Flexural behavior of RCC beams with externally bonded FRP

Arun Vignesh S  A Sumathi  and  K Saravana Raja Mohan
School of Civil Engineering, SASTRA University, Thanjavur –613 401, India

*Email: sumathi@civil.sastra.edu

Abstract: The increasing use of carbon and glass fibre reinforced polymer (FRP) sheets for strengthening existing reinforced concrete beams has generated considerable interest in understanding the behavior of the FRP sheets when subjected to bending. The study on flexure includes various parameters like percentage of increase in strength of the member due to the externally bonded Fiber reinforced polymer, examining the crack patterns, reasons of debonding of the fibre from the structure, scaling, convenience of using the fibres, cost effectiveness etc. The present work aims to study experimentally about the reasons behind the failure due to flexure of an EB-FRP concrete beam by studying the various parameters. Deflection control may become as important as flexural strength for the design of FRP-reinforced concrete structures. A numerical model is created using FEM software and the results are compared with that of the experiment.

Key words: FRP laminates Flexural study, External bonding, Numerical Analysis, Load carrying capacity

1. Introduction

Fibre reinforced composites have been widely used to strengthen reinforced concrete (RC) members. Mostly because they have a high strength-to-weight ratio, require relatively limited time to cure, and have mechanical properties that can be engineered to meet the desired structural performance. Fibre-reinforced polymer (FRP) composites are made up of continuous fibres and a thermosetting organic resin, are currently the most common type of composite system used for structural strengthening applications. Fibre reinforced cementitious matrix (FRCM) composite was another type of composite that was recently developed which contains continuous fibres with a cementitious (inorganic) matrix. The substantial increase in energy absorption capacity is the most significant improvement imparted by adding fibres to a concrete.

The present work aims to study experimentally about the reasons behind the failure due to flexure of an EB-FRP concrete beam by studying the various parameters stated above. Deflection control may become as important as flexural strength for the design of FRP-reinforced concrete structures.

The strengthening effect of EB-FRP using composite element involving glass fibre was studied [1]. Use of glass fibre laminates in composite sections in external bonding is well established. Flexural response was better recorded using the epoxy adhesive. Use of carbon – glass hybrid was studied the stiffness contribution of the composite in bridge decks in rehabilitation [2]. The uniaxial tests under compression was performed based on deflection control condition, stress-strain behaviour for fiber concrete was studied [3]. The numerical model developed was referred the research done on the bending tests on FRP in slabs [4] Parameters varied here were thickness and the effect of changing the thickness is studied under the four point loading test [5]. An increase in the width of the FRP will produce an increase in the load-carrying capacity. Interfacial crack propagation and strain distribution during shear debonding is influenced by the width of the FRP laminate in comparison to that of the beam [6]. Variation of mechanical properties in terms of composite carbon, composite glass sheets and their hybrid combinations is by their hybrid combinations. Different failure modes that can occur is...
also studied [7]. Studies show that Strength increases provided by SRP bonded with cementitious grout were smaller than those obtained using epoxy. [8]. Although use of cementitious matrix is in practice the transfer of stresses was found to be more efficient by use of epoxy strengthening adhesive [9]  

2. Materials and methods  

2.1 Materials  

Ordinary Portland Cement (OPC) of grade 53 confirming to IS 12269 was utilized in the study. The specific gravity of the OPC sample was found to be 3.12 with an initial setting time of 40 minutes and a standard consistence of 28 % with its chemical composition is given in Table 1. FRP plates are non-capillary and non-hygroscopic. Therefore, they provide good moisture resistance. CFRP has a very high temperature resistance and is virtually inert.  

| Property      | CFRP   | GFRP   |
|---------------|--------|--------|
| Yield stress ($\sigma_y$) | 200MPa | 125MPa |
| Elastic modulus | 1.5GPa | 26GPa |
| Poisson's Ratio | 0.28   | 0.28   |
| Density       | 1.5 g/cm$^3$ | 1.8g/cm$^3$ |

Table 2. Properties of aggregates.  

| Properties            | Fine aggregate | Coarse aggregate |
|-----------------------|----------------|-----------------|
| Specific gravity      | 2.58           | 2.72            |
| Fineness modulus      | 2.56           | 6.97            |
| Bulk density, kg/m$^3$| 1697           | 1488            |
| Water absorption, %   | 1.37           | 0.77            |

Aggregate passed through 16 mm sieve and retained on 12.5 mm sieve, were used as in the concrete mixture. The specific gravity of the coarse aggregate was 2.7. Wire basket method based on ASTM C 127 was used to determine the specific gravity. The steel bars of 12 and 8 mm high yield strength deformed bars were used as reinforcement in the cube specimens.  

2.2 Methodology  

High strength concrete of the grade M50 was designed in order to obtain a characteristic compressive strength of 50 MPa. The design mix ratio arrived was 1:0.8:2.13(Cement: FA: CA). The addition of high range water reducer reduced the w/c ratio to 0.32 and the workability was based on slump cone test according to ASTM C14. Beam specimens were cast and water cured for 28 days to study the flexural behavior.
Table 3. Properties of FRP laminates.

| Property               | Unit   | CFRP | GFRP |
|------------------------|--------|------|------|
| Density                | g/cm³  | 1.5  | 1.8  |
| Width                  | mm     | 100  | 100  |
| Thickness              | mm     | 2.1  | 2.1  |
| Length                 | mm     | 1000 | 1000 |
| Ultimate Tensile Strength | MPa   | 550  | 530  |
| Poisson’s ratio        | -      | 0.28 | 0.28 |

The most widely applied basic FRP strengthening technique, involves the manual application of hand lay-up or prefabricated systems by means of cold cured adhesive bonding. The specimens were categorized as follows:

- **CC**
  - Normal RCC beam as control specimen
- **GFRP**
  - Beam reinforced with GFRP plate of 2mm thickness
- **CFRP**
  - Beam reinforced with CFRP plate of 2mm thickness
- **C-G1**
  - Beam reinforced with CFRP and GFRP plate
- **C-G2**
  - Beam reinforced with CFRP and GFRP plate

Figure 1. Reinforcement design
3. Results and discussion

3.1 Flexural Behaviour Test

The specimens cast were in the dimensions of 100 mm x 150 mm x 1200 mm beam prototypes. Curing was done for a total of 28 days. The test was carried out using 1000kN capacity flexural strength testing machine. The test setup includes two point loading using a single point loading system by which the loads are transferred equally to the two points using a spreader beam and two rollers. Deflections were measured in the beam by placing strain gauges at the bottom of the beam. Strains occurring at the points were also measured under using a LVDT strain gauge that was placed at particular intervals. The gauge length between the force points is 333.33 mm in the top and 100 mm from either corner of the beam at the supports. All the specimens were capped for uniform loading prior testing. The control of load over the test was 10 kN/min. All the data like displacement load and strain were recorded using Automatic data acquisition system which in turn connected to the computer.
3.2 First crack load
The first crack load and moments for beams cast with different EB-FRP beams as well as for the control beam are given in Table 4.

Table 4. Load values of the beams.

|                | First Crack Load (kN) | Ultimate load (kN) |
|----------------|------------------------|--------------------|
| Control        | 29.75                  | 65                 |
| GFRP           | 34.2                   | 70.12              |
| CFRP           | 33.75                  | 68.02              |
| C-G1           | 45.7                   | 74                 |
| C-G2           | 30.6                   | 64.1               |
Figure 4. First crack and Ultimate load for beams

The load deflection curves for beams are shown in figure 5. It could be noted that with each application of load, the deflection value changes or in this case increases from the control beam. This implies that the addition of FRP makes the concrete beam more ductile. However, it could also be noted that the deflection for the CC and C-G2 beams are the same.

Figure 5. Load – deflection plot for the beams
3.3 Energy absorption capacity

The energy absorption capacity of all the beams was calculated from the area under the load-deflection curve. The values are presented in the Figure below:
It can be observed that the energy absorption capacity increases significantly from the control beam. However, the value for the beam with CFRP content registers the highest value. The beam C-G2 registered a low value of energy absorption, this was due to the debonding occurred between the concrete and FRP. Also due to the brittle nature of the lesser thickness of carbon in the hybrid FRP laminate.

3.4 Load carrying capacity

The theoretical value for load carrying capacity has been arrived at by ACI method. From calculating the depth of the neutral axis, it could be identified that the section was under reinforced. Hence, the theoretical value was arrived at and presented in the Table below:

| Mix Label | Theoretical load in kN | Experimental load in kN |
|-----------|------------------------|------------------------|
| Control   | 42.34                  | 65.0                   |
| GFRP      | 42.34                  | 70.12                  |
| CFRP      | 42.34                  | 68.02                  |
| C-G1      | 42.34                  | 74.3                   |
| C-G2      | 42.34                  | 64.1                   |

It could be inferred from the above figure that the addition of FRP laminates increases the load carrying capacity of the beam. The addition of CFRP laminates was observed a lesser load value because CFRP was more brittle compared to GFRP. Similarly C-G 2 beam failed due to debonding of the FRP element.
4. Numerical analysis:

4.1 Proposed method of analysis:

For the current research, a beam of length 1200mm, width 100mm and depth 150mm is considered. The top longitudinal reinforcement consists of two hangar bars of 8mm diameter and the bottom longitudinal reinforcement consists of two bars of 12mm diameter with spacing 150 mm. The stirrups were made up of 6mm bars at the spacing of 150mm c/c.

In ANSYS 15, the beams are created as elements. The elements involved in creating the model are Solid 65, Link 180 and Solid 185. The concrete beam was modeled as the as three dimensional element, Solid 65. Solid 185 was used for creating the model for the CFRP and GFRP. Link 180 is a linear line element to be used as the element for the steel reinforcements. In this element, shear deformation effects are included. The elements are given in Table

4.2 Properties of the Elements:

Table 6. Elements and their details.

| Material     | Element     | No of nodes |
|--------------|-------------|-------------|
| Concrete     | SOLID 65    | 8           |
| Steel        | LINK 180    | 2           |
| CFRP,GFRP    | SOLID 185   | 8           |

The material properties of concrete given as input for it ANSYS model are given in Table 7.

Table 7. Property inputs for concrete.

| Property                              | Value          |
|---------------------------------------|----------------|
| Young’s modulus(kN/m²)                | 2.23*10⁴       |
| Poisson’s ratio                       | 0.15           |
| Open shear transfer co-efficient      | 0.23           |
| Closed shear transfer co-efficient    | 0.9            |
| Uniaxial cracking stress              | 2.5            |
| Uniaxial crushing stress              | -1             |

The material properties of steel given as input for it ANSYS model are given in Table 8.
Table 8. Property input for steel bars.

| Property                        | Value  |
|---------------------------------|--------|
| Young’s modulus of steel (kN/m²) | $2 \times 10^5$ |
| Poisson’s ratio                  | 0.3    |
| Yield stress (MPa)               | 415    |

The material properties of CFRP & GFRP given as input for it ANSYS model are given in Table 9.

Table 9. Property input for GFRP AND CFRP.

| PROPERTY                | GFRP   | CFRP   |
|-------------------------|--------|--------|
| Elastic modulus(kN/m²)  | $E_X$  | $2.1 \times 10^5$ | $2.3 \times 10^5$ |
| Poisson’s ratio         | PRXY   | 0.28   | 0.28   |
| Shear modulus kN/m²     | $G_{XY}$ | 1520  | 11790  |

The support, boundary conditions and loading points are shown in the image below.
Figure 9. Boundary conditions of the beam.

Figure 10. Strain profile along the length of the beam.
Figure 11. Stress profile along the length of the beam.

Table 10. Deflection at ultimate load obtained from the analysis.

| Beam  | Deflection (mm) |
|-------|-----------------|
| CC    | 9.44            |
| GFRP  | 10.5            |
| CFRP  | 10.76           |
| C-G1  | 10.012          |
| C-G2  | 7.55            |

Figure 12. Load deflection curves for the beams obtained from the numerical analysis.
5. Conclusion

External bonding of FRP laminates affects the resistance in terms of durability characteristics. From the results the beam that was fitted with C-G1 beam and GFRP beam has higher load deflection behavior in the experimental analysis and in the numerical analysis. Two different failure modes were observed depending upon the type of FRP laminate used. Rupture and debonding of plates were observed. The ultimate load of the specimen with FRP laminates has also increased in the case of all the beams when compared to the control beam. However, comparing the trends observed in first crack load, the ultimate load, the resilience and the energy absorption capacity, the corresponding values increased till the C-G1 and were very close to the values of the control beam in case of C-G2 specimen. CFRP being more brittle compared to the GFRP tends to rupture first in case of the composite laminates. Hence laminate composite of CFRP- 1mm and GFRP – 2mm is considered to have a optimum load carrying capacity and energy absorption capacity.

Acknowledgements

The authors extend their sincere thanks to Vice Chancellor of SASTRA University for providing us laboratory facilities in school of civil engineering to successfully complete this work.

References

[1] Tamim A A Abed F H Rahmani A A Effects of harsh environmental exposures on the bond capacity between concrete and GFRP reinforcing bars, 2014 Adv. Concr. Constr., 2(1), 1-11.

[2] Chakrabortty Khennane A Failure mechanisms of hybrid FRP-concrete beams with external filament-wound wrapping 2014, Adv. Concr. Constr, 2(1), 57-75

[3] Hong, K. N Cho C G Lee S H Park Y Flexural Behavior of RC Members UsingExternally Bonded Aluminum-Glass Fiber Composite Beams. 2014, Polymers, 6, 667-685.
[4] Balsamo A Nardone F Iovinella I Ceroni F Pecce M Flexural strengthening of concrete beams with EB-FRP, SRP and SRCM: Experimental investigation 2013 *Compos.Part B*, **46**, 91–101.

[5] Barros J A O Figueiras J A Flexure Behavior Of SFRC: Testing And Modelling 1999, *J. Mater. Civ. Eng*, **11**(4), 331-339

[6] Sneed L H Verre S, Carloni C Ombres L Flexural behavior of RC beams strengthened with steel-FRCM composite 2016, *Eng. Struct*. **127**, 686–699.

[7] Subramaniam K V Carloni C Nobile L Width effect in the interface fracture during shear bonding of FRP sheets from concrete, 2007, *Eng. Fract. Mech*. **74**, 578–594.

[8] Hawileh R A Obeidah A A Abdalla J A, Tamimi A A Temperature effect on the mechanical properties of carbon, glass and carbon–glass FRP laminates, 2015 *Const. Build. Mater.* **75**, 342–348.

[9] Prota A Tan K Y Nanni Pecce M Manfredi G Performance of Shallow Reinforced Concrete Beams with Externally Bonded Steel-Reinforced Polymer, 2016, *ACI Struct. J*. **103**, 163 – 170.