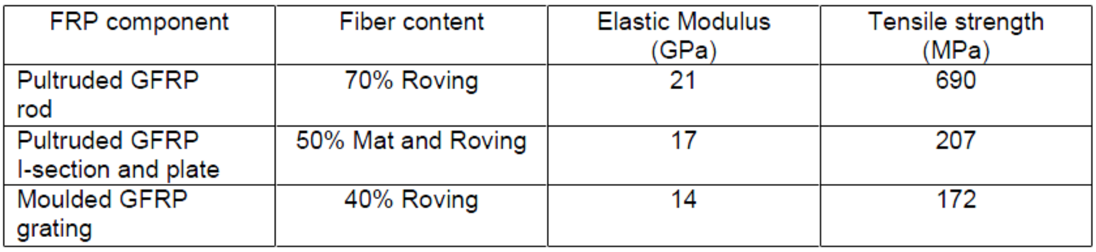


Fig. 3.17 Fabrication of the grating specimen (Gai et al., 2009)

Table 3.6 The material properties of FRP components (Gai et al., 2009)



FRP component	Fiber content	Elastic Modulus (GPa)	Tensile strength (MPa)
Pultruded GFRP rod	70% Roving	21	690
Pultruded GFRP I-section and plate	50% Mat and Roving	17	207
Moulded GFRP grating	40% Roving	14	172

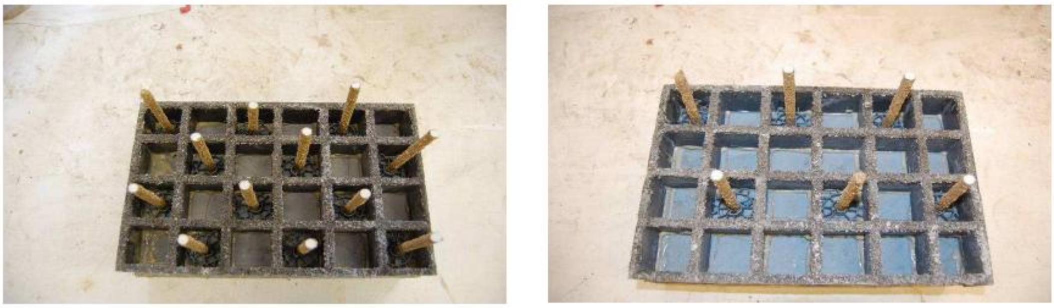


Fig 3.18 Configuration of rod specimens (Gai et al., 2009)

Table 3.7 Specimens and summary of test results (Gai et al., 2009)

Specimen	No. of GFRP rod	Peak average bond stress (MPa)	Failure mode
Pultruded grid	No	1.96	Longitudinal splitting at web-flange interface of I-sections
Moulded grating 1	No	5.02	Sudden bonding failure between the concrete and the grating
Moulded grating 2	24	7.08	Rupture of the grating
Moulded grating 3	12	6.08	Progressive bonding failure between the concrete and grating
Moulded grating 4	6	4.17	Progressive bonding failure between the concrete and grating

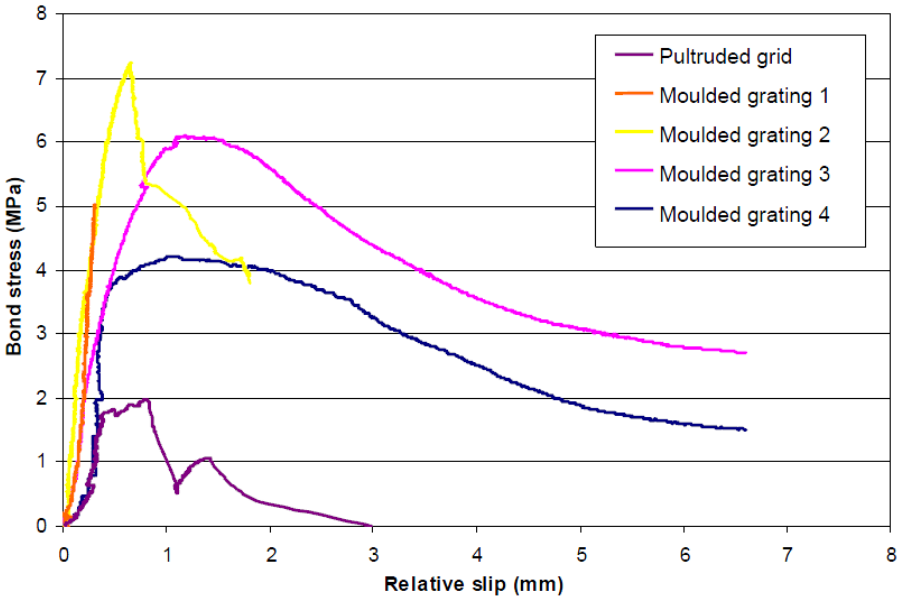


Fig 3.19 Bond stress versus Relative slip graph (Gai et al., 2009)

Reema (2010) performed tests on double layer base forms stiffened with single layer channel sections and four layer base forms stiffened with four no. four layer channel sections. The sections were hand laid. The single layer 3-channel failed in deflection caused by buckling of channel (Fig 3.20). Section with longitudinal and transverse channel also failed in deflection.

Aggregate coated four layer sections and without coating section didn’t show much deflection. These sections underwent brittle failure when load was applied. Few cracks were generated and failure was along the central crack (Fig 3.21). Also debonding of form was seen (Fig 3.22).

Fig 3.20 Buckling of channels (Reema, 2010)

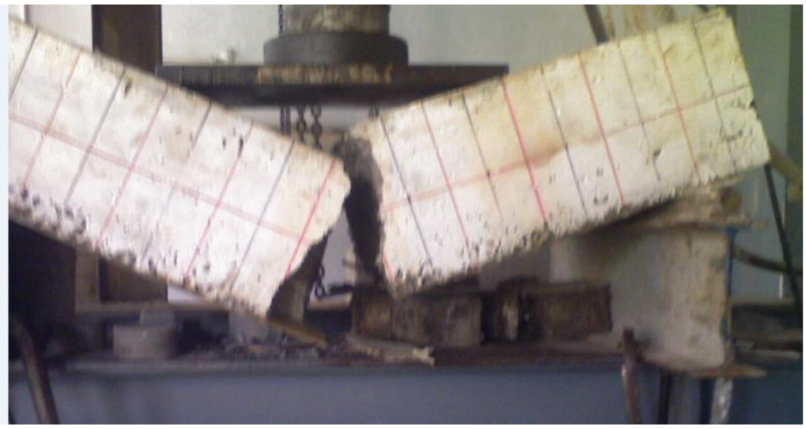


Fig 3.21 Sudden brittle failure (Reema, 2010)

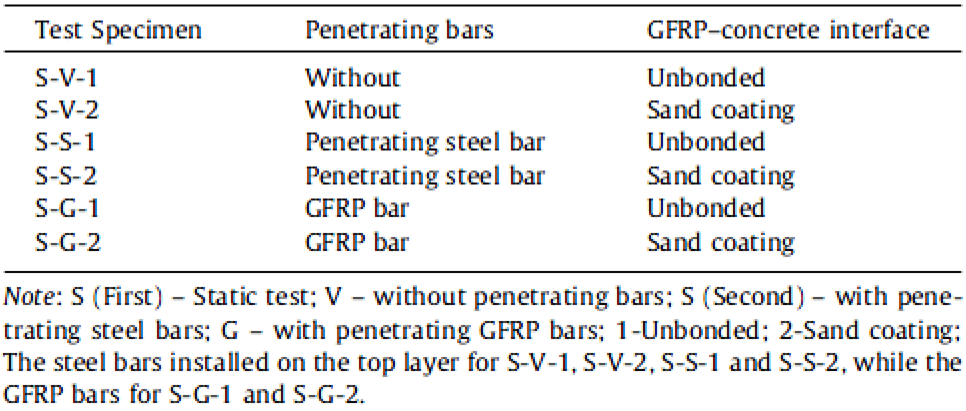
Fig 3.22 Debonding of form (Reema, 2010)

He et al. (2012) did experiments on deck consisting of corrugated pultruded GFRP plate with T-upstands for the tension part and concrete with reinforcing bars for the compression part. They did several tests to find load carrying capacity, strength and stiffness, load-displacement relationship, etc., but our interest in their investigation lies is results of bonding between composites.

The tests were done on six full-scale models with different influencing factors such as penetrating bars (types and presence or absence) and surface treatment (with or without sand coating). Table 3.8 shows different test specimens. Two kinds of relative slip results were observed according to the surface treatment. For specimens without sand coating, Fig.3.23, detachment of T-upstands with concrete at both ends before ultimate load was observed, while for specimens with sand coating, Fig 3.24., no such slip was observed until ultimate load.

Results denote that the surface treatment improved the connection performance, and neutral axis position moved down without sand coating as the load increased due to stiffness reduction and slip occurrence. Both surface treatment and penetrating bars improve the connection between GFRP plate and concrete, and promote the strength and whole rigidity of hybrid deck. However, the effect of surface treatment was better than that of penetrating bars.

Table 3.8 Specimen's details (He et al., 2012)



Test Specimen	Penetrating bars	GFRP–concrete interface
S-V-1	Without	Unbonded
S-V-2	Without	Sand coating
S-S-1	Penetrating steel bar	Unbonded
S-S-2	Penetrating steel bar	Sand coating
S-G-1	GFRP bar	Unbonded
S-G-2	GFRP bar	Sand coating

Note: S (First) – Static test; V – without penetrating bars; S (Second) – with penetrating steel bars; G – with penetrating GFRP bars; 1-Unbonded; 2-Sand coating; The steel bars installed on the top layer for S-V-1, S-V-2, S-S-1 and S-S-2, while the GFRP bars for S-G-1 and S-G-2.

Fig. 3.23 Relative slip between GFRP plate and concrete, unbonded (He et al., 2012)

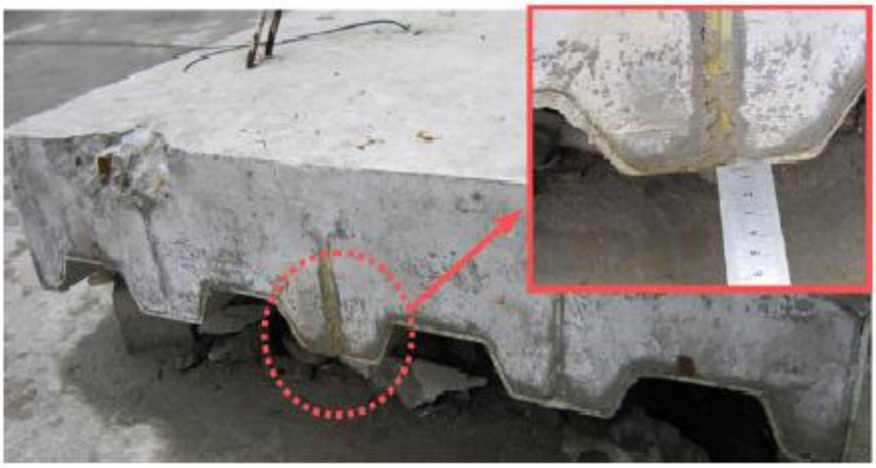


Fig 3.24 Relative slip at the end of specimens, bonded (He et al., 2012)

3.3 DUCTILITY

Ductility is a desirable structural property because it allows stress redistribution and provides warning of impending failure. Steel-reinforced concrete beams are under-reinforced by design, so that failure is initiated by yielding of the steel reinforcement, followed, after considerable deformation at no substantial loss of load carrying capacity, by concrete crushing and ultimate failure. This mode of failure is ductile and is guaranteed by designing the tensile reinforcement ratio to be substantially below (ACI 318 requires at least 25 % below) the balanced ratio, which is the ratio at which steel yielding and concrete crushing occur simultaneously. The reinforcement ratio thus provides a metric for ductility, and the ductility corresponding to the maximum allowable steel reinforcement ratio provides a measure of the minimum acceptable ductility.

The performance of FRP as external reinforcement for flexure is fairly rational and straightforward. It is based on Bernoulli’s hypothesis of strain compatibility that plane sections remain plane, which requires perfect bonding between FRP and concrete, and the ability of the concrete to transfer stresses to the FRP laminate by shear. In a beam reinforced internally with steel and externally with FRP, there is usually substantial reserve capacity at steel yielding. After the steel reinforcement yields, the beam can still carry increasing loads, albeit at a lower rate (with respect to deflections) than prior to steel yielding, and the FRP maintains elastic behavior until failure occurs suddenly. Failure is precipitated by FRP debonding, rupturing, or concrete crushing. All of these modes of failure are brittle, i.e., load capacity is reached with little inelastic deformation.

Naaman et al. (2001, 1999) reported on a series of tests of RC beams strengthened in flexure or shear with carbon FRP and loaded under static or cyclic loads, at room or low temperatures. The test parameters included the amounts of reinforcing steel and FRP, concrete cover thickness and condition (with repair mortar used to simulate damaged concrete), and anchorage configurations. It was found out that, for a given reinforcement ratio, the ultimate load capacity increased but the ultimate deflection, and therefore ductility, decreased with the strengthening level. The three beams with various anchorage conditions (extended length, perpendicular wrap or normal condition, i.e., with no extra effort to enhance anchorage) had the same ultimate load and deflection. Naaman et al. recommended limiting the increase in strength due to FRP to 20 % of the nominal flexural strength of the beam with the maximum steel reinforcement ratio allowed by the ACI 318 Code.

Bank et al.(2007,2010) tests (explained earlier) further support the fact that brittle failure of FRP SIP formwork is an undesirable result. But no literature from this author us yet available as how to incorporate ductility.

Gai et al. (2011) tried to overcome the issue of lack of ductility in the FRP/concrete system by a novel mechanical shear connector along the Concrete-FRP interface and a concrete filled FRP grating in the compression zone to enhance the strain capacity in the concrete. Their FRP formwork is a composite structure consisting of two layers of different materials: pultruded hollow GFRP box section for the tension and moulded GFRP grating filled with concrete for the compression, as shown in Fig 3.25. They provided a robust connection between the GFRP box section in tension and the concrete in compression is addressed by using GFRP dowels embedded into the concrete as shown in Fig 3.26.

The concept of utilizing the moulded GFRP grating to confine the concrete in the compression zone in order to introduce the ductility through controlled concrete crushing was investigated by comparing a plain concrete block with a concrete filled grid block in compression. The plain concrete block failed due to concrete crushing with little ductility, while the concrete filled grid block failed due to concrete crushing around the grid cells and longitudinal splitting of the fibres in a much more gradual manner, as shown in Fig 3.27. The concrete confined by the FRP grating led to a 100% increase in ultimate compressive strength, and a 100% increase in ultimate strain capacity compared to an identically sized plain concrete specimen, Fig. 3.28. The dramatic increase in compressive strain demonstrates that the grid structure of moulded GFRP grating confines the concrete effectively due to its bi-directional fibre orientations, resulting in significant deformability. Thus, it might be possible to utilize the increase in concrete strain capacity to provide ductility to the overall system through the concrete in compression.

Fig. 3.25 Proposed FRP formwork system (Gai et al., 2011)

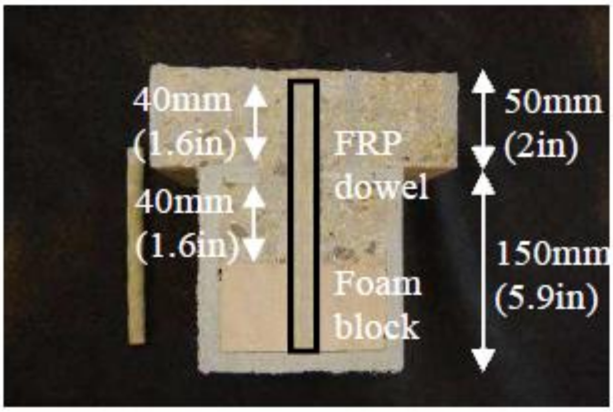


Fig. 3.26 GFRP dowels embedded in to concrete (Gai et al. 2011)

Fig. 3.27 Failure of block specimens (Gai et al., 2011)

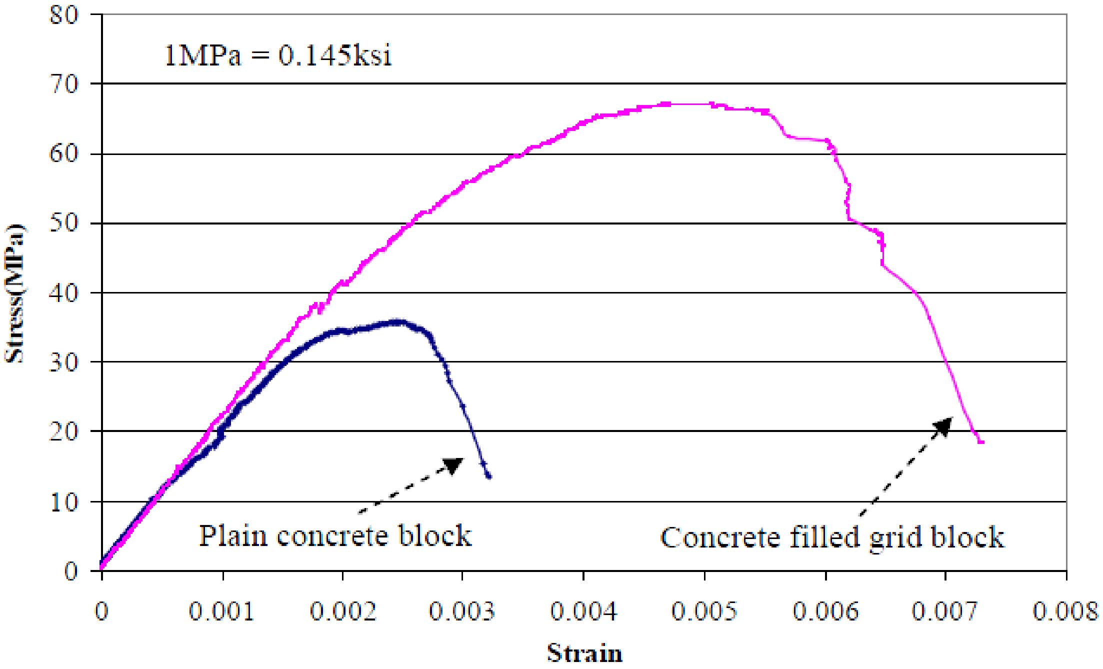


Fig.3.28 Stress-strain graph comparing the plain concrete and concreted filled grating Compression tests (Gai et al., 2011)

Chapter 4

Materials and Methods

4.1 INTRODUCTION

This chapter deals with the preparations and pre-analytical investigations done for selecting the specimens and carrying out the research work. Firstly materials involved are described and then brief introduction to necessary theories/methods is done.

4.2 MATERIALS

4.2.1 Concrete

Concrete is a construction material composed of Portland cement and water combined with sand, gravel, crushed stone or other inter material such as expanded slag.

Portland Pozzolana Cement 53 (PPC) was used to carry out the investigation. The fine aggregates used was clean river sand passing through 4.75 mm sieve. Machine crushed granite broken stone angular in shape was used as coarse aggregates. The maximum aggregate size was 20 mm. Ordinary clean potable water free from suspended particles and chemical substances was used for both mixing and curing of concrete.

The concrete was designed to have a compressive strength of 25MPa at 28 days. Design mix used was 1:1:1.9 with water: cement ratio as 0.45.

4.2.2 GFRP Planks

Commercially easily available planks are simple girders attached to base plate running longitudinally. For the research work ‘ERCON COMPOSITES’ company was visited and four different type of specimens were finalized. These specimens are as under:-

1. Standard Plain Plank
2. Plain Plank with cross rods @ 200 mm spacing (6 CR)
3. Plain plank with cross rods @ 100 mm spacing. (12 CR)
4. Plain plank with cross rods @ 200 mm spacing along with Studs places in zig-zag manner.

The planks are shown as in fig. 4.1 to fig. 4.4

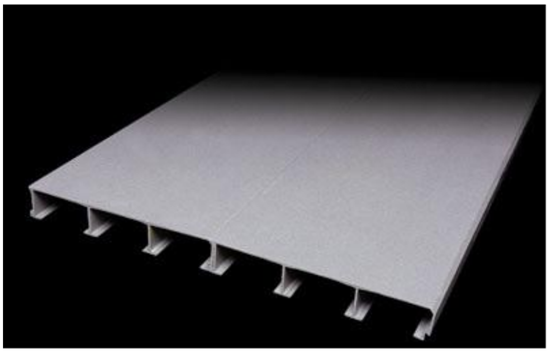


Fig. 4.1 standard plain plank

Fig. 4.2 Plain Plank with cross rods @ 200 mm spacing (6 Cross rods)

Fig. 4.3 Plain plank with cross rods @ 100 mm spacing. (12 Cross rods)

Fig. 4.4 Plain plank with cross rods @ 200 mm spacing along with 18 Studs places in zig-zag manner.

The dimension of basic plank is 1200x600 mm. The cross sectional details are shown in table 4.1:-

Table 4.1 section details

Thickness of base plate	5 mm
Thickness of web	4 mm
Thickness of flange	44 mm
Height of flange (inside)	4 mm
Height of studs	75 mm

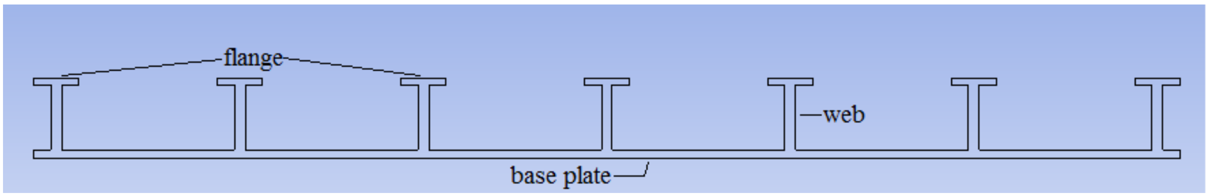


Fig. 4.5 details of cross section of plank

Work of ***Hall and Mottram (1998) & Dieter et.al (2002)*** clearly shows that the bonding between concrete and form is required for composite action and efficiency. Now this bonding action can be achieved by following methods:-

- Bonding by sand.
- Bonding by aggregates.
- Bonding by studs/penetrating rods.
- Bonding by wet adhesive.

To develop efficient bond system between fresh concrete and plank, prior a layer of white sand (average size 2.36mm) was adhesively bonded to the plate with the help of 'ARALDITE' epoxy.

The test results of typical properties of the base plank provided by the manufacturer are presented in table 4.1.

Table 4.1 Typical properties of planks

S.No	Property	Unit	Average test result
1	Tensile strength	N/mm^2	405
2	Tensile modulus	KN/mm^2	36.326
3	Flexural strength	N/mm^2	426
4	Flexural modulus	N/mm^2	27273
5	Compressive strength	N/mm^2	158

4.3 Shear capacity of concrete members without shear reinforcement

In concrete beams or slabs without shear reinforcement, two different failure modes can be expected: flexural failure, which entails either crushing of the compression zone, or tensile failure of the reinforcement, or shear failure in the core. Shear failure can occur in two different zones: within the span or at the supports, where the load is directly transmitted through a compression diagonal. It has been recognized that the shear span-to-depth ratio, 'a/d', is an indicator of the governing failure mode, where 'a' is the distance from the load axis to the support axis, and d the effective depth of the slab as shown in fig 4.6.

As 'a' decreases, shear resistance increases, because the load can be directly transmitted by a compression diagonal to the support. For longer distances, however, compression diagonals interfere with crossing tension diagonals, which lower the shear resistance compared to the shear resistance over the supports (for concrete without shear reinforcement).

Web shear cracking begins from an interior point in a member when the principal tensile stresses exceed the tensile strength of concrete. Flexure-shear cracking is initiated by flexural cracking. When flexural cracking occurs, the shear stresses in the concrete above the cracks are increased. The flexure-shear crack develops when the combined shear and tensile stress exceeds the tensile strength of concrete.

When inclined cracking occurs in a nonprestressed concrete member, it is generally of the flexure-shear type. Web-cracking generally occurs near the supports of deep flexural members with thin webs or near the inflection point.

What Actions Contribute To Total Shear Resisting Force - No Shear Reinforcements

Cracked Beam without any shear reinforcement

1. Force resulting from aggregate interlock at crack.
2. Concrete shear stress in compression zone
3. Dowel shear from longitudinal flexural reinforcement.

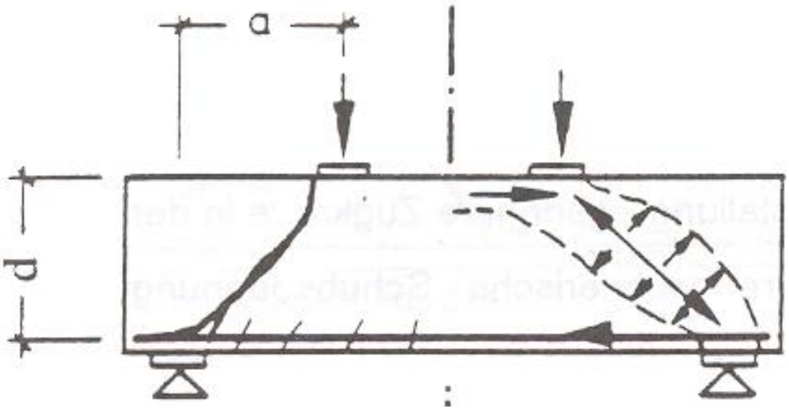


Fig. 4.6 shear cracking in concrete

CHAPTER -5

EXPERIMENTAL INVESTIGATIONS

5.1 Introduction

This chapter provides experimental investigation into the behavior of one way concrete slabs casted on GFRP formwork used simultaneously as formwork and tensile reinforcement. In this investigation four different types of sections were investigated. This chapter details the design of experimental program, measuring deflection of the forms due to sand loading, wet concrete loading and one point loading test. Basic aim of this research is to find out suitable GFRP cross section having potential to be used as beams along with satisfying strength and serviceability limits. The performance of beams casted on base forms with aggregate bonding was assessed and the failure modes were examined. The four sections are:-

Table 5.1 details of specimens

Name	Type	No. of longitudinal girders	No. of cross rods	No. of studs
Specimen 1	plain	6	-	-
Specimen 2	plain	6	6	-
Specimen 3	plain	6	12	-
Specimen 4	plain	6	6	18

5.2 Non-Structural Testing (Sand Loading)

Basic aim of this research is to find out whether the GFRP pultruded plank can serve the purpose of base form or not. Suitability of a material as a form depends upon how much deflection is caused when concrete is poured on the form during casting stage. The formwork should be such that it takes the concrete load when it is in the plastic stage while satisfying the deflection limits.

In non-structural testing, before actual pouring of concrete, sand testing was carried out. This was so because with this it could easily be find out if the form is suitable for concrete casting or not.

Unit weight of sand 17 KN/m^3. To compensate for concrete load additional 100mm mould was attached to basic 200mm side mould. This made total depth of beam for sand loading as 340mm.

Setup and finished sand loading is shown as in fig.5.1. Details of dial gauges places are as per fig.5.2 points 1,3 corresponds to quarter sections, 2 corresponds middle and 4 corresponds to transverse quarter.

Fig. 5.1 finished sand loading

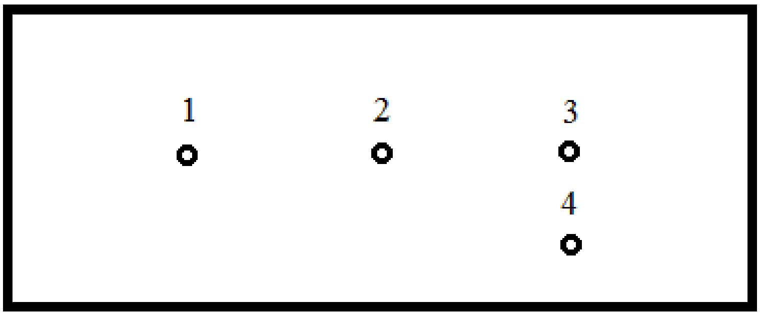


Fig. 5.2 details of points for dial gauges

Fig 5.3 arrangement of dial gagues

The load-deflections of specimens are as under.

__Specimen 1__

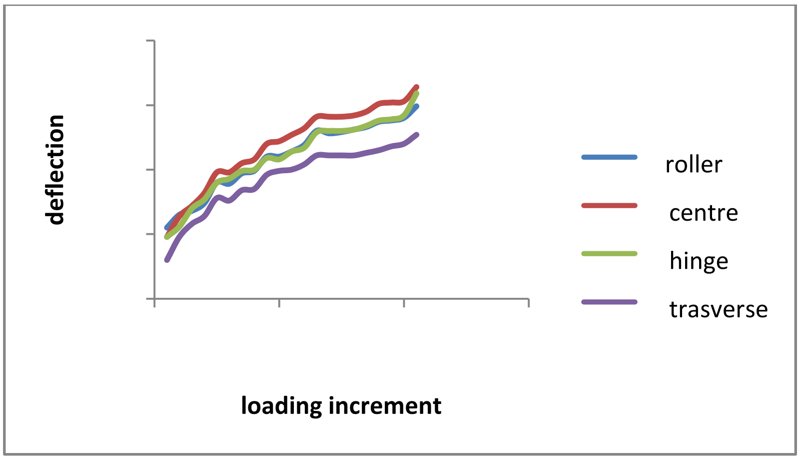


Fig 5.4 load-defection curve for specimen1 (sand)

__Specimen 2__

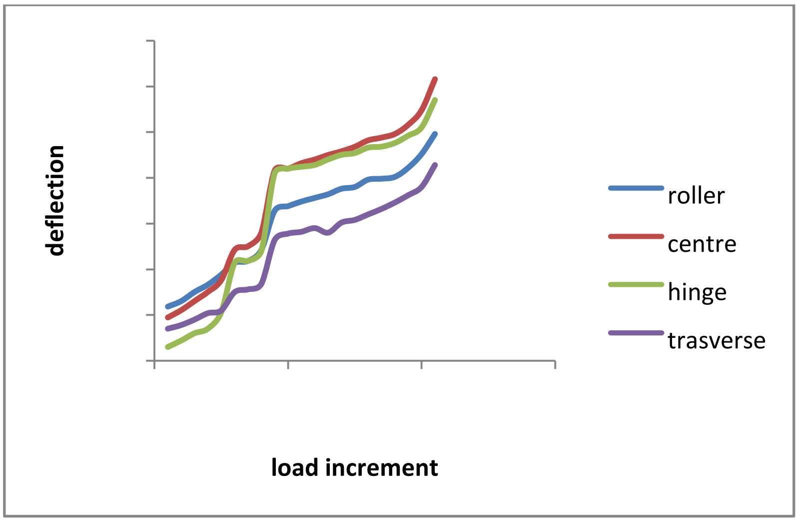


Fig 5.5 load-defection curve for specimen2 (sand)

__Specimen 3__

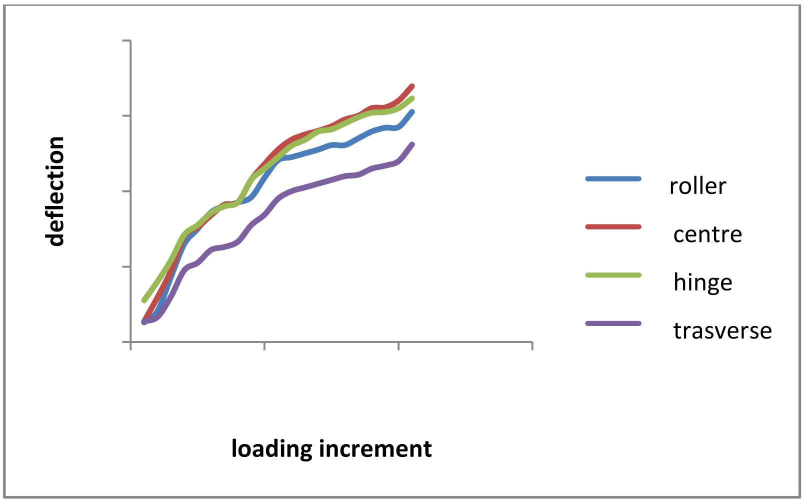


Fig 5.6 load-defection curve for specimen 3 (sand)

__Specimen 4__

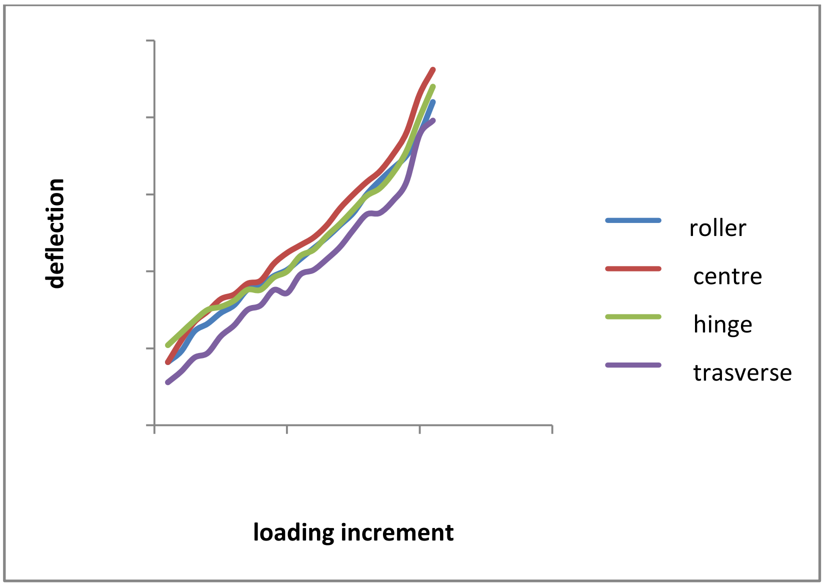


Fig 5.7 load-defection curve for specimen 4 (sand)

From above curves, it is observed that the specimen 1exhibited least deflection followed by specimen 4, specimen 2, specimen 3.

5.3 Casting of Beams (Wet Concrete Loading)

Prior to casting, for improving bonding, white sand was adhesively bonded to planks with the help of epoxy and left for drying. After preparation of the GFRP planks, simple wooden wall systems were erected between each of the GFRP plates to form the sides of the slabs. A 240mm deep beam was cast on each specimen. M25 Concrete was then cast, and the surface was finished and moist-cured for at least 7 days. Details are as per fig.5.8.

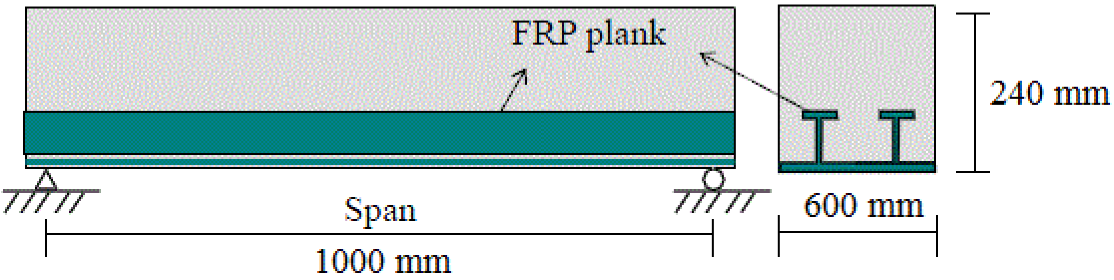


Fig 5.8 details of casted bea

Setup for casting of beams is shown in fig.5.9. Placement of dial gauges and points are same as used in sand loading test. Fig 5.10 shows finished beam

Fig 5.9 setup for casting of beams

Fig. 5.10 finished beam

Deflections of all specimens during wet concrete loading were noted down and these are as under.

Specimen 1

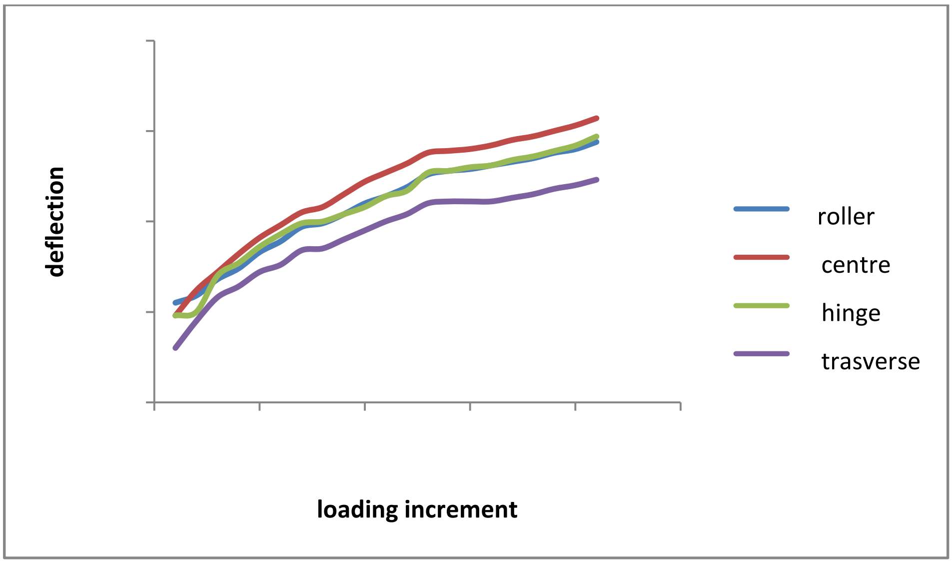


Fig.5.11 load-defection curve for specimen 1 (concreting)

Specimen 2

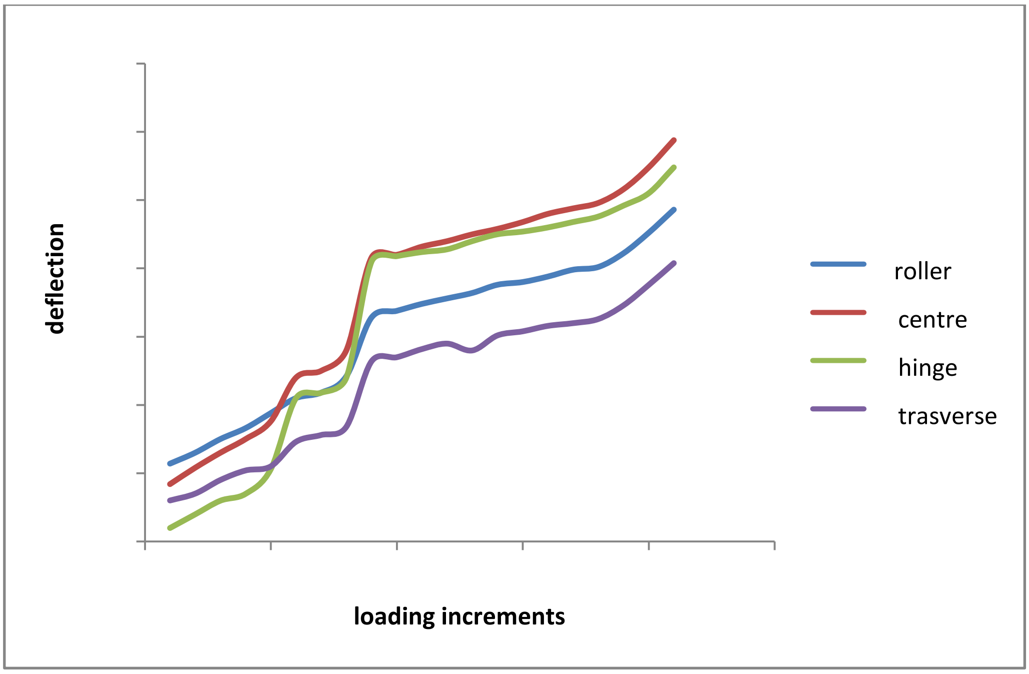


Fig.5.12 load-defection curve for specimen 2(concreting)

Specimen 3

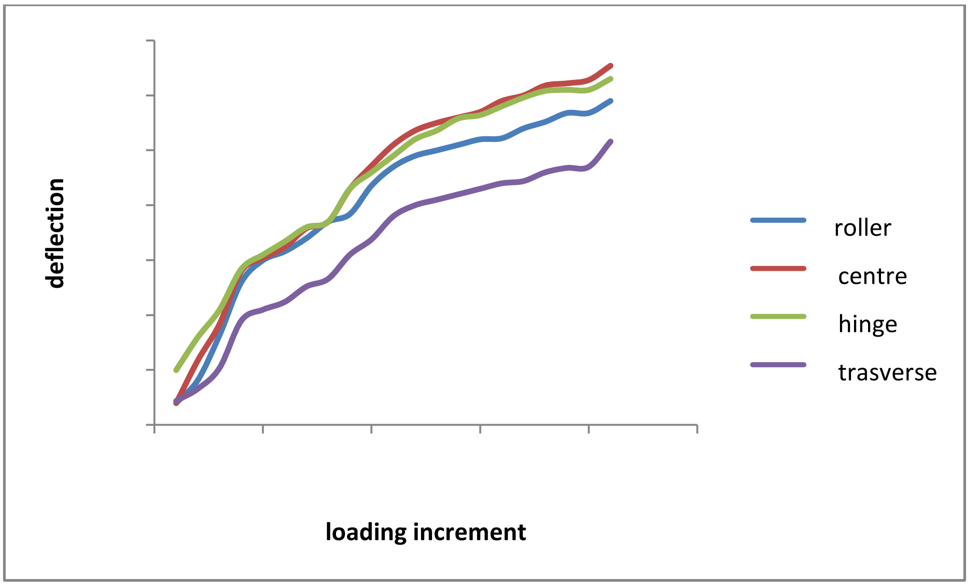


Fig.5.13 load-defection curve for specimen 3(concreting)

Specimen 4

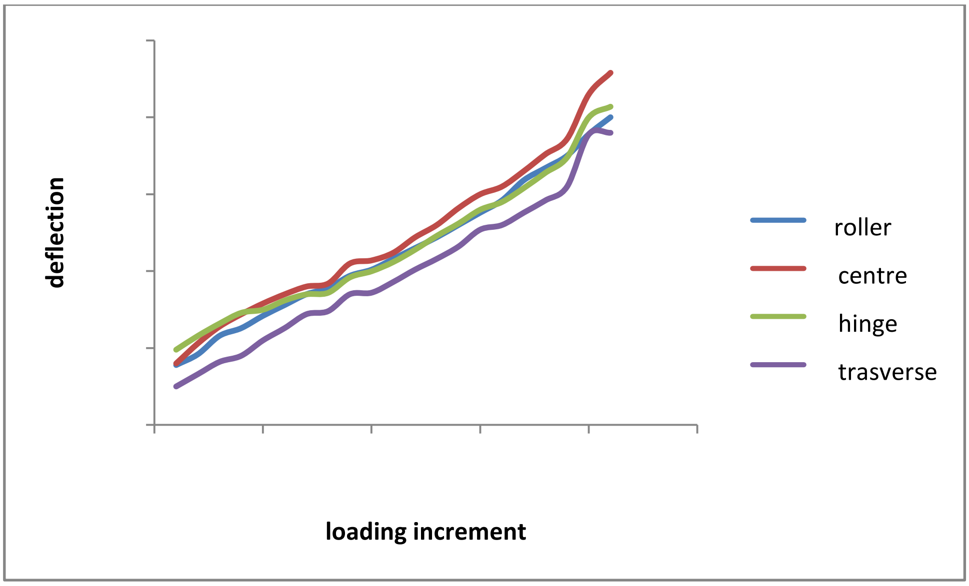


Fig.5.14 load-defection curve for specimen 4(concreting)

From above curves, same observation can be made as in sand loading test. Specimen 1 exhibited least deflection followed by specimen 4, specimen 2, specimen 3.

5.4 Test Setup and Instrumentation

All the specimens were tested in the loading frame of the 'structural engineering' laboratory of Thapar University, Patiala. The testing procedure of all specimens was same. The beam test specimens were placed on two ISMB 300 girders, 600mm wide in a simply supported configuration. The center-to-center spacing of the bearing plates was 1000 mm. A steel roller was place under the center of each girder to allow rotation at the supports. The testing was done idealizing the situation when column gives load to beam, that is, a patch of load. Load was applied through a hydraulic jack of capacity 400KN in control at a rate of 0.1KN/sec. Deflections were recorded with two digital strain gauges that were installed inverted on top of beam.

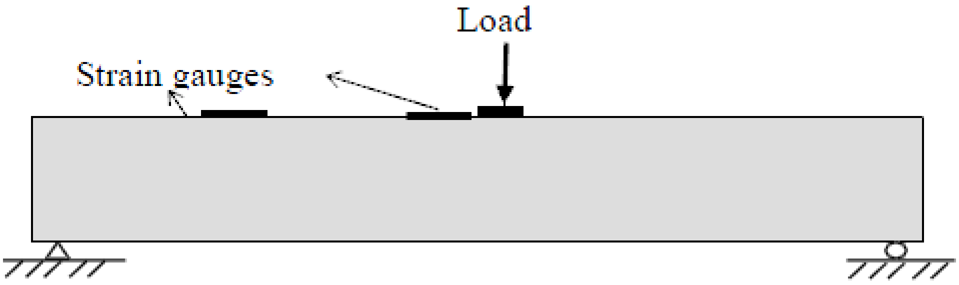


Fig 5.15 test setup for loading

The failure loads, load-deflection of specimens are as under.

Specimen 1

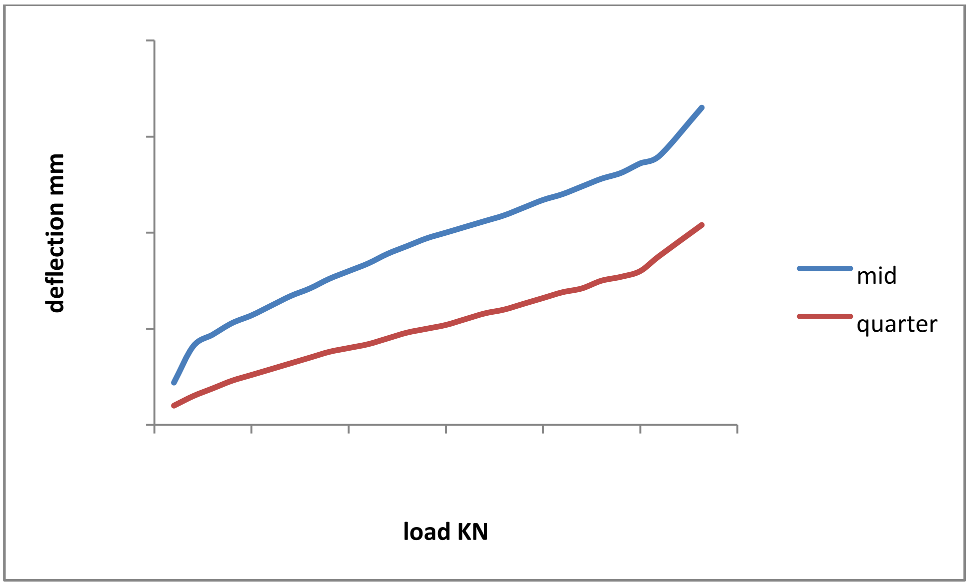


Fig 5.16 load-deflection for specimen 1(testing)

Specimen 2

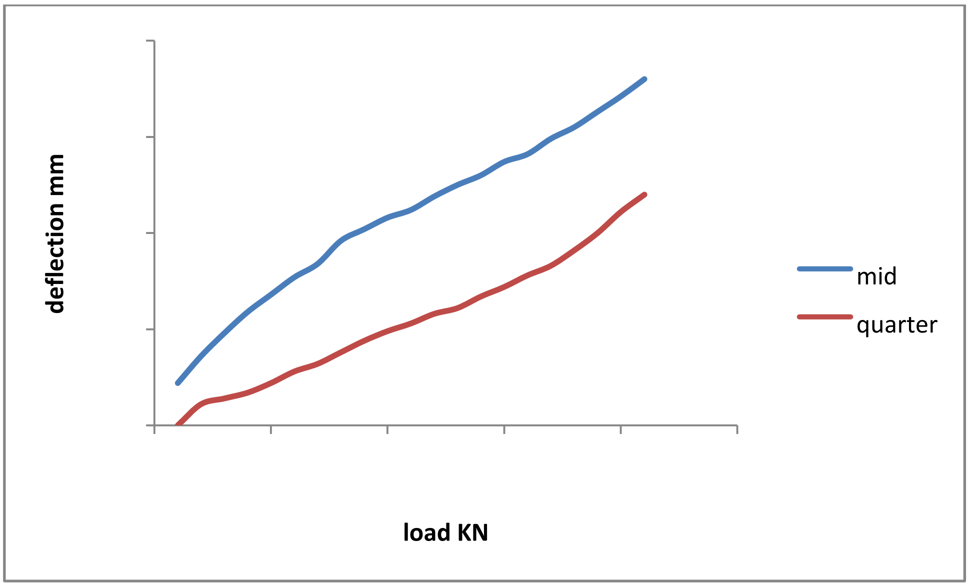


Fig 5.17 load-deflection for specimen 2(testing)

Specimen 3

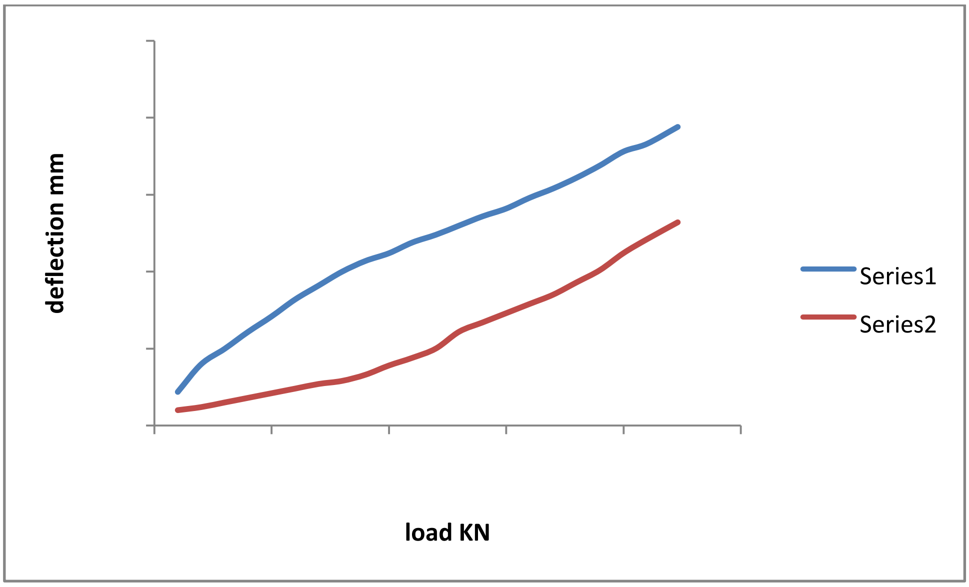


Fig 5.18 load-deflection for specimen 3(testing)

Specimen 4

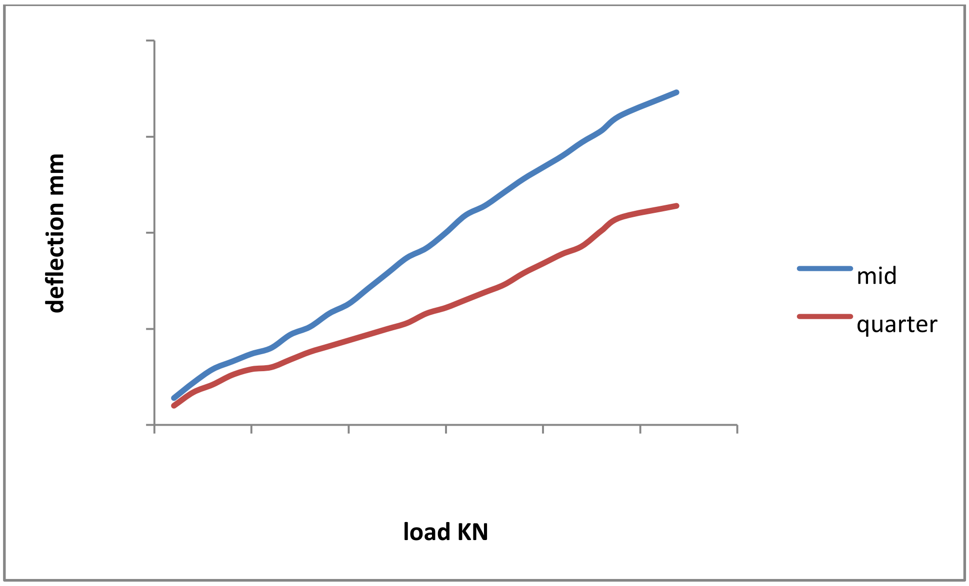


Fig 5.19 load-deflection for specimen 4(testing)

Chapter 6

Results and Discussions

6.1 Introduction

This chapter describes the experimental results of the different specimens. Their behaviour is described with respect to failure and ultimate load carrying capacity. The crack patterns and mode of failure is also described in this chapter. Further, in end various comparisons are also done with other research works.

6.2 Failure Modes

The following flexure and shear failure modes should be investigated for a FRP section:-

- Crushing of concrete in compression
- Debonding of FRP from the concrete
- Excessive slip
- Diagonal tension shear

A number of failure modes have been observed in the experiments of FRP SIP formwork from previous literature review presented. These include flexure failure, shear failure, flexural failure due to GFRP rupture and crushing of concrete on top. Concrete crushing is assumed to occur if the compressive strain in concrete reaches its maximum usable strain. Rupture of the FRP laminate is assumed to occur if the strain in the FRP reaches its design rupture strain before the concrete reaches its maximum usable strain. Cover debonding can occur if the force in the FRP cannot be sustained by the substrate. In order to prevent debonding of the FRP laminate, a limitation should be placed on the strain level developed in the laminate.

SPECIMEN 1

The GFRP SIP formworks were tested to find out their ultimate load carrying capacity. It was found that the specimen 1 failed in flexure-shear cracking showing deficient in flexure and shear respectively. Along with flexure shear cracks significant amount of debonding and slippage occurred at interface of concrete and GFRP form. Crack width was around 2 cm. Failure was brittle and a little catastrophic. Ultimate load carrying capacity was 281.68 KN, which is highest amongst the four specimens.

Fig 6.1 flexure shear cracks in specimen 1

Fig 6.2 crack width in specimen 1

Fig 6.3 debonding in specimen 1

SPECIMEN 2

The specimen also underwent flexure shear failure with insignificant debonding and slippage. Failure was governed by a major shear crack as seen in fig. the ultimate load carrying capacity was 210.21 KN.

Fig 6.4 shear crack in specimen 2

SPECIMEN 3

This specimen showed flexure shear cracks clearly proving that the specimen is weak in shear. No debonding and slippage occurred. Ultimate load carrying capacity was 223.12 KN.

Fig 6.5 cracks in specimen 3

Specimen 4

Failure in this specimen was also flexure-shear failure, but it was more towards flexure failure. Specimen showed more shear strength that the specimens without it. Little significant debonding was noticed at the bottom of beam below crack. No slippage occurred. Ultimate load carrying capacity was 268.68 KN.

Fig. 6.6 crack in specimen 4

6.3 Conclusions

The following conclusions drawn from the present research are structured in accordance with the objectives formulated in the Introduction.

- Plain GFRP SIP formwork beam has maximum ultimate load carrying capacity compared to rest specimens. This means that addition of cross rods decreases ultimate load carrying capacity. The reason can be that drilling holes in main longitudinal girders for transverse cross rods decreases the load carrying capacity.
- Specimen 4 has second maximum load carrying capacity. Addition of studs increases load carrying capacity as it increased shear strength of specimen which in turn required more load for shear failure.
- Cross rods help in preventing brittle failure and less debonding and slippage was noticed in specimens with cross rods.
- GFRP SIP formwork has potential to be used as beams.
- Load vs deflection was least observed in specimen 1 followed by specimen 4, specimen 2, specimen 3 in all tests, that is, sand loading, concreting, ultimate load carrying capacity.

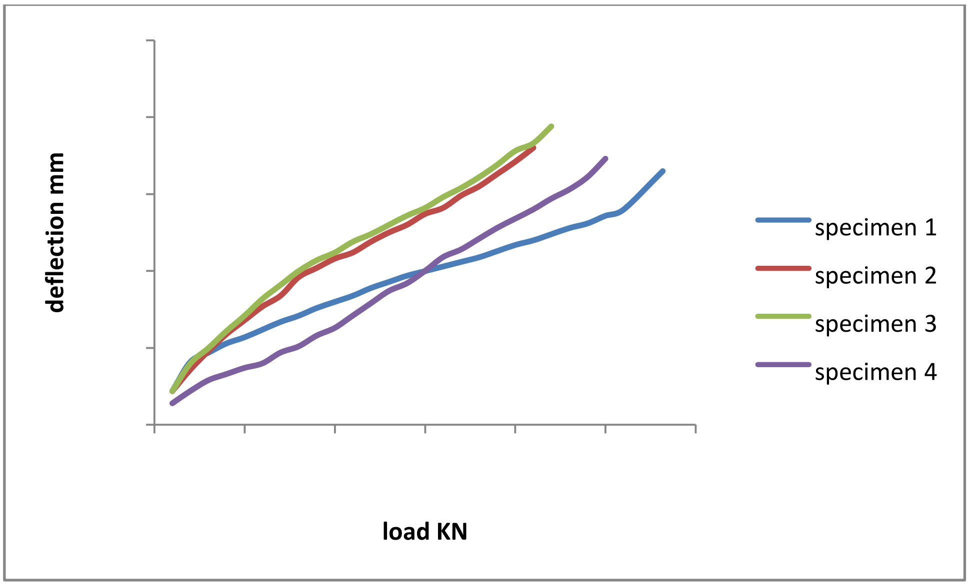


Fig.6.7 mid point deflection of all specimens (testing)

From previous literature review done in *Chapter 3*, it is observed that pultruded sections are better that hand layup planks as done by ***Reema et.al. (2010)***, when compared on basis of ultimate load carrying capacity. Highest load carrying capacity in ***Reema et.al (2010)*** work was 220 kN, which is lower than the lowest load carrying capacity of the four pultruded sections. Also failure of pultruded sections was less brittle as compared to hand layup sections.

Work done on dowels embedded by ***GAI et. al. (2010)*** gave similar results as by specimen which had studs embedded by improving the shear strength of specimen.

6.4 Scope for future work

The use of FRPs in concrete as formwork is relatively a new development in the construction industry and lot of research must go in before these forms are actively used in construction. Further work which should be done is summarised below:

Different sections can be tried out to work as forms.

Different types of Fibers should be tried to work as forms.

Different type of connecters should be assessed, so that multiple span forms can be used.

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