An Experimental Study of Monolithic & Hybrid Fiber Reinforced Polymer for Strengthening Reinforced Concrete Beams in Bending

V.Shakila
Structural Engineering
Gnanamani College of Engineering
Namakkal.

Mr.K.Soundhirarajan, M.E.,
Assistant Professor and Head of Dept. of Civil Engineering
Gnanamani College of Engineering
Namakkal

Abstract — Due to the increasing deterioration of reinforced concrete heritage structures, the repair and strengthening industry has become a very hot business in most parts of the world. There are also various methods to prolong the service life of these deteriorated structures varying in their effectiveness and initial cost. There are also various repair principles from organizations, which are sometimes difficult to attain in the real world. These principles have a wide range of influence on reinforced concrete heritage structures which should pass from generation to generation. To select an effective repair method for a deficient concrete member or structure, the effect or damage of the cause should be studied deeply using field and laboratory investigation techniques. If the cause of the damage is known, an appropriate strengthening technique can be selected. Mostly the damages are expressed in terms of cracks of a member or structure. To meet up the requirements of advance infrastructure, new innovative materials/ technologies in Civil engineering industry has started to make its way. Any technology or material has its limitations and to meet the new requirements new technologies have to be invented and used. With structures becoming old and the increasing bar for the constructed buildings the old buildings have started to show a serious need of additional retrofits to increase their durability and life.

The aim of this project work is use of FRP for confinement has proved effective in retrofitting and strengthening applications. The Confinement in seismically active regions has proven to be one of the early applications of FRP materials in infrastructure applications. Confinement may be beneficial in non-seismic zones too, where, for instance, survivability of explosive attacks is required or the axial load capacity of a column must be increased due to higher vertical loads, e.g. if new storey's have to be added to an existing building or if an existing bridge deck has to be widened. In any case, confinement with FRP may be provided by wrapping RC columns with prefabricated jackets or in situ cured sheets, in which the principal fiber direction is circumferential. Beams, Plates and columns may be strengthened in flexure through the use of FRP composites bonded to their tension zone using epoxy as a common adhesive for this purpose. The direction of fibers is parallel to that of high tensile stresses. Both prefabricated FRP strips, as well as sheets (wet-layup) are applied. Hence, FRP composites are finding ways to prove effective and economical at the same time.

Keywords - *Monolithic Fibre Reinforced Polymers, Hybrid Polymer,specimen test, strengthening test.*

I. Introduction

In recent years repair and retrofit of existing structures such as buildings, bridges, etc., have been amongst the most important challenges in Civil Engineering. The primary reason for strengthening of structures includes upgrading of its resistance to withstand underestimated loads, increase in the load carrying capacity for higher permit loads, such as due to increased perceived risk from seismic excitations, eliminating premature failure due to inadequate detailing, restoration of lost load carrying capacity due to corrosion or other types of degradation caused by aging, etc. To remedy for insufficient capacity the structures need to be replaced or retrofitted. Different types of strengthening materials are available in the market. Examples of these are ferrocement, steel plates and fibre reinforced polymer (FRP) laminate. Retrofitting of reinforced concrete (RC) structures by bonding external steel and FRP plates or sheets is an effective method for improving structural performance under both service and ultimate load conditions. It is both environmentally and economically preferable to repair or strengthen structures rather than to replace them totally. With the development of structurally effective adhesives, there have been marked increases in strengthening using steel plates and FRP laminates. FRP has become increasingly attractive compared to steel plates due to its advantageous low weight, high stiffness and strength to weight ratio, corrosion resistance, lower maintenance costs and faster installation time. It is well known that reinforced concrete beams strengthened with externally bonded fibre-reinforced polymer (FRP) or CFRP to the tension face can exhibit ultimate flexural strength greater than their original flexural strength. However, these FRP and CFRP strengthened beams could lose some of their ductility due to the brittleness of FRP and CFRP plates.

Various types of Fibre reinforced polymer (FRP) products are widely used around the world especially in the repair and strengthening of reinforced concrete structures. The major constituents of FRP are the fibre and the resin.

The mechanical properties of FRP are controlled by the type of fibre and durability characteristics are affected by the type of resin. The following are some of the types of FRPs that can be used for strengthening of concrete structures.

1.1 OBJECTIVE

The objective of the study is

- To evaluate the flexural behaviour of distressed RC beams rehabilitated with the monolithic and hybrid fibres of sisal and polypropylene fibres.
- To compare its performance with that of the control beams.
- To validate its performance using FEM (Abacus) software..

1.2 SCOPE

To evaluate flexural behaviour of distressed RC beams rehabilitated with the monolithic and hybrid fibres of sisal and polypropylene fibres.

- ➢ To study the compressive strength and split tensile strength of concrete cubes and cylinders
- ➢ To Determine the Ultimate Load and Young's Modulus of specimens of FRP
- ➢ To study the compressive strength of beams
- ➢ To carryout the Preliminary test on beams for comparative study
- ➢ To Strengthening of Beams by Monolithic sisal fibres, Monolithic polypropylene fibres and Hybrid fibres separately.
- ➢ To carryout testing on strengthening beam for the comparative study of each one.
- ➢ To carryout Finite Element Analysis for comparative study with experimental study.
- ➢ To achieve flexural behaviour of Reinforced concrete beams by strengthening.
- ➢ To encourage using monolithic and hybrid fibres of sisal and polypropylene for Reinforced concrete beams strengthening.

II LITERATURE REVIEW

2.1 LITERATURE SURVEY

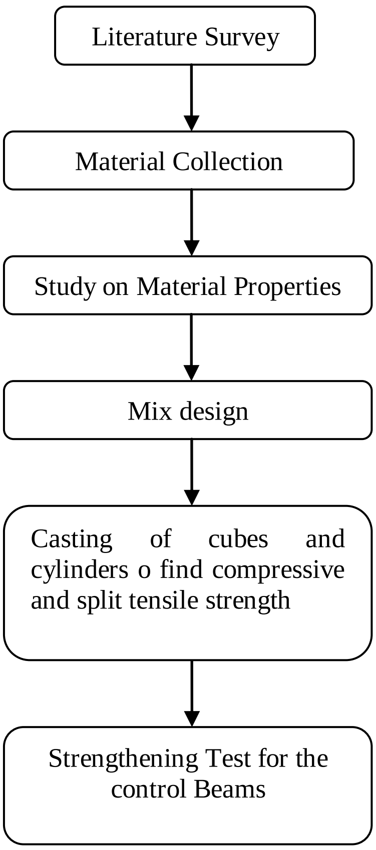
The necessary literature studies were carried through national/international journals, periodical conferences, books, and recent data from internet source.

R. Balamuralikrishnan and C. Antony Jeyaseha (2009) this paper explores the flexural behaviour of carbon fibre reinforced polymer (CFRP) strengthened reinforced concrete (RC) beams. For flexural strengthening of RC beams, total ten beams were cast and tested over an effective span of 3000 mm up to failure under monotonic and cyclic loads. The beams were designed as under-reinforced concrete beams. Eight beams were strengthened with bonded CFRP fabric in single layer and two layers which are parallel to beam axis at the bottom under virgin condition and tested until failure; the remaining two beams were used as control specimens. Static and cyclic responses of all the beams were evaluated in terms of strength, stiffness, ductility ratio, energy absorption capacity factor, compositeness between CFRP fabric and concrete, and the associated failure modes. The theoretical moment-curvature relationship and the load-displacement response of the strengthened beams and control beams were predicted by using FEA software ANSYS. Comparison has been made between the numerical (ANSYS) and the experimental results. The results show that the strengthened beams exhibit increased flexural strength, enhanced flexural stiffness, and composite action until failure.

Ahmed Ghobarah (2002)[1] Shear failure of beam-column joints is identified as the principal cause of collapse of many moment-resisting frame buildings during recent earthquakes. Effective and economical rehabilitation techniques for the upgrade of the joint shear-resistance capacity in existing structures are needed. The objective of this research is to develop effective selective rehabilitation schemes for reinforced concrete beam-column joints using advanced composite materials. Several reinforced concrete beam-column joints were constructed. The joints were designed to simulate non ductile detailing characteristics of pre-seismic code construction. The control specimens showed joint shear failure when subjected to cyclic loading at the beam tip. Different fibre-wrap rehabilitation schemes were applied to the joint panel with the objective of upgrading the shear strength of the joint. The tested rehabilitation techniques were successful in improving the shear resistance of the joint and in eliminating or delaying the shear mode of failure.

Ines G. Costa (2010)[9] Experimental, numerical and analytical investigations have revealed that Carbon Fibre Reinforced Polymer (CFRP) strips with larger cross section height improve the effectiveness of the Near Surface Mounted (NSM) technique for the flexural strengthening of existing reinforced concrete (RC) beams. However, this height is limited to the concrete cover thickness of the longitudinal steel bars, since the application of strips of cross section height larger than the cover thickness requires that the bottom arm of the steel stirrups be cut. This work aims to assess the influence, in terms of shear resistance, of cutting the bottom arm of steel stirrups to install NSM strips for the flexural strengthening of RC beams. The obtained results showed that, for monotonic loading, cutting the bottom arm of steel stirrups led to a decrease of the beam's load carrying capacity of less than 10%. Due to the high effectiveness of the adopted NSM flexural strengthening systems, shear can be a predominant failure mode for these beams. To avoid this type of failure mode, strips of wet lay-up CFRP sheets with U configuration were used, resulting in effective strengthening solutions for RC beams. In the present paper the experimental program is described, and the obtained results are presented and discussed

III METHODOLOGY AND MATERIALS



3.1MATERIALS USED FOR EXPREMENTAL WORK

The experimental work consists of casting 3 cubes and 3 cylinders (control specimens) to find out the compressive strength and tensile strength of the concrete. The number of beams cast were 8 out of which, 2 beams are control beams, 2 beams retrofitted with monolithic fibres of sisal, 2 beams retrofitted with monolithic fibres of polypropylene and 2 beams retrofitted with hybrid fibres of sisal and polypropylene. The strengthening of the beams is done with the varying fibres in monolithic and hybrid manner at the soffit of the beam. Experimental data on load, deflection and energy absorption of the beams were obtained. Table 3.1 shows the Specimen specifications.

Table 3.1 Specimen specifications

Beam ID	No of specimens	Type of strengthening	Thickness of FRP(mm)
C1	2	-	-
F1	2	Monolithic fibres of sisal	3
F2	2	Monolithic fibres of polypropylene mat	3
F3	2	Hybrid fibres of sisal and polypropylene	3

3.1.1 Parameters to be studied

- Yield load
- Ultimate load
- Stiffness at yield
- Stiffness at ultimate
- Deflection at yield
- Deflection at ultimate
- Deflection ductility

3. 2 Materials and Methods

Cement concrete having characteristic compressive strength of 20 MPa was used for casting the beams. The longitudinal steel reinforcement was provided using Fe 415 grade steel rods and shear stirrups were provided using Fe 250 grade steel rods. HYSD bars of 10 mm diameter of 2 bars were used as tension reinforcement and 2 bars of 8 mm diameter were used as the compression reinforcement. The stirrups of 6 mm diameter with a spacing of 120 mm were used for the investigation. The fibres used were sisal and polypropylene mat and strengthened in monolithic and hybrid manner at the soffit of the beam. The adhesive used is epoxy resin of grade Araldite GY257 and Hardener HY840 in the ratio 1:0.5 by weight. The ratio of resin to fibres is 1:0.5 by weight.

3.3 Preliminary Tests

The material properties such as specific gravity, Bulk density, % voids for materials such as cement, coarse aggregate and fine aggregate has been calculated by conducting preliminary tests as per Indian Standard Specifications.

3.3.1 Cement

Cement is a material generally in the material form, which can be made in to a paste usually by the addition of water. The colour of the cement is mainly due to iron oxide. Most commonly used cement is Portland cement and in this study ordinary Portland cement was used and the specific gravity of cement was calculated and the value obtained was 3.05.

3.3.2 Fine aggregate and coarse aggregate

The fine aggregate clear from all sorts of organic impurities was used in this experimental program. The fine aggregate was passing through 4.75 mm sieve and the grading zone of fine aggregate was zone III as per Indian Standard Specifications. The coarse aggregates used were aggregates passing through 10 mm sieve but retained on 20 mm sieve. The table 3.2 shows the material properties of fine aggregate and coarse aggregate.

Table 3.2 Material properties

Sl. no	Materials	Specific gravity	Bulk density	% voids
1	Fine aggregate	2.64	1.542	1.305
2	Coarse aggregate	2.72	41.566	51.73

3.4 Mix proportion

The requirement of the materials to arrive the mix proportion was calculated using the material properties values and the mix proportion was arrived. The requirement of the materials to arrive the mix proportion was in the table 3.3.

Table 3.3 Materials required

Materials	Quantity
cement	360 kg
water	191.8 kg/m^3
Fine aggregate	660.738 kg
Coarse aggregate	1054.98 kg

The mix proportion was 1: 1.92: 3.22

The water cement ratio adopted was 0.5.

3.5 Casting of cubes and cylinders to find compressive and split tensile strength

3.5. Cube casting to find compressive strength

The 3 cubes of 150x150x150 mm as control specimens has been cast and cured for 28 days to attain the strength and tested to find out the compressive strength of the concrete. The figure 3.1shows the cube testing and the table 3.4 shows the cube results.

Table 3.4 Cube results for compressive strength

Specimen designation	Load in kN
C1	650
C2	630
C3	620

The Compressive strength of the concrete tested after 28 days of curing was found to be 28.15 N/mm^2.

3.5.2 Cylinder casting to find split tensile strength

The 3 cylinders of 150 mm diameter and 300 mm height as control specimens has been cast and cured for 28 days to attain the strength and tested to split tensile strength of the concrete. Table 3.5 shows the cylinder results.

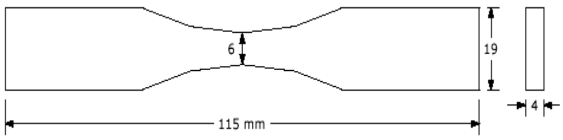
Table 3.5 Cylinder results for split tensile strength

Specimen designation	Load in kN
C4	200
C5	210
C6	220

The split tensile strength of the concrete tested after 28 days of curing was found to be 2.97 N/mm^2.

3.6 Determination of Ultimate Load and Young's Modulus

The ultimate load and Young's modulus are determined experimentally by performing unidirectional tensile tests on specimens as described in ASTM standard D638-1968. A thin flat strip of specimen as shown was prepared in all cases. The figure 3.1 shows the specimen specifications used for the tensile test.



The specimen is loaded in universal testing machine. Specimens were fixed in the upper jaw first and then gripped in the movable jaw (lower jaw). Initially strain was kept at zero. The load as well as the extension was recorded digitally with the help of a load cell and an extensometer respectively. From these data, stress strain curve was plotted; the initial slope of which gives the young's modulus. The ultimate stress and ultimate load were obtained at the failure of the specimen.

3.7 Casting of Beams

Totally Eight beams were cast for this experimental program. The dimensions of the beams are 175x175 mm cross section and the length is 1500 mm. The beams were cast and cured for 28 days to attain the maximum strength.

3.7.1 Reinforcement details

The longitudinal steel reinforcement was provided using Fe 415 grade steel rods and shear stirrups were provided using Fe 250 grade steel rods. HYSD bars of 10 mm diameter of 2 bars were used as tension reinforcement and 2 bars of 8 mm diameter were used as the compression reinforcement. The stirrups of 6 mm diameter with a spacing of 120 mm were used for the investigation. The clear cover adopted was 25 mm. The reinforcement details designed were according to IS 456:2000.

3.7.2 Mixing of concrete and compaction

Mixing of concrete should be done thoroughly to ensure that concrete of uniform quantity is obtained. A clean surface is needed for the purpose, such as a clean, even and paved surface. Moisten the surface and level the platform, spread cement over the sand and then spread the coarse aggregate over the cement. Turn the dry materials at least three times until the colour of the mixture is uniform. Add water slowly while you turn the mixture again at least three times, or until you attain the proper consistency. Usually 10% extra cement is added in case of hand mixing to account for inadequency in mixing.

3.7.3 Curing of concrete

The concrete is cured to prevent or replenish the loss of water which is essential for the process of hydration and hence for hardening. Also curing prevents the exposure of concrete to a hot atmosphere and to drying winds which may lead to quick drying out of moisture in the concrete and thereby subject it to contraction stresses at a stage when the concrete would not be strong enough to resists them. Curing is done by spraying water or by spending wet heissian cloth over the surface. Curing makes the concrete more durable, more impermeable and more resistant to abrasion and to frost.

3.8 Preliminary Test on Beams

3.8.1 Testing of Control Beams

After the curing period of 28 days was over, the control beams were tested initially. The most commonly used load arrangement for testing of beams will consist of two-point loading. This has the advantage of a substantial region of nearly uniform moment coupled with very small shears, enabling the bending capacity of the central portion to be assessed; the load will normally be concentrated at a suitable shorter distance from a support. Figure 14 shows the experimental setup.

Two point loading can be conveniently provided by the arrangement shown in figure 1.The load is transmitted through a load cell to the spreader beam. This beam bears on rollers seated on steel plates bedded on the test member.

The loading frame must be capable of carrying the expected test loads without significant distortion. Ease of access to the middle third for crack observations, deflection readings, and possibly strain measurements is an important consideration, as is safety when failure occurs.

The specimen was placed over the 2 steel rollers leaving 50 mm from the ends of the beam. The remaining 1400 was divided into 3 equal parts of 470 mm. Loading was done by hydraulic jack of 100 kN. Three deflectometres were used for recording the deflection of the beams. One was placed at the centre of the beam and the other was placed just below the point loads to measure deflections.

The load was given through the hydraulic jack to the beams and the corresponding deflection was noted. The initial crack load was noted and the yield and ultimate loads and their corresponding deflections were noted. Figure 15 shows the deflection of control beam.

The ultimate load taken by the control specimens are 52 kN. About 75% of the ultimate load of the control specimens (C1) can be loaded to other beams to distress them. Finally the beams were given a load of 39 kN to get damaged and then rehabilitated with monolithic and hybrid fibres of sisal and polypropylene fibres. Table 3.3 shows the control beam results.

Table 3.3 control beam results

Control beams	Yield load (kN)	Yield deflection (mm)	Ultimate load(kN)	Ultimate deflection (mm)
C1	34	5.32	52	21.64

3.8.2 Distressed beams

The beams were distressed by applying a load of 39 kN. All the beams were placed in the loading frame and the settings are made. Then the beams were given a load of 39 kN. Once the required load was attained the load must be stopped and the beams are released for strengthening process. The figure 16 shows some of the distressed beams. This distressed beams were rehabilitated with monolithic and hybrid fibres of sisal and polypropylene at the bottom of the beam.

3.9. Materials used for strengthening

3.9.1 Fibres

A fibre is a material made into a long filament. The aspect ratio can be ranging from thousand to infinity in continuous fibres. The main functions of the fibres are to carry the load and provide stiffness, strength, thermal stability and other structural properties in the FRP. To perform these desirable functions, the fibres in FRP composite must have:

- high modulus of elasticity
- high ultimate strength
- high stability of their strength during handling
- high uniformity of diameter surface dimension among fibres
- low variation of strength among fibres

3.9.2 Adhesive

The adhesive used is the epoxy resin. The epoxy resins are characterized by the presence of a three membered ring containing two carbons and an oxygen. The success of the strengthening technique critically depends on the performance of the epoxy resin used. These epoxy resins are generally a two part systems, a resin and a hardener.

The adhesive used in this research was Araldite GY257 and Hardener HY840 in the ratio of 1:0.5.The ratio of epoxy resin to the fibres is 1:0.5.The figure shows the Epoxy resin. The table 3.4 shows the properties of resin used in this study.

Table 3.4 Epoxy resin Specifications

Sl.no	Properties	Araldite GY 257	Hardener HY 840
1	Density @ 25^0 c	1.15	0.98
2	Specific gravity	1.8	2.0
3	Flexural strength N/mm^2	45-55	30-40

3.10 Strengthening Of Beams

Before bonding the composite material onto the concrete surface, the required region of concrete surface was made rough using chisel and hammer and cleaned well to remove all dirt and debris. Figure 20 shows the roughened surface at the bottom of the beam which is to be rehabilitated to find out the flexural behaviour. Once the surface was prepared to the required standard, the epoxy resin (Araldite GY257 and Hardener HY840) was mixed in a plastic container and continued until the mixture was in uniform colour.

The mixing of resin in a plastic container. When this was completed and the fabrics had been cut to size, the epoxy resin was applied to the concrete surface. The composite fabric was then placed on top of the epoxy resin coating. Concrete beams strengthened with fabrics were cured for 24 hours before testing. Figure 21 shows the mixing of resin.

3.10.1 Strengthened Beam

The beams were then strengthened with the monolithic and hybrid fibres of sisal and polypropylene fibres at the soffit of the beams to find out the flexural behaviour of beams. The figure 22,23,24 shows the strengthened beams with monolithic and hybrid fibres of sisal and polypropylene.

- F1 –monolithic fibres of sisal
- F2- monolithic fibres of polypropylene
- F3- hybrid fibres of sisal and polypropylene fibres

3.11 Testing Of Strengthened Beams

After the curing period of 28 days was over, the strengthened beams were tested again till ultimate. The most commonly used load arrangement for testing of beams will consist of two-point loading. This has the advantage of a substantial region of nearly uniform moment coupled with very small shears, enabling the bending capacity of the central portion to be assessed; the load will normally be concentrated at a suitable shorter distance from a support. Figure 25 shows the experimental setup of the strengthened beam.

Two point loading can be conveniently provided by the arrangement shown in figure 1.The load is transmitted through a load cell to the spreader beam. This beam bears on rollers seated on steel plates bedded on the test member.

The loading frame must be capable of carrying the expected test loads without significant distortion. Ease of access to the middle third for crack observations, deflection readings, and possibly strain measurements is an important consideration, as is safety when failure occurs.

The specimen was placed over the 2 steel rollers leaving 50 mm from the ends of the beam. The remaining 1400 was divided into 3 equal parts of 470 mm. Loading was done by hydraulic jack of 100 kN. The dial gauge was placed below the centre of the beam to note the deflection.

3.11.1 Procedure

After setting and reading all deflection dial gauges, the load was increased incrementally up tos calculated working load, with loads and deflections calculated at each stage. Loads will then normally be increased again in similar increments up to failure, with dial gauges replaced by a suitably mounted scale as failure approaches. This is necessary to avoid damages to deflection dial gauge. Cracking and failure mode was checked visually, and a load/deflection curve was plotted

IV RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter describes the experimental results of F1 beams (strengthened with monolithic fibres of sisal) F2 beams (strengthened with monolithic fibres of polypropylene) and F3 beams (strengthened with hybrid fibres of sisal and polypropylene). Their behaviour throughout the static test to failure is described using recorded data on deflection behaviour and the ultimate load carrying capacity.

In this experimental investigation the flexural behaviour of Reinforced concrete beams strengthened using monolithic and hybrid fibres of sisal and polypropylene are studied. The F1 beams showed lower load carrying capacity but the deflection is higher when compared to F2 beams. This shows that the member is ductile. The F2 beams showed higher load carrying capacity but the deflection is lower when compared to F1 beams. This shows that the member is brittle. The F3 beams showed higher load carrying capacity and higher deflection which shows that the benefits of both the fibres are achieved in the hybrid combination.

4.2 Introduction

4.2.1 Monolithic sisal specimen results

Table 4.1Monolithic sisal specimen results

S. No.	Results	Value	units
1	Area	57	mm^2
2	Yield Force	1619.73	N
3	Yield Elongation	2.31	mm
4	Break Force	2841.95	N
5	Break Elongation	2.69	mm
6	Tensile Strength at Yield	28.42	N/ mm^2
7	Tensile Strength at Break	49.85	N/ mm^2
8	% Elongation	2.34	%

The specimen was tested and the following results were obtained as shown in the table 4.1. The stress strain graph was plotted and the initial slope of which gives the Young's modulus. The area of the specimen was 57 mm^2. The Tensile strength at yield and break was calculated. The Young's modulus and Poisson's ratio was found to be

- **Young's modulus -1421.5 N/mm^2**
- **Poisson's ratio -0.02**

4.2.2 Hybrid specimen results

The specimen was tested and the following results were obtained as shown in the table 11. The stress strain graph was plotted and the initial slope of which gives the Young's modulus. The area of the specimen was 57 mm^2. The Tensile strength at yield and break was calculated. The Young's modulus and Poisson's ratio was found to be

- **Young's modulus - 318.2 N/mm^2**
- **Poisson's ratio - 0.11**

Table 4.2 Hybrid specimen results

S. No.	Results	Value	units
1	Area	57	mm^2
2	Yield Force	1619.73	N
3	Yield Elongation	2.31	mm
4	Break Force	2841.95	N
5	Break Elongation	2.69	mm
6	Tensile Strength at Yield	28.42	N/ mm^2
7	Tensile Strength at Break	49.85	N/ mm^2
8	% Elongation	2.34	%

4.3 Load Deflection history

The load deflection history of all the beams was recorded. The mid-span deflection of each beam was compared with that of their respective control beams. Also the load deflection behaviour was compared between three wrapping schemes, having the same reinforcement. It was noted that the behaviour of the strengthened beams were better than their corresponding control beams. The mid-span deflections were much lower in strengthened beams when compared with the control beams. The use of FRP sheet had effect in delaying the growth of crack formation.

4.3.1 Beams F1

In beams F1 the strengthening was done with the monolithic fibres of sisal which was bonded to the soffit of the beam to find out the flexural behaviour. The thickness of the FRP laminate was 3 mm.The following observations has been made in the investigation.

- In F1 beams, the ultimate load carrying capacity was increased by 30.76% when compared to control beams.
- The F1 beams showed lower ultimate load carrying capacity of 68 kN when compared to F2 and F3.
- The deflection in the F1 beams are higher when compared to F2 &F3. For the corresponding load the deflection was higher in the F1 beams.This shows that the natural fibre behaves in ductile manner when compared to artificial fibres.
- The deflection ductility was calculated as 1.97.
- The stiffness at yield and stiffness at ultimate was found to be 10.50 and 7.25.

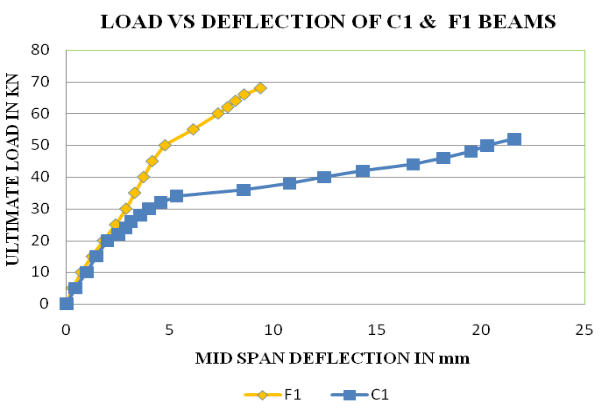


Figure 4.1 Load deflection curve for F1 beams

4.3.2 Beams F2

In beams F2 the strengthening was done with the monolithic fibres of polypropylenel which was bonded to the soffit of the beam to find out the flexural behaviour. The thickness of the FRP laminate was 3 mm.The following observations has been made in the investigation.

- In F2 beams, the ultimate load carrying capacity was increased by 46.15 % when compared to control beams.
- The F2 beams showed higher ultimate load carrying capacity of 76 kN when compared to F1 beams.
- The deflection in the F2 beams are lower when compared to F1. For the corresponding load the deflection was lower in the F2 beams.This shows that the artificial fibre shows brittle nature which leads to failure without warning.
- The deflection ductility was calculated as 2.258
- The stiffness at yield and stiffness at ultimate was found to be 11.34 and 5.965.

4.3.3 Beams F3

In beams F3 the strengthening was done with the hybrid fibres of polypropylene which was bonded to the soffit of the beam to find out the flexural behaviour. The thickness of the FRP laminate was 3 mm.The following observations has been made in the investigation.

- In F3 beams, the ultimate load carrying capacity was increased by 57.69 % when compared to control beams.
- The F3 beams showed higher ultimate load carrying capacity of 82 kN when compared to F1 and F2 beams.
- The deflection in the F3 beams are higher when compared to F1 &F2 beams. For the corresponding load the deflection was also higher in the F3 beams.This shows that the hybrid combination of natural and artificial fibres leads to higher load carrying capacity with higher deflection.
- The deflection ductility was calculated as 1.688.
- The stiffness at yield and stiffness at ultimate was found to be 8.93 and 5.76.

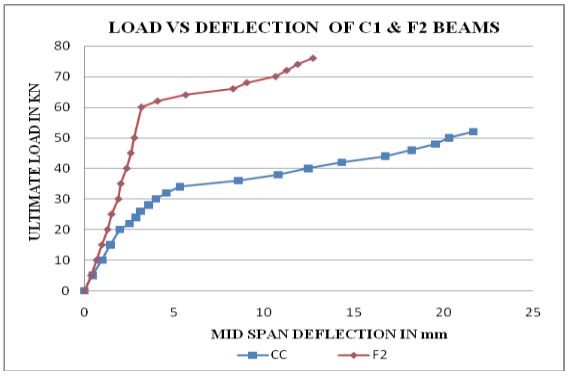


Figure 4.2 Load deflection curve for F2 beams

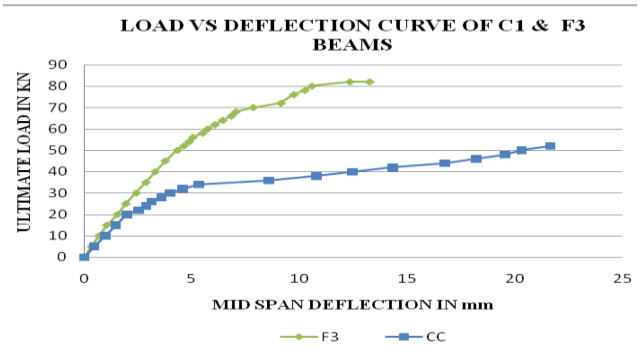


Figure 4.3 Load deflection curve for beams F3

4.3.4 Load deflection curves for beams F1, F2, F3

From the figure 4.4, we can infer that the control beam has higher ultimate deflection of 21.64 mm but the ultimate load is lower. In the strengthened beams, the load carrying capacity is increased when compared with the control beams but the deflection is lower in the strengthened beams than the control beams. The addition of fibres reduces the mid-span deflection, thereby arresting the cracks. Among the three beams, the F2 beams (strengthened with monolithic fibres of polypropylene) showed lower deflection when compared to other beams, however the load carrying capacity may be higher.

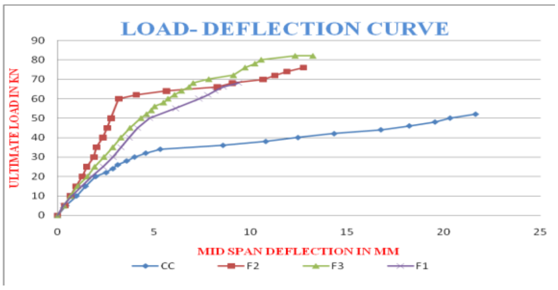


Figure 4.4 Load deflection curve for beams F1,F2,F3

4.3.4.1 Comparison of the results

Table 4.3 shows the results of the beams with that of the control beams. The table infers that the load carrying capacity of the strengthened beam is higher when compared to the control beams. The deflection is minimum when compared to the control beams. This shows that the use of FRP decreases the deflection by arresting the crack formation. The Hybrid strengthened beams (F3) showed higher load carrying capacity with higher deflection when compared to the monolithic strengthened beams (F1 & F2).The artificial fibres strengthened beams shows higher stiffness at yield and ultimate loads.

Table 4.3 Results of F1, F2, F3 beams

Parameters	C1	F1	F2	F3
Initial crack load (kN)	23	32	38	46
Yield load (kN)	34	50	64	70
Yield deflection (mm)	5.32	4.76	5.64	7.84
Ultimate load (kN)	52	68	76	82
Ultimate deflection (mm)	21.64	9.37	12.74	13.24
Deflection ductility	4.08	1.97	2.258	1.688
Stiffness @ yield	6.39	10.50	11.34	8.93
Stiffness @ ultimate	2.40	7.25	5.965	5.76

4.4 Initial crack load

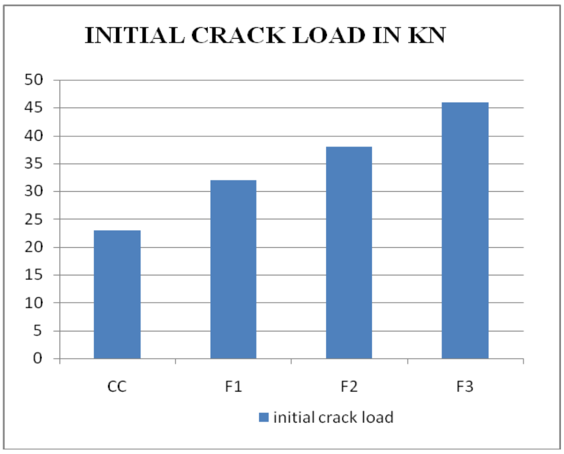


Figure 4.5 Initial crack load of the beams

4.5 Ultimate load carrying capacity

The Ultimate load carrying capacity of the control beams and the strengthen beams were found out and is shown in figure 4.6. The control beams were loaded upto their ultimate loads.It was noted that all the beams, the strengthen beams F1,F2,F3 had the higher load carrying capacity when compared to the control beams C1. An important behaviour of the FRP sheets is the high ductile behaviour of the beams.The use of FRP can delay the initial cracks and further development of the cracks in the beams.

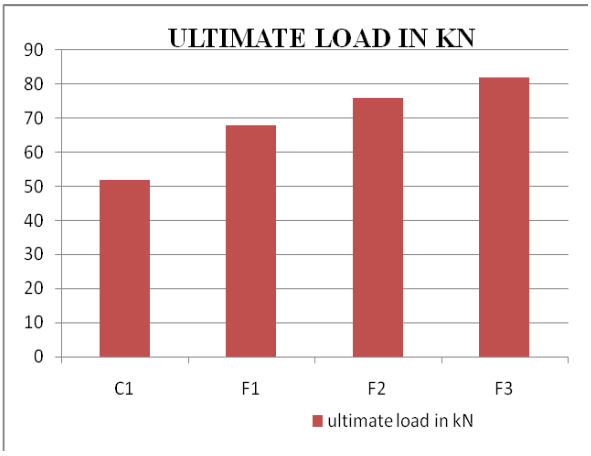


Figure 4.6 Ultimate crack loads of the beams

V FINITE ELEMENT ANALYSIS

5.1 Introduction

In this research, we use the finite element method to model the behaviour of beams strengthened with FRP. For validation, the study was carried out using a series of beams that had been experimentally tested for flexural behaviour. The models are used for analysing beams retrofitted with sisal fibre at the soffit of the beam.

5.2.6 Comparative results for control beam

There is good agreement between FEM and experimental results for the control beam. The results of the model done using abaqus for control beam are nearly equal to the experimental results.

Control beams	Yield load (kN)	Yield deflection (mm)	Ultimate load(kN)	Ultimate deflection (mm)
C1(experimental)	70	7.84	82	13.84
C1(Abaqus)	68	6.89	80	12.56

Table 5.1Comparative results for control beam

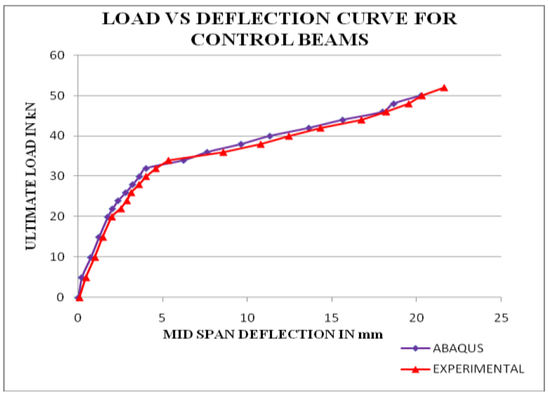


Figure 5.1 Load deflection curves of control beams, obtained by Experiments and Abaqus model

5.2.7 Comparative Results for hybrid FRP strengthened beam

Debonding failure, which occurred in the experiments, is not possible with the perfect bond model. After cracks start appearing, the perfect bond models increasingly overestimate the stiffness of the beam. This is due to the fact that the perfect bond does not take the shear strain between the concrete and CFRP into consideration. This shear strain increases when cracks appear and causes the beam to become less stiff. So we go for cohesive bond model. The cohesive models show good agreement with the experimental results. Table 5.2 shows the comparative results. Figure 5.8 shows the load deflection curve for hybrid FP.

Table 5.2 Comparative results for strengthened beam

Control beams	Yield load (kN)	Yield deflection (mm)	Ultimate load(kN)	Ultimate deflection(mm)
C1(experimental)	34	5.32	52	21.64
C1(Abaqus)	32	4.02	50	20.24

There are several possible causes for the differences between the experimental data and the finite element analysis. One is, as for the control beam, the assumed perfect bond between concrete and steel reinforcement.

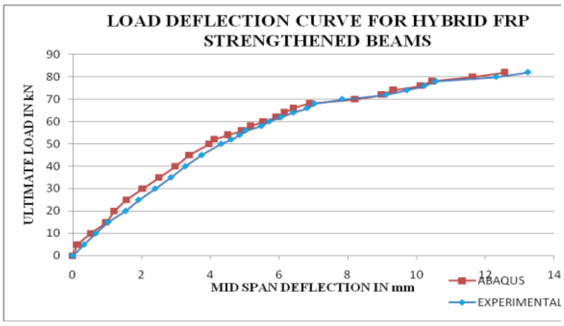


Figure 5.2 Load deflection curves for strengthened beams, obtained by Experimental and Abaqus model

V1 CONCLUSIONS

In this experimental investigation the flexural behaviour of Reinforced concrete beams strengthened using monolithic and hybrid fibres of sisal and polypropylene are studied. Two beams (C1) of control specimens, two beams (F1) retrofitted with monolithic fibres of sisal, two beams (F2) retrofitted with monolithic fibres of polypropylene mat and two beams (F3) retrofitted with hybrid fibres of sisal and polypropylene mat were cast and tested.

- In F1 beams, the ultimate load carrying capacity was increased by 30.76% when compared to control beams. The F1 beams showed lower ultimate load carrying capacity of 68 kN among the strengthened beams.
- The deflection in the F1 beams are higher when compared to F2 beams. For the corresponding load the deflection was higher in the F1 beams.This shows that the natural fibre behaves in ductile manner when compared to artificial fibres.
- In F2 beams, the ultimate load carrying capacity was increased by 46.15 % when compared to control beams. The F2 beams showed the ultimate load carrying capacity of 76 kN.
- The deflection in the F2 beams are lower when compared to F1 &F3. For the corresponding load the deflection was lower in the F2 beams.This shows that the artificial fibre shows brittle nature which leads to failure without warning.
- In F3 beams, the ultimate load carrying capacity was increased by 57.69 % when compared to control beams. The F3 beams showed higher ultimate load carrying capacity of 82 kN among the strengthened beams.
- The deflection in the F3 beams are higher when compared to F1 &F2 beams. For the corresponding load the deflection was also higher in the F3 beams.
- This shows that the hybrid combination of natural and artificial fibres leads to higher load carrying capacity with higher deflection.
- A finite element model was developed to analyse beams retrofitted with FRP. Elastic isotropic behaviours were used to represent the FRP behaviour; also a cohesive model was used to address the interfacial behaviour between CFRP and concrete.
- The finite element results show good agreement with the experimental results.

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