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# Experimental Study on Steel Fibre Reinforced Concrete Beams Strengthened with Fibre Reinforced Polymer Laminates

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***Abstract: This paper presents the results of a non linear finite element analysis conducted on steel fibre reinforced concrete beams strengthened with glass fibre reinforced polymer (GFRP) laminates. Four beams were cast and tested for the present study. One beam was kept as control beam and the other one was provided with steel fibres of 1% volume fraction. The remaining two fibre reinforced concrete beams were restricted with UDCGFRP laminates of 3mm and 5mm thickness. All the beams were tested under four-point bending till failure. ABAQUS finite element software was used for modeling purpose. The results obtained through non liner FEM analysis show good agreement with the experimental test results.***

***Index Terms - ABAQUS, FEM analysis, GFRP, SFRC***

## I. INTRODUCTION

Plain concrete fails suddenly when the tensile strength exceeds its allowable value depending on the grade of concrete. And the other hand fiber reinforced concrete (FRC) continuous to sustain considerable loads. The FRC composite will carry increasing loads after cracking of the matrix, if the pullout resistance of fibers is greater than the load at first cracking. With an increasing load on the composite, the fibers will tend to transfer the additional stress to the matrix through bond stress. If the bond stress does not exceed the bond strength, then there may be additional cracking in the matrix. The process of multiple cracking will continue until either fibers fail or the accumulated local de-bonding leads to fiber pullout.

Spadea et al[1] conducted a study on strength and ductility of RC beams repaired with CFRP laminates. The authors examined the effects of retrofitting on strength, deflection, curvature and energy. The principal variables included longitudinal steel ratio, volume of internal links and configuration of end anchorage. The authors reported that suitably designed and positioned external anchorage enabled more ductile failures of the CFRP strengthened beams.

Hamid Rahimi et al[2] studied the structural behavior of reinforced concrete beams strengthened with adhesively bonded FRP plates experimentally and analytically. The variable included steel ratio as well as the type and amount of external reinforcement. The analysis included 2D non-linear finite element modeling incorporating the concrete damage model for concrete. The authors reported that pre-cracked beams performed well; strength and stiffness of strengthened beams increased substantially; the magnitude of performance was influenced by tensile reinforcement and also by type & amount of external reinforcement; the non-linear finite element modeling can be utilized for predicting the performance of the externally strengthened concrete beams.

Soudki et al[3] addressed the viability of carbon fibre reinforced polymer (CFRP) laminates for the strengthening of corrosion damaged reinforced concrete bridge girders. The beams were strengthened by externally epoxy bonded CFRP laminates to the soffit of beams. The authors reported that all the strengthened beams exhibited increased stiffness over the unstrengthened specimens and marked increases in the yield and ultimate strength.

Amer Ibrahim[4] performed Numerical analysis on RC beams by ANSYS finite element program and results show that the general behavior of the finite element models represented by the load-deflection curves at mid span show good agreement with the test data. They also conclude that the load carrying capacity of the Flexure strengthening beam predicted by the finite element analysis is higher than that of the control beam.

Wang wenwei et al[5] presented experimental and analytical results of RC beams strengthened with CFRP laminates under sustained loading. Six reinforced concrete beams were used for the investigation. The effects of initial load and load history on the ultimate strength of strengthened reinforced concrete beams were examined. An analytical model was also proposed. The analytical results showed good agreement with experimental results.

Saadatmanesh et al[9] presented experimental and analytical studies on damaged concrete beams retrofitted with CFRP sheets with respect to shear and flexure. The beams were pre-cracked and retrofitted with three different CFRP systems. The authors observed different modes of failure and gain in ultimate strength based on the orientation of the fibre.

Gopalratnam et al[6] studied the fracture toughness of fibre reinforced concrete beams. The authors indicated four important factors that can influence the load-deflection response of the beam specimens. The above factors include the specimen size; depth and its span; loading configuration; control of different parameters such as load-point deflection and load; and rate of loading. The authors concluded the method of measuring the specimen deflection used in the work in relation to neutral axis of the beam at its support.

Banthia et.al[10] studied the crack growth resistance of hybrid fibre reinforced cement composites. Two types steel and polypropylene fibres were used in their study. The fibre volume fraction of polypropylene fibre was varied as 0.1% and 0.2% by volume. The authors reported the hybrid combination of steel-polyproplene fibres enhanced the resistance to both nucleation and growth of cracks.

Hsuan-Teh Hu et al[7] performed a numerical analysis using ABAQUS program to predict the ultimate load caring capacity of RC beams strengthened with fiber reinforced plastics applied at the tension face of the beams. The authors investigated the influence of reinforcement ratio, fiber orientation and beam length on the ultimate strength of beams. The authors reported that the use of fiber reinforced plastics significantly increase the stiffness as well as ultimate strength of reinforced concrete beams. They also concluded that the ultimate strength of RC beams strengthened by fiber reinforced plastics at the soffit of beams is higher than those strengthened by fiber reinforced plastics on side faces of the beams. The predictions of the model through ABAQUS were found to agree well with the experimental results.

Lua et al[8] proposed a finite element model for FRP sheet/plates bonded concrete members. In the model concrete in compression was treated as an elastic-plastic material and the behavior of cracked concrete was represented using smeared crack approach. The authors concluded that the results obtained through finite element model showed good agreement with the test results. The predicted variables are ultimate load, effective bond length and strain distribution in the FRP plate at different load levels.

## II. MATERIAL AND METHODS

### A. *Beam details*

150 x 250 x 3000mm beam were cast and subjected to four-point bending test as shown in Fig 2. The Table 1 shows the specimen details used in the present study. The properties of fibres used in the experimental work are shown in Table 2. The concrete mix proportion adopted is shown in Table 3.

Steel fibre reinforced concrete beams were strengthened with uni-directional cloth (UDC) type GFRP laminates with 3mm & 5mm thickness. After the completion of beam soffit preparation two-part epoxy adhesive was used to bond the GFRP laminates. The different stages involved in application of FRP at the soffit of beam were shown in Fig 1.

Surface Grinding Resin Under Mixing Resin Application FRP Sheet -Placement

Fig 1. Application of FRP

Table 1 Specimen Details

| Si. No | Beam Designation | Fibre Volume fraction ($V_f$) | % of steel reinforcement | Steel fibre with (1 % of $V_f$) | GFRP Laminates | |
|---|---|---|---|---|---|---|
| | | | | | Type | Tk |
| 1 | CB | - | 0.669 | - | - | - |
| 2 | SF | 1% | 0.669 | 100 | - | - |
| 3 | SFU3 | 1% | 0.669 | 100 | UDC | 3mm |
| 4 | SFU5 | 1% | 0.669 | 100 | UDC | 5mm |

Table 2: Properties of Fibres

| Si. No | Fibre properties | Fibre Details |
|---|---|---|
| | | Steel |
| 1 | Length (mm) | 60 |
| 2 | Size/Diameter (mm) | 0.75 mm dia |
| 3 | Aspect Ratio | 80 |
| 4 | Density (kg $m^{-3}$) | 7850 |
| 5 | Specific Gravity | - |
| 6 | Young’s Modulus (GPa) | 210 |
| 7 | Tensile strength (MPa) | 1225 |
| 8 | Shape | Hooked at ends |

Table 3: Concrete Mix

| Ingredient | Quantity |
|---|---|
| 53 grade OPC | 450 kg/$m^3$ |
| Fine aggregate | 780 kg/$m^3$ |
| Course aggregate 20mm | 680 kg/$m^3$ |

| | |
|---|---|
| 12mm | 450 kg/m$^3$ |
| Water | 160 lit/m$^3$ |
| Silica flume | 25 kg/m$^3$ |
| Hyper plasticizer | 0.80 % |

### *B. Test Set-up*

All the beams were tested under four-point bending in a loading frame of 500kN capacity. The deflection at mid span and at load points were measured using dial gauges of 0.01mm accuracy. Crack width was measured using a crack detection microscope. The loading arrangement & instrumentation adopted is shown in Fig 3. Table 4 summarises the test results at yield and ultimate stage of unstrengthened and strengthened HFRC beams.

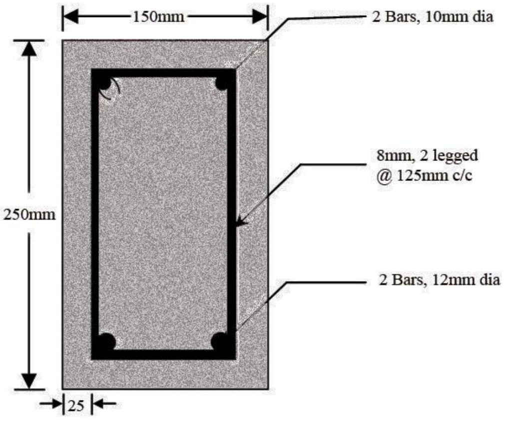


**Fig 2. Beam Details**

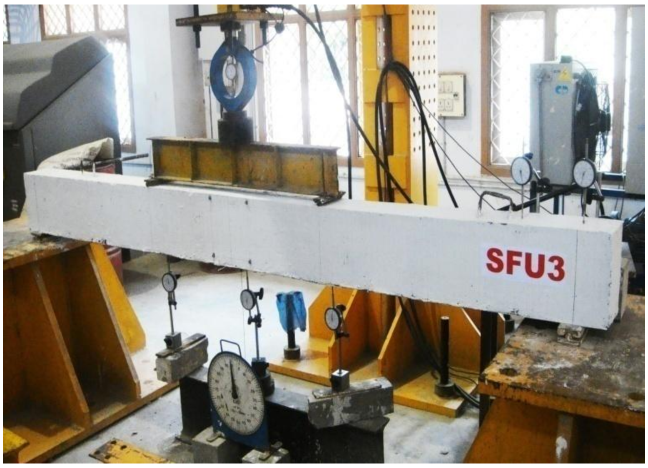


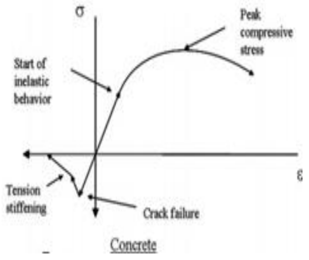
**Fig 3. Experimental Test Set-up**

## III. ANALYTICAL MODELING

### *A. Material Properties and Constitutive Models*

#### *Concrete*

A plastic damage model was used to model the concrete. This model assumes that the main two failure modes are tensile cracking and compressive crushing. Under uni-axial tension, the stress–strain response follows a linear elastic relationship until the value of the failure stress is reached. The failure stress corresponds to the onset of micro-cracking in the concrete material. Beyond the failure stress, the formation of micro-cracks is represented with a softening stress-strain response. Hence, the elastic parameters required to establish the first part of the relation are elastic modulus $E_c$, and tensile strength $f_{ct}$, (Fig 4). The compressive strength of concrete used for the investigation was 66.10 Mpa.



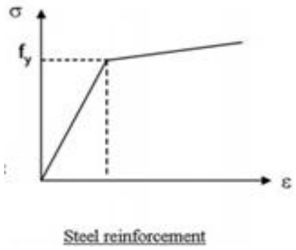


**Fig 4. Material Constitutive Models of Concrete, Steel Reinforcement, FRP, and Epoxy**

### *Steel Reinforcement*

The steel was assumed to be an elastic–perfectly plastic material and identical in tension and compression as shown in Fig 4.

### *FRP Composite*

The GFRP was modeled as an isotropic linear elastic material throughout this study. The unidirectional GFRP composite actually shows an orthotropic behaviour, but it was shown in Fig 4 that only the axial modulus is of importance in an application of this type. The elastic modulus and strength were considered.

### *Interface Layer*

Cohesive elements were used together with a traction separation law which defines the traction function of the separation distance between interface elements as shown in Fig 4. The material has an initial linear elastic behaviour. The elastic response is followed by damage initiation and evolution until total degradation of the elements.

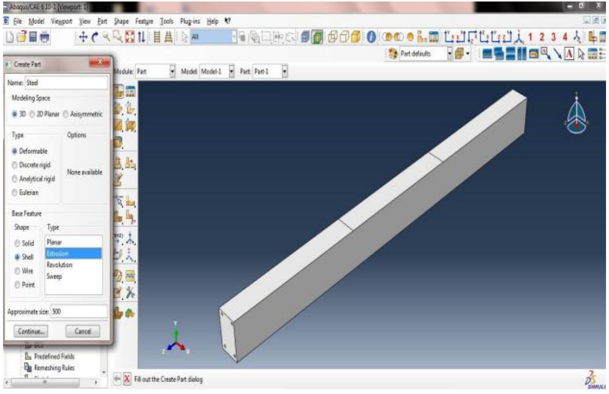
## *B. Element Types*

### *Solid Element*

ABAQUS contains a library of solid elements for two-dimensional and three-dimensional applications. The two-dimensional elements allow modeling of plane and axis symmetric problems and include extensions to generalized plane strain (when the model exists between two planes that may move with respect to each other, providing thickness direction strain that may vary with position in the plane of the model but is constant with respect to thickness position). The material description of three-dimensional solid elements may include several layers of different materials, in different orientations, for the analysis of laminated composite solids. A set of nonlinear elements for asymmetric loading of axis symmetric models is also available, and linear infinite elements in two and three dimensions can also be used to model unbounded domains. The solid element library includes iso-parametric elements; quadrilaterals in two dimensions and "CONCRETE" (hexahedra) in three dimensions. These iso-parametric elements are generally preferred for most cases because they are usually the more cost-effective of the elements that are provided in ABAQUS. They are offered with first- and second-order interpolation and are described in detail in "Solid iso-parametric quadrilaterals and hexahedra". For practical reasons it is sometimes not possible to use iso-parametric elements throughout a model; for example, some commercial mesh generators use automatic meshing techniques that rely on triangulation to fill arbitrarily shaped regions. Because of these needs, ABAQUS includes triangular, tetrahedron, and wedge elements. For most cases it is recommended that these elements be only used to fill in awkward parts of the mesh and, in particular, that well-shaped isoparametric elements be used in any critical region (such as an area where the strain must be predicted accurately). The concrete model using solid element is shown in Fig 5.

### *Rebar Element*

The definition of rebar in shell, membrane, or surface elements is based on three geometric properties, the cross-sectional area of each individual rebar, the spacing between the rebar and the orientation of the rebar with respect to the local coordinate system of the element. For shell elements, the rebar definition also requires the distance from the mid-surface to the rebar (Fig 6). In ABAQUS an equivalent "smeared" orthotropic layer is created based on these geometric properties and the elastic modulus of the rebar material. The equivalent rebar layer lies parallel to the mid-surface of the element.



Create Part

Name: Steel

Modeling Space: ● 3D ○ 2D Planar ○ Axisymmetric

Type: ● Deformable ○ Discrete rigid ○ Analytical rigid ○ Eulerian

Options: None available

Base Feature

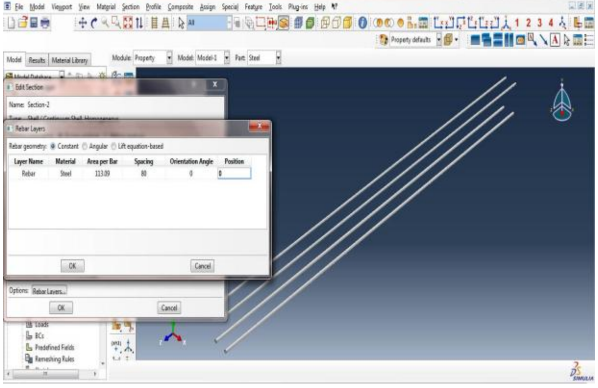
Shape: ○ Solid ● Shell ○ Wire ○ Point

Type: Planar, Extrusion, Revolution, Sweep

Approximate size: 500

Fill out the Create Part dialog

Fig 5. Concrete Solid Element



Edit Section

Name: Section-2

Rebar Layers

Rebar geometry: ● Constant ○ Angular ○ Lift equation-based

| Layer Name | Material | Area per Bar | Spacing | Orientation Angle | Position |
|---|---|---|---|---|---|
| Rebar | Steel | 113.09 | 80 | 0 | 0 |

Options: Rebar Layers...

Fig 6. Rebar Shell Element

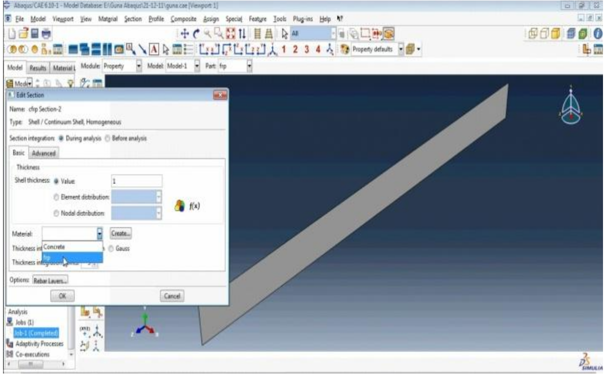
### *Fiber Reinforced Polymer (FRP)*

As the FRP material has been assumed to behave as a linearly elastic and orthotropic material, a "lamina" option for the elastic behaviour of the material was chosen. For this type of material, ABAQUS requires the longitudinal, transverse and shear modulus of elasticity. The manufacturer provided the longitudinal and transverse modulus of elasticity, but not the shear modulus. As the "lamina" option requires all this data, the data finally assumed was based on the average properties of carbon fibres.

For the near surface mounted system, the strips were modeled in the same way as the reinforcing steel was. Meanwhile the reinforcing steel was modeled with surface elements and the FRP strips were modeled using membrane elements. Membrane elements represent thin surfaces in space that offer strength in the plane of the surface, but have no bending stiffness.

An ABAQUS tool called "Skin Reinforcement" was used to model the FRP strips externally bonded to the beams (Fig 7). This tool defines a skin that is perfectly bonded to the surface of an existing part and specifies its engineering properties. Each skin is defined by a surface, a section name and material orientation.

Each skin is defined by a surface and a section. The properties of the FRP strips are defined in the section. As long as only one skin can be placed on a surface of an element (skins cannot overlap), to model the cases for 2 layers of strips, the same section used for 1 layer cases was applied, but doubling the value for the thickness of the section.



Edit Section

Name: cfrp Section-2

Type: Shell / Continuum Shell, Homogeneous

Section integration: ● During analysis ○ Before analysis

Basic | Advanced

Thickness

Shell thickness: ● Value: 1

○ Element distribution:

○ Nodal distribution:

Material: Concrete, frp

Thickness in… ○ Gauss

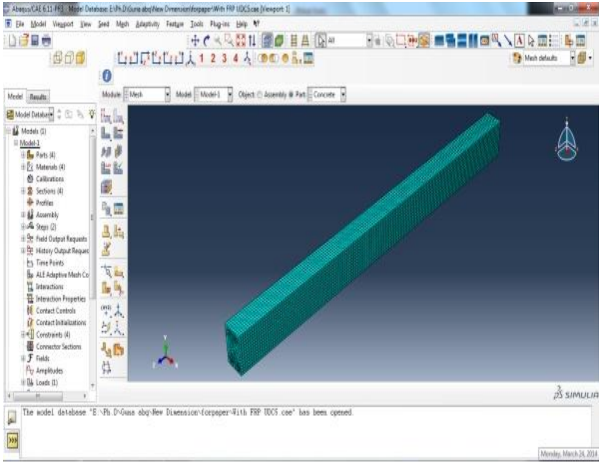
Thickness in…

Options: Rebar Layers...

Fig 7. FRP shell Element

### C. *Modeling Procedure of Beam*

The modeling and loading conditions are shown in Fig 8.



Abaqus/CAE 6.11-PR3 - Model Database: E:\Ph.D\Guna abq\New Dimension\forpaper\With FRP UDCS.cae [Viewport: 1]

Module: Mesh  Model: Model-1  Object: ○ Assembly ● Part: Concrete

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The model database "E:\Ph.D\Guna abq\New Dimension\forpaper\With FRP UDCS.cae" has been opened.
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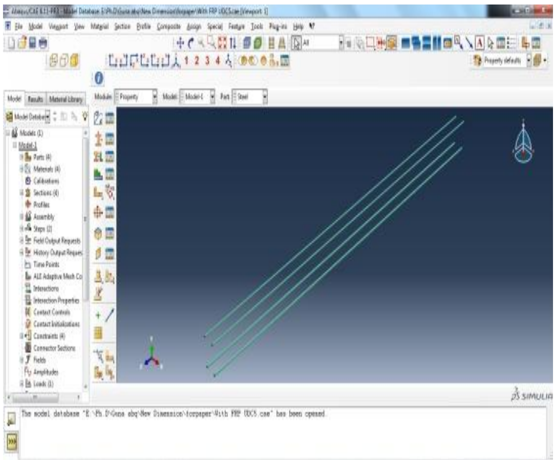
Monday, March 24, 2014

Fig 8(a). Concrete Beam Modeling



Abaqus/CAE 6.11-PR3 - Model Database: E:\Ph.D\Guna abq\New Dimension\forpaper\With FRP UDCS.cae [Viewport: 1]

Module: Property  Model: Model-1  Part: Steel

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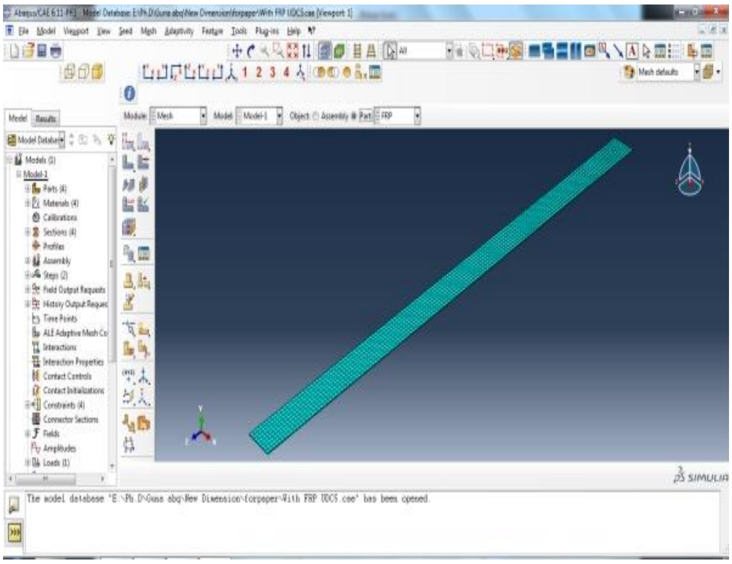
Fig 8(b). Reinforcement in Beam



Abaqus/CAE 6.11-PR3 - Model Database: E:\Ph.D\Guna abq\New Dimension\forpaper\With FRP UDCS.cae [Viewport: 1]

Module: Mesh  Model: Model-1  Object: ○ Assembly ● Part: FRP

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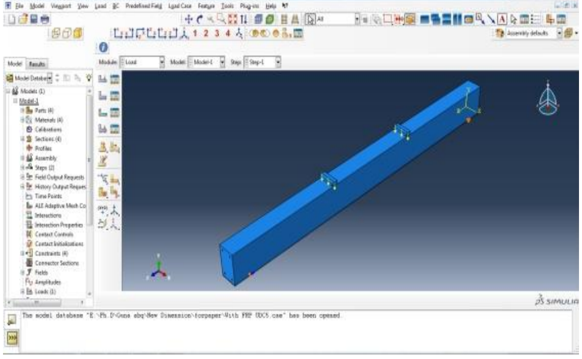
Fig 8(c). FRP wrap in Beam



The model database "E:\Ph.D\Guna abq\New Dimension\forpaper\With FRP UDC5.cae" has been opened.

**Fig 8(d). Loading and Support condition**
**Fig 8. Modeling and loading procedure**

**Table 4. Test Results**

| S.No | Beam Designation | Yield Load in kN | Deflection at yield Load in mm | | Ultimate Load in kN | Deflection at Ultimate Load in mm | | Deflection Ductility | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Exp | Abq | | Exp | Abq | Exp | Abq |
| 1 | CB | 65.00 | 6.17 | 5.76 | 85.00 | 12.00 | 10.76 | 1.94 | 1.86 |
| 2 | SF | 95.00 | 5.98 | 8.42 | 165.00 | 15.00 | 14.66 | 2.50 | 1.74 |
| 3 | SFU3 | 110.00 | 7.50 | 9.74 | 235.00 | 26.00 | 20.87 | 3.22 | 2.14 |
| 4 | SFU5 | 140.00 | 8.85 | 12.3 | 315.00 | 30.00 | 27.85 | 3.38 | 2.25 |

## IV. LOAD-DEFLECTION RESPONSE

The load-deflection response for tested beams is presented in Fig 9.

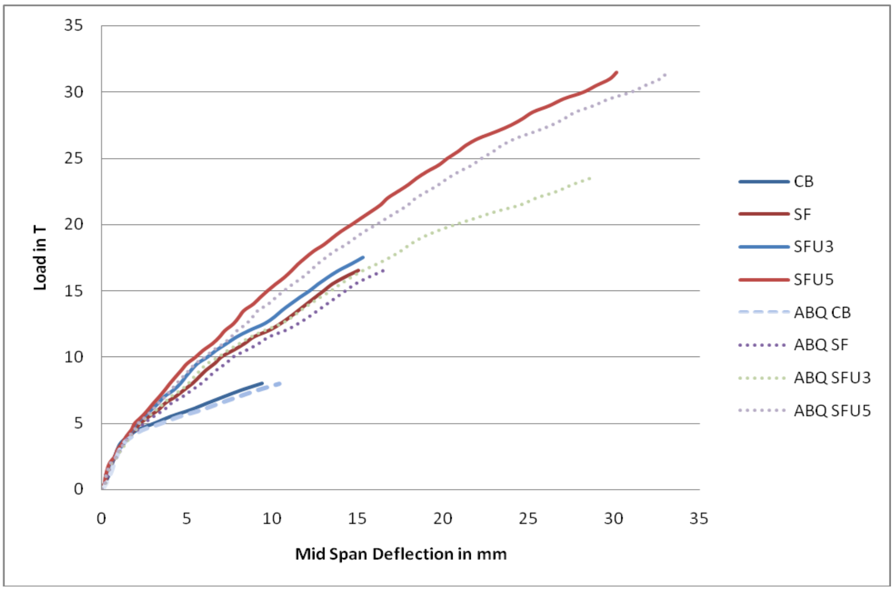


**Fig 9. Load – Deflection Response of Beams**

### A. *Ductility of beams*

Ductility indices for the tested beams are shown in Figs. 10 to 12. The ductility values were calculated based on deflection. The deflection ductility for the strengthened beam showed a maximum increase of about 26.03 %.

### B. *Results and Discussion*

The load-deflection curves obtained through experimental and analytical results for all beams are shown in Fig 8. GFRP strengthened SFRC beams exhibit increase in flexural strength upto 29.78% with 3mm UDCGFRP and 47.61% with 5mm UDCGFRP. GFRP strengthened beams exhibit a decrease of deflection upto 56.66% with 3mm UDCGFRP and 62.50% with 5mm UDCGFRP.

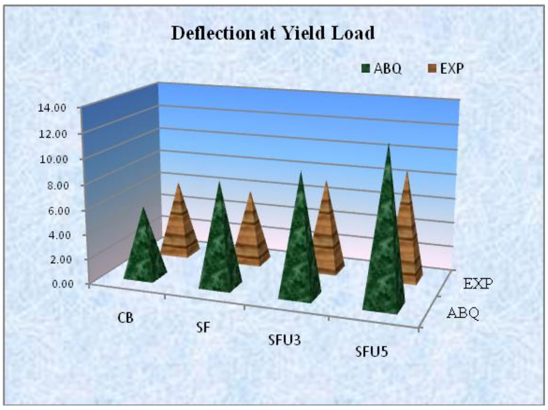


**Fig 10. Deflection at Yield Load**

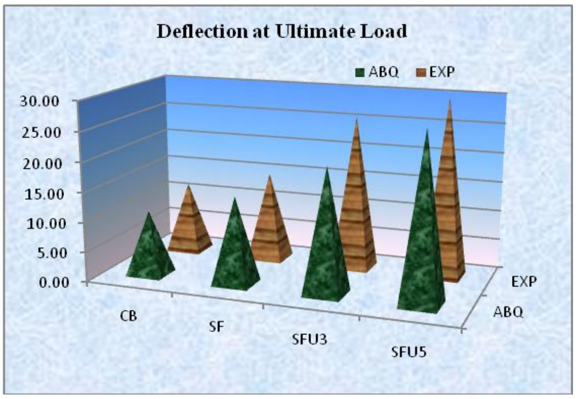


**Fig 11.Deflection at Ultimate Load**

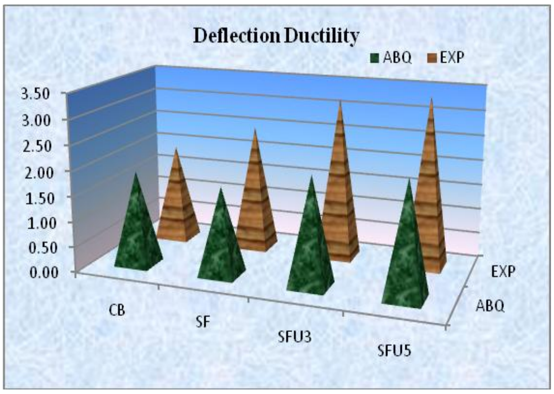


**Fig 12. Deflection Ductility**

All the beams strengthened with GFRP laminates experienced flexural failure. None of the beams exhibit premature failure of laminate. The beams strengthened with GFRP laminates provide adequate ductility to ensure ductile mode of failure. The ultimate load carrying capacity obtained through ABAQUS modeling showed a percentage error which varied from 2.26% to 19.73%.

## V. CONCLUSIONS

Based on the experimental and analytical results the following conclusions are drawn

1. GFRP strengthened SFRC beams resulted in higher load carrying capacity. The percentage increase in the ultimate load was 47.61% for beams strengthened with 5mm UDCGFRP laminates.
2. The percentage decrease in deflection at ultimate stage was 62.50% for SFRC beams strengthened with 5mm UDCGFRP laminates.
3. The SFRC beams strengthened with FRP laminates show enhanced ductility. The increase in ductility was 26.03%.
4. All the strengthened beams failed in flexural mode only.
5. The results obtained through the finite element analysis (ABAQUS) show good agreement with the experimental results.

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