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Flexural Behaviour of Concrete Oneway Slabs Reinforced with Hybrid FRP Bars

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Abstract

This paper focuses mainly the flexural response of concrete one-way slabs reinforced with Hybrid FRP (Combination of Glass FRP and Carbon FRP) bars. It also deals with the interaction of design parameters, to examine some of the critical issues and challenges that arise while designing Hybrid FRP slabs to satisfy ultimate strength and serviceability criteria using the ACI 440.1R-03 Guide. The insufficiency of design standards is a significant stumbling block for the extensive use of fibre-reinforced polymers (FRPs) in reinforced concrete (RC). The sole pivot of this paper is to concentrate on the properties of concrete and reinforcement in different aspects and finally the flexural behaviour of the slabs has been analyzed experimentally and analytically. Two point static loading has been adopted to study the flexural behaviour. A finite element software ANSYS is used to analyse the flexural behavior of the slabs. Cracking and deflection of Hybrid FRP reinforced concrete structures are prudently studied. A general non-linear procedure found on slip and bond stresses, is adopted for the prediction of cracking and deflections.

Keywords: Hybrid FRP, Flexural behaviour, ANSYS, Theoretical prediction

INTRODUCTION

The major advantage and benefit of FRP rebars are that they can be engineered to have preferred mechanical and physical properties. Over the last few decades, polymer composite materials have been used in civil engineering applications in various modes including rebars for concrete structures, sheets for flexural and shear strengthening to wrap concrete columns and bridge piers to increase confinement. FRP rebars behave as notable alternatives to steel rebars, particularly where corrosion occurs.

The corrosion of steel reinforcement stands as the central trait of limiting the life expectancy of reinforced concrete structures. In order to overcome the shortcomings of durability several actions have been taken. Increased concrete cover, introduction of additives to make the concrete less permeable, use of stainless steel reinforcement or epoxy coated steel rebars exist as the essential methods to resolve the corrosion of the rebars. However, none of these efforts result in an absolute desired outcome. Owing to the lack of ferrous material, the non- metallic (FRP) reinforcements offer a promising substitute to steel reinforcement apart from electrolytic corrosion in concrete structures Borosnyói, Balázs, 2001[1]. Different fibres like glass, carbon, aramid or basalt coalesce together with a range of resins like polyester, vinyl ester or epoxy are used to produce fibre reinforced polymers. They possess mechanical properties and surface characteristics which are to a great extent different from that of the conventional steel reinforcements that furnish unbelievable resistance to the environmental effects such as freeze-thaw cycles, chemical attack etcBorosnyói, 2013; Sólyom, Balázs, 2015 [2,3]. The significant dissimilarities between FRP and steel reinforcements are their linear elastic behavior up to failure without any flexibility and substantial release of elastic energy at failure.

Aggressive environment is the major reason for carbonation and chloride contamination of concrete which in turn results in the disintegration of concrete. As a consequence, the steel reinforcement in concrete structures starts to corrode resulting in the cracking and spalling of concrete at the reinforcement level due to the bulking of steel reinforcement. During mid-1950s, alternative FRP materials were developed in various forms and configurations. This development of FRP composite has been widened to address many more applications in the construction industries. Therefore it has become mandatory to study the feasibility of using the FRP composites in concrete and a lot of researchers have shown interest on the examination of FRP materials in all dimensions.

FRP materials are the composite materials consisting of matrix (resin) and reinforcing fibres. The fibres are stronger than the matrix. FRP rebars have many merits comprising of high tensile strength, corrosion resistance, and non-magnetic properties comparing to that of steel reinforcement for RC structures. Owing to its low elastic modulus and brittle nature, FRP has been not actively applied as the reinforcement or structural materials in civil engineering structures. For the past two decades, several authors have investigated the flexural behaviour of FRP reinforced concrete beams and slabs. The observed modes of failure such as brittleness and low elastic modulus have been tried to be improved by hybridization. Many scholars and researchers have investigated the hybridization of FRP. This study encompasses of one such hybridization of FRP composite rebar.

Tensile strengths and Young's moduli of FRP reinforcements primarily depend on the type or the variety of fibre and resin, volumetric ratio of fibres (usually 60-70 %), angle between the fibres and the longitudinal axis of reinforcement, and shape and size of the cross section of the reinforcement. FRP rebars' tensile strengths are in the range of 450 to 3 500 N/mm^2, Young's moduli are in the range of 35 000 and 580 000 N/mm^2 and failure strains are in the range of 0.5 to 4.4% Borosnyói, 2013, Balázs, Borosnyói, 2000; Fib, 2007[2,4,5]. The bond performance due to various constituent materials, manufacturing processes and surface treatments of non-metallic reinforcement are quite different from the conventional steel reinforcement Sólyom, Balázs, Borosnyói, 2015 [6]. Abdalla, 2002[7] asserted that due to low modulus of elasticity and brittle nature of GFRP bars, the slabs undergo large deflections and wider crack widths.Sherif EI Gamal, *et.al* 2007[8] compared the punching shear capacities of GFRP slabs with theoretical values. It is concluded that the ultimate load carrying capacity of GFRP deck slabs are three times more than factored design load (208.25kN).

From all these literature studies, a common technology observed is that the efficiency of reinforcement essentially depends on the adhesion between matrix and fiber, so this in turn an important factor in determining the mechanical properties or strength of the composite material. Many research journals related to the mechanical properties of FRP rods as given above have been referred, and the present work depicts the influence of carbon-glass fiber reinforced epoxy polymer matrix on the mechanical properties. As per the ASTM standards, the tensile properties, compressive properties, hardness, impact strengths are studied.

OBJECTIVES

The objectives of the present study are as follows.

- The mechanical properties of the hybrid rod are to be studied.
- The flexural behaviour of one way slabs reinforced with hybrid bars are to be studied
- The flexural capacity of hybrid slabs is tested and compared with conventionally reinforced slabs.
- Slabs are to be tested under static loading conditions.
- The flexural limits, pre cracking behaviour, cracking pattern, crack width, deflections, ultimate load carrying capacity and mode of failure are to be studied and compared with the control specimen.
- The flexural behaviour of one way slabs are given importance and the analytical values are to be compared with the experimental results. Shear strength and shear mode of failure are not considered.

EXPERIMENTAL INVESTIGATIONS

The experimental investigations are carried out in the current study as shown in the flow chart.

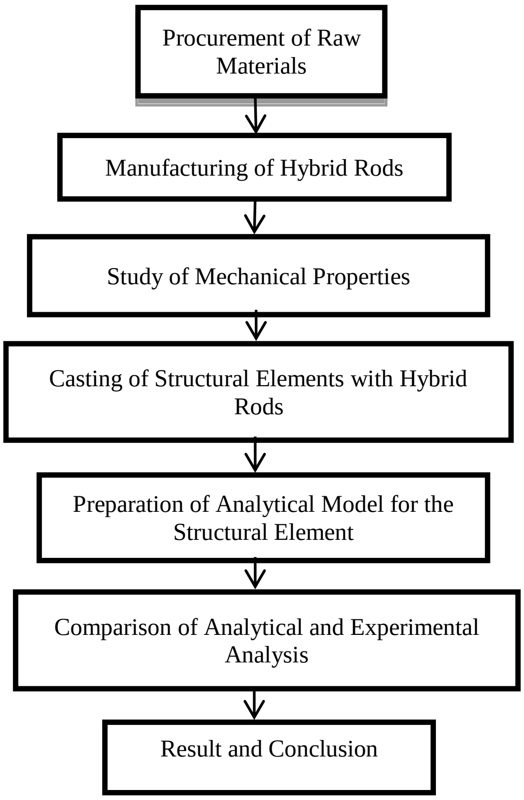


Figure 1. Methodolgy –Flow Chart

Fig.1 directs the flow chart of the methodology adopted in the present study.

Materials and Manufacturing Methods

Hybrid reinforcements used in this study are manufactured by Meena Fiberglass Industries, Pondicherry, India. All the reinforcements supplied by the industry are formulated by pultrusion process with the E-glass fibre volume approximately 60% and these fibres are reinforced with epoxy resins.

The glass fibers and carbon fibers are preferred as reinforcements and epoxy as matrix material. The epoxy resin, hardener Tri Ethylene Tetra Amine (TETA) and Catalyst (Methyl ethyl Kethone Peroxide) are used. The glass fiber of bi-directional woven mat with 200 gm and the density of 2.5 gm/cc are used. The carbon fiber of bi-directional woven mat with 200 gm and the density of 1.78 gm/cc are used. The glass fiber and carbon fiber are used in the fabrication of hybrid fiber reinforced composites are shown in figure 2.

(a) (b)

Figure 2. (a) Raw Carbon and (b) Glass fibres Rovings

Pultrusion process is the pulling of material such as any type of fibres and resin, through a shaped die having a constant cross section. The raw resin is always a thermosetting resin, and is sometimes combined with fillers, catalysts, and pigments. The resin impregnation system is left by the resin rich fiber, the un-cured composite material is guided through a series of tooling which aids to organize the fibre into the correct shape, and the excess resin squeezed out is called debulking. The die is heated to a constant temperature of about 145^{o}, which will cure the thermosetting resin. The profile that exits the die is now a cured pultruded Hybrid Fiber Reinforced Plastic (H- FRP) composite. According to ASTM standards, the manufactured hybrid rods are subjected to tensile test, compression test, hardness test and impact test.

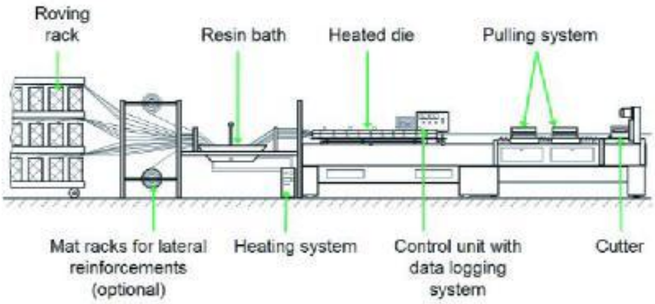


Figure 3. Pultrusion process for manufacturing Hybrid FRP rods

Properties of Reinforcement

1. The conventional steel reinforcement used for comparison in this study is high yield strength deformed bars of grade 415 MPa. The stress- strain curve of reinforcing steel is obtained by performing a standard tension test. About five samples of the manufactured hybrid FRP rods of 10mm diameter are tested in the universal testing machine.
2. Before loading the specimens in the machine, the computer system connected to the machine must be set up by inputting necessary information of gauge length and width of the specimen. The computer system is then prepared to the record data and necessary output load-deflection graphs.
3. The specimens are loaded into the machine, and a tensile test is performed. The data is recorded electronically in the text files and the load-deflection curve is displayed on the computer screen as a visual representation. The test is continued until the specimen gets ruptured or there is a sudden drop in the applied load. Only the results in which failure occurs in the free-length of the specimen are considered for the determination of tensile strength. From the experimental observation the tensile strength of the Hybrid rod is noted as *994.83 Mpa*which is two times greater than that of conventional rod.

(a) (b)

Figure 4. Rupture of Hybrid rod

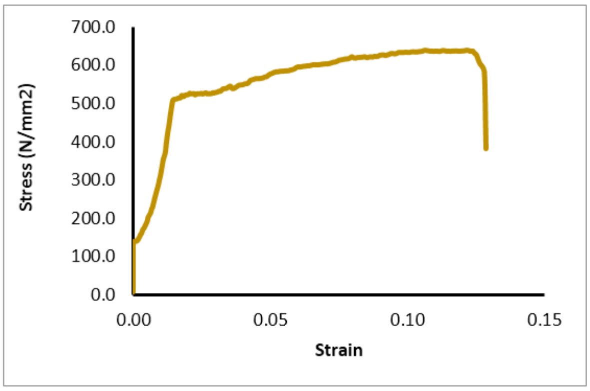


Figure 5. Stress Strain Curve for Steel Rod

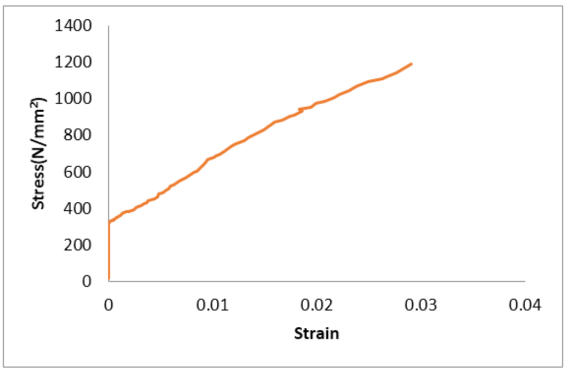


Figure 6. Stress Strain Curve for Hybrid Rod

The stress strain curves for steel and hybrid FRP reinforcements are obtained by performing a standard tension test. The stress strain curve for steel rod is characterized by initial elastic part followed by a strain hardening range in which stress increases with an intensifying strain until the stress reaches its peak. In the absence of yield point 0.2 percent, proof stress is taken as yield point for Fe415 grade steel. In the case of hybrid FRP rods there is no yielding stage i.e., the rupturing of rod takes place without yielding. From the stress strain graph the modulus of elasticity is determined as 78000 Mpa which is 2.5 times lower than that of conventional rod. It was found that the Hybrid FRP rods display a linear elastic behaviour up to failure with a modulus of elasticity lower than that of steel. The elastic modulus is mainly dependent on fibre type and volume percentage. Unlike steel rods the hybrid and GFRP rods exhibit the rupture of rods along the longitudinal direction without yielding at the breaking stage.

Properties of Concrete

The one-way slabs are designed based on the working stress method**.** The process of specifying the most economical and practical combination of materials or selecting suitable materials for producing concrete of required strength is known as mix design. The standard grade concrete is used in this study and the mix proportions of standard grade of concrete M25 is designed based on IS 10262-2009, stipulations. The mix proportions are fixed based on the trial and error method. The Value of slump for fresh concrete is 55mm.The fine aggregate, coarse aggregate, cement of specific gravity 2.68, 2.77 and 3.15 are used to make the concrete. Cube specimens are casted and tested to verify the compressive strength of design mix. Six cubes of size 150 mm ×150 mm × 150mm are casted to determine the compressive strength of concrete, out of which three cubes are tested for about 7 days strength. It has been observed that 70% of target mean strength is achieved. After 28 days of curing, the remaining cubes are tested for its compressive strength. The cube specimen is placed in the universal testing machine in such a way that the axis of test specimens is carefully aligned with center of thrust of the steel plate of the testing machine. The movable part is rotated gently by hand so that uniform seating may be obtained. The load is applied gradually without shock and increasing continuously until the failure of specimen takes place. The maximum load at which the specimen fails is then recorded and the compressive stress is determined from the following formula,

$$\text{Compressive strength} = \frac{compressive load}{area of the cube} \text{ N/mm}^2$$

The average compressive strength of 3 cubes after 28 days of curing is ***36.9 N/mm²***

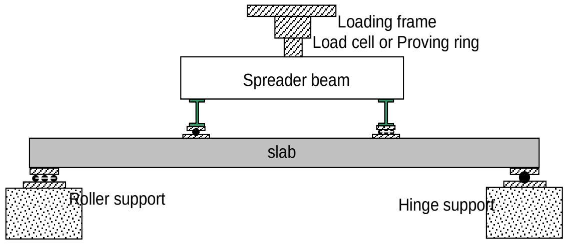


Figure 7. Slab Loading

Static loading Test set up

Load frame of capacity 50 tonnes is used for testing the slab specimens. Slabs are supported with following end condition; i.e. one end of the slab rests on roller support and the other end rests on hinge support. Two point loading (line loads) system is used with the help of spreader beams. Thick rubber or neoprene pads are kept under the spreader beams to avoid local effects. The support end levels of the slabs are maintained properly by spirit levels. The static loads are applied with the help of hydraulic jacks manually (250 kN capacity) and are monitored by proving ring or load cells. The deflections or deformations of the slab are measured by dial gauges, strain gauges (with strain rosettes), LVDTs, Demec gauges. All slabs are pasted with internal and external surface strain gauges. Internal strain gauges are pasted on the surface of the steel/GFRP reinforcements at the time of casting the slabs with due precaution. External strain gauges are pasted on the surface of the slabs at top and bottom fibres. Dial gauges are also fixed at centre, one-third load points and at supports. Dial gauges are fixed at the supports to carry out support corrections. Demec gauges are also used at centre and one-third load points to measure the linear strains. To measure strains with help of Demec gauges, a standard gauge distance is required and it is done with the help of brass pellets pasted at a known distance at top, bottom and centrefibres. Apart from these, LVDTs of range 0-100 mm are used at mid span and at one-third load points to monitor vertical deflections. A Data acquisition system is used to record all LVDT and electrical strain gauge signals. These electrical signals are converted into strains and are processed with the help of computers. The load is gradually applied with an increment of 2 kN up to the failure of the slabs. The crack widths are measured periodically by using crack width detection microscope.

FLEXURAL BEHAVIOUR OF ONE WAY SLABS UNDER STATIC TWO POINT LOADING

The experimental programme consists of five one-way slabs of length 2400 and 600mm width out of which two analogous steel slabs (having the same parameters) and other three are analogous Hybrid slabs to check the genuinity of the results. The reinforcements of size 8 mm are used as secondary reinforcements in the transverse direction of slab i.e., widthwise and 10 mm reinforcements are used as main reinforcements in the span direction of slab i.e., lengthwise at spacing viz., 186.6 mm c/c, and secondary Hybrid reinforcements are tied with help of Nylon zip ties and are spaced at 350mm c/c. Main reinforcements are given a bottom cover of 20mm for all the slabs. Mixing of concrete is done with the help of rotary mixers.

(a) (b)

Figure 8. Photograph of Test Set up for Static loading

A clear span of 2200 mm is kept constant for all the specimens. The slabs are kept on the loading frame and the static load is applied on the slabs gradually at a rate of 2kN in each load increment with the help of hydraulic jack. At the end of each load increment, mid span deflections and deformations on the slab surface are measured manually with the help of dial, and demecgauges also are recorded with the help of data acquisition system. The formation and development of crack widths are noted. The crack widths are measured using crack detection microscope.

STATIC LOADING OBSERVATIONS

The slabs are tested till the ultimate load is reached and the results are compiled as follows. The test result of static loading includes load deflection response, strain distribution across the width of the slab, modes of failure and crack growths.

Load –Deflection Response of Slabs

Load deflection response due to static loading shows a greater reduction in stiffness in the case of GFRP reinforced slabs than the conventional slabs. In the case of conventional slabs, the yielding of reinforcement leads to a larger increase in deflection with little change in load, whereas GFRP reinforced slabs show no yielding of reinforcements and the deflection continues to increase with the increase in load, there by exhibiting some ductility despite the brittle nature of GFRP rebars. The ultimate load of hybrid and conventional slabs are similar with the same reinforcement ratio. The deflection is two times greater than the conventional slab. This may be due to the low stiffness of Hybrid reinforcements. The Load versus deflection of conventional slab and Hybrid slab is shown in Fig. 9 (a), & (b) and 10.

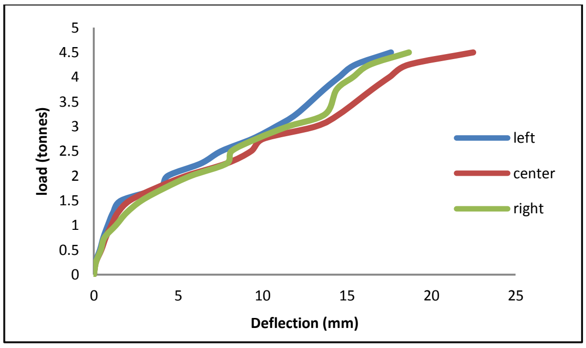


Figure 9(a). Load deflection curve for conventional slab

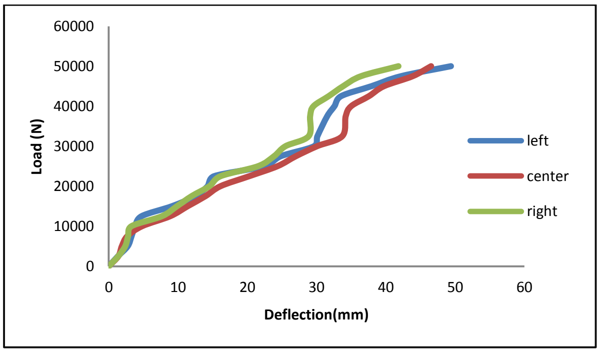


Figure 9(b). Load deflection curve for Hybrid slab

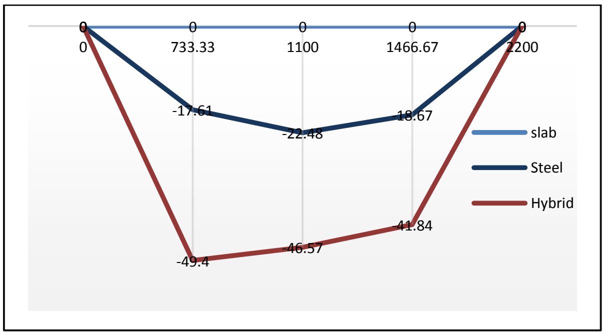


Figure 10. Deflection profile of slabs

Strain Distribution

The strain distributions across the thickness of GFRP/steel reinforced slabs are shown in Fig.11 (a) and 11 (b). It has been observed that the Hybrid reinforcements in tension side of the concrete slabs behave similar to the naked GFRP reinforcements tested under pure tension. Therefore it implies a perfect bond exists between the reinforcing bars and the concrete as assumed in reinforced concrete design. The concrete surface strain in Hybrid reinforced slabs is approximately two to three times greater than the conventional slabs under the same load level.

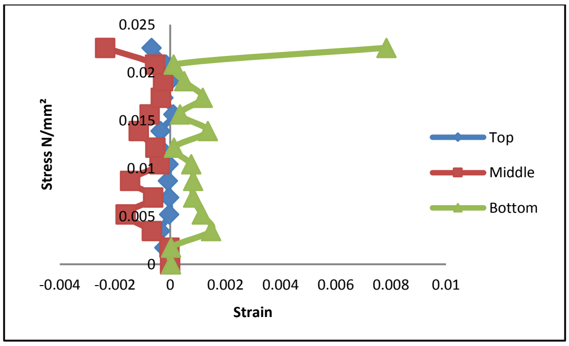


Figure 11 (a). Stress strain curve for conventional slab

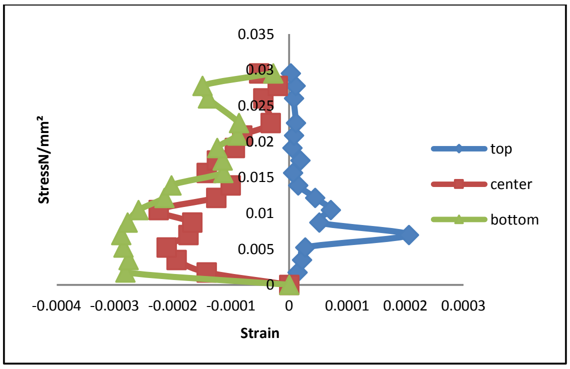


Figure 11 (b). Stress strain curve for hybrid slab

Crack Growths and Modes of Failure

Cracks occur at the surface of the bottom of concrete slabs whenever the tensile stresses exceed the modulus of rupture of concrete. The first crack appears at the middle of the slab and develops slowly across the width of the slab. Further development of cracks occurs, on increasing the application of load under static loading conditions. All the slabs experience flexural type of failure. At ultimate load, Hybrid reinforced slabs experience concrete crushing followed by the rupture of Hybrid reinforcements. But the failure mode observed in the case of Hybrid slab is concrete crushing without rupture of Hybrid reinforcements slab due to the higher reserved strength of Hybrid slab and equal values of the modulus of elasticity for Hybrid reinforcements and concrete in addition to the linear-elastic behaviour of Hybrid reinforcements. Steel reinforced slabs show the tension failure i.e., yielding of rebars and then concrete crushing failure. Figs 12(a) and 12(b) depict the crack pattern of slabs.

(a)

Figure 12 (a). Crack pattern of conventional slab

(b)

Figure 12(b). Crack pattern of hybrid slab

ANALYTICAL INVESTIGATIONS

Three dimensional non-linear finite element analyses were carried out for numerically evaluating the performance of one way slabs. The load condition and support condition for conventional and hybrid slabs are same and it is shown in the fig 13. Three dimensional brick elements are used for the modeling. This element is defined by eight nodes having three degrees of freedom at each node. A unique feature of this element is the treatment of non-linear properties. This element has plasticity, stress stiffening, large deflection and large strain capabilities. There are two restrictions associated with this element namely, all elements must have eight nodes and zero volume elements are not allowed.

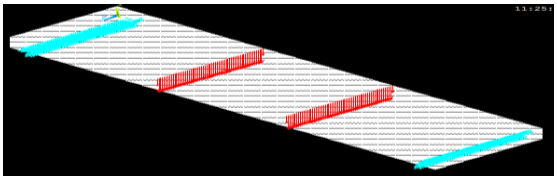


Figure 13. Loading and support conditions

5.1 Modeling of Concrete and Reinforcements

A linear isotropic material model is used to represent the concrete. This material is known as quasi brittle material and has different behaviour in compression and tension. In this present study Solid 65 element is used to model the concrete. This element has eight nodes having three degrees of freedom at each node, i.e. translations in the nodal X, Y and Z directions respectively and the element is capable of cracking and crushing in three orthogonal directions.

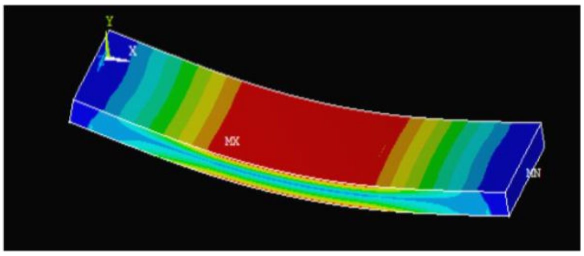
A multi linear isotropic material model is used to represent steel reinforcements and a multi linear orthotropic material model was used to represent hybrid reinforcements. A link 180 element is used to model the reinforcements. It is two node elements and each node has three degrees of freedom. Translations are in the nodal X, Y and Z directions. This element is also capable of undergoing plastic deformation. The stress strain curve for reinforcement was obtained from bars tested in tension. The properties of hybrid rods were obtained from the experimental results.Table.1 presents the properties required for the software analysis.

Table 1. Mechanical Properties

Properties of concrete	
Poisson's ratio	0.15
Modulus of elasticity	25,000 N/mm^2
Open shear transfer coefficient	0.2
Closed shear transfer coefficient	0.4
Uniaxial cracking stress	3.5
Uniaxial crust stress	35
Properties of steel reinforcements	
Modulus of elasticity	2E- 005
Poisson's ratio	0.3
Yield stress	496.6
Tangent modulus	210
Properties of hybrid FRP reinforcements	
Modulus of elasticity	70E- 03
Poisson's ratio	0.2
Yield stress	915.3
Tangent modulus	0

Analytical results

An analysis of concrete slabs with conventional and fiber reinforced plastics including material and geometric non linearities are performed. A dual criterion for yielding and crushing in terms of stresses and strains are considered in the analysis. The material law for unidirectional composites is linear elastic or brittle. The deflected profiles of analyzed (Hybrid and conventional) slabs are shown in the Fig.14 (a) and 14(b).



(b)

Figure 14. Deflected profile of Hybrid and conventional one way slabs

The finite element model developed in this study is used to simulate the static experimental tests performed. The load-deflection responses of both slabs are determined using ANSYS. The results of the finite element study are compared with experimental study. It has been observed, from the Fig. 15(a) and Fig.15(b) that the experimental ultimate load of conventional slab and Hybrid slabs are more or less same whereas the deflections of Hybrid slab are twice that of conventional slab .

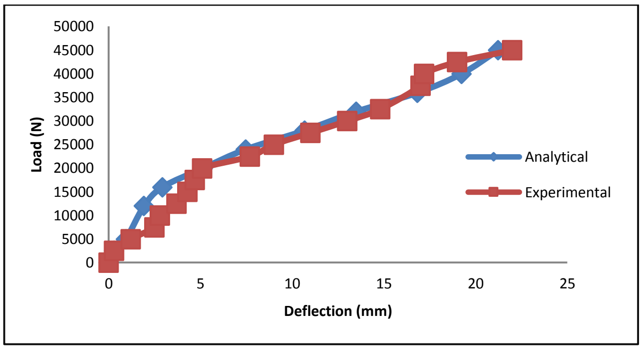


Figure 15 (a) Load deflection curve for conventional slab

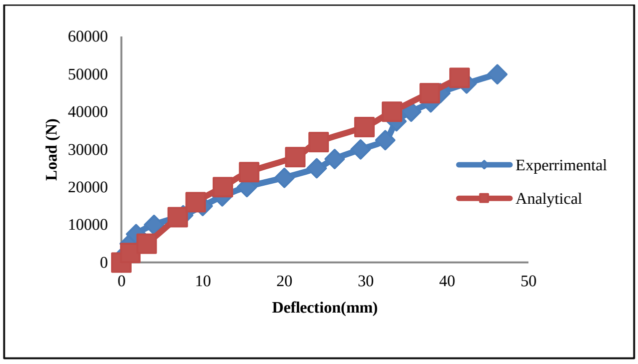


Figure 15 (b) Load deflection curve for hybrid slab

Table 2. Comparison between experimental and analytical values

Specimen	**Parameters**	**Experimental value(b)**	**Analytical value(a)**	**b/a**
Conventional slab (1)	Ultimate load (kN)	45	45	1
	Deflection (mm)	22	21.23	1.04
Conventional slab (2)	Ultimate load (kN)	40.6	45	0.9
	Deflection (mm)	25	21.23	1.18
Hybrid FRP slab (1)	Ultimate load (kN)	50	49	1.02
	Deflection (mm)	46.2	41.53	1.11
Hybrid FRP slab (2)	Ultimate load (kN)	49.6	49	1.012
	Deflection (mm)	45	41.53	1.08
Hybrid FRP slab (3)	Ultimate load (kN)	50.2	49	1.02
	Deflection (mm)	53.2	41.53	1.28

Table 2 depicts the comparison between the experimental observations and analytical findings. The ratios (b/a) of experimental and analytical values conclude that the analytical and experimental values are in good agreement. As per the ratio determined in the Table.2, the average value of the ultimate load is found out as 0.9904 for which the standard deviation is 0.051 MPa and the coefficient of variation is 0.0026%. Similarly, the average value of the ultimate deflection is found out as 1.138 for which the standard deviation is 0.094 MPa and the coefficient of variation is 0.00892.

CONCLUSIONS

The Hybrid FRP rods exhibited a linear elastic behaviour up to failure with a modulus of elasticity lesser than that of steel. The elastic modulus is primarily reliant on fibre type and volume percentage. The hybrid rods which are distinct from steel rods, exhibit the rupture of rods along the longitudinal direction without yielding at the breaking stage.

The slab reinforced with hybrid FRP slabs undergoes larger deflection compared to the conventional slab. In case of conventional slabs the yielding of reinforcement results in larger deformation at lower load rates leading to ductile mode of failure but in the case of hybrid FRP slabs there is no yielding of reinforcements and hence the concrete fails by crushing prior to the reinforcements. It has been observed that the Hybrid reinforcements in tension side of the concrete slabs behave similar to the FRP reinforcements tested under pure tension. Therefore it implies a perfect bond exists between the reinforcing bars and the concrete as assumed in reinforced concrete design. The concrete surface strain in Hybrid reinforced slabs is approximately two to three times greater than the conventional slabs under the same load level.

The conventional slab shows an increase in curvature prior to collapse indicating the typical ductile mode of failure where yielding of reinforcement followed by the crushing of concrete in compression. Whereas in the case of hybrid slabs, there is no yielding of reinforcements the concrete fails in the compression zone. The curvature and deflections remains low up to the failure hence this type of failure is termed as brittle failure. The experimental ultimate load of conventional slab and Hybrid slabs are more or less same whereas the deflections of Hybrid slab are twice that of conventional slab. Cracks appear at the bottom surfaces of concrete slabs whenever the tensile stresses exceed the modulus of rupture of concrete. The first crack appears at the middle of the slab and develops slowly across the width of the slab. Further development of cracks occurs, on increasing the application of load under static loading conditions.

All the slabs experience flexural type of failure. At ultimate load, Hybrid reinforced slabs experience concrete crushing followed by the rupture of Hybrid reinforcements. But the failure mode observed in the case of Hybrid slab is concrete crushing without rupture of Hybrid reinforcements slab due to the higher reserved strength of Hybrid slab and equal values of the modulus of elasticity for Hybrid reinforcements and concrete in addition to the linear-elastic behaviour of Hybrid reinforcements. Steel reinforced slabs show the tension failure i.e., yielding of rebars and then concrete crushing.

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