Flexural behaviour of high strength basalt FRP rebar concrete

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Abstract. In this paper, the flexural behaviour of under-reinforced M70 grade basalt FRP rebar concrete beams in terms of first crack load, pre-cracking and post-cracking behavior, deflection pattern, crack development pattern and ultimate load carrying capacity is evaluated. Loads at first crack in basalt FRP rebars beams are higher than the normal steel rebar concrete beams confirming that basalt FRP rebars beams offer greater resistance to cracking. The ultimate flexural strength of basalt FRP rebar concrete beams have improved when compared to normal steel rebar concrete beams. First crack formation was delayed in basalt FRP rebar concrete beams due to which fatigue strength is increased which in turn increases the time taken for first crack occurrence and thereby increasing the load carrying capacity. The deflection at the mid span decreased in basalt FRP rebar concrete beams which indicates the improved flexural stiffness of the elements thereby reducing the structural member’s deformability, increasing strength and hence controlling deflection. Mid-span deflections at peak load reduced in basalt FRP rebar concrete beams. The ultimate deflection in case of basalt FRP rebar concrete beams is less than that of normal steel rebar concrete beams.

Keywords: Basalt fibres, BFRP rebars, flexural behaviour, load carrying capacity, reinforced beams

1. Introduction

Ductility is the deformation capacity of a member or structure after the first yield. It gives a measure of energy dissipation capacity of a member or structure. Work done on a structure after yield cannot be stored in the material so it is converted into heat energy and is dissipated to the environment. Energy dissipation is desirable for structures because the heavy energy imparted by the ground motions, etc., are to be released.

Up to application of load at first crack the curve is linear and on further application of load multiple cracks are caused and the deviation in curve is observed. For under reinforced beams with the increase in load the multiple cracks increased. After the multiple cracking stages, it is found that there is yield in steel so the P-δ curve become more or less flat till the ultimate load is reached. On further increase in load a drop in the load is observed with propagation of cracks. All the beams failed by compression of concrete and the load deformation curves are plotted up to failure stage.
In beams, curvature increases gradually with increase in moment up to the multiple cracking stages and beyond, the curvature increased drastically at constant moment or with small variation in the moment. The M-Φ curve becomes more or less flat till the ultimate moment is reached. Finally all the beams failed by compression of concrete and the moment curvature plots are drawn up to failure stage.

2. Objectives
To evaluate the flexural behaviour of under-reinforced M70 grade basalt FRP rebar concrete beams in terms of first crack load, pre-cracking and post-cracking behavior, deflection pattern, crack development pattern and ultimate load carrying capacity

3. Experimental Investigations
A M70 grade basalt FRP rebar concrete, under-reinforced beams of size 100 x 150 x 1200 mm were cast and tested under two point loading as per IS: 9399 – 1979 and their behaviour in flexure was investigated to understand the effect of Basalt FRP rebar on its deflection characteristics and cracking behavior. The beams are tested under symmetrical two-point flexural loading. From the above investigations, the parameters observed are first crack load, pre-cracking and post-cracking behavior, deflection pattern, crack development pattern and ultimate load carrying capacity of basalt FRP rebar agent incorporated beams. The beam sizes and length were chosen to ensure that the beams would fail in flexure. The beam dimensions were also sufficiently large to simulate a real structural element. The beam details are shown in Table 1 and 2 and Figure 1 shows reinforcement arrangement. The beam specimen is simply supported over an effective span of 1000 mm. The clear cover of the beam was 20 mm.

| Table 1. | Rebar details of M70 grades beams |
|----------------|-----------------|-----------------|----------------|
| Grade of the concrete beam | Steel on compression side | Steel on tension side | Shear reinforcement |
| M70 | 2-10 mm Dia. | 2-16 mm Dia. | 8 mm Dia. @90 mm c/c |

![Figure 1. Geometry of beam specimens (All measurements are in meters)](image)

| Table 2. | Beam descriptions |
|----------------|-----------------|-----------------|----------------|
| Beam Description | Grade | Size of Beam L x B x H | Type of rebar | Type of Section |
| M70N-UR | M70 | 1200 mm x 100 mm 150 | Steel | Under-reinforced |
High yield strength deformed steel bars of diameter 16 mm and 10 mm were used as the longitudinal reinforcement in the specimens. The reinforcement details are given in the table 2 for both compression steel and tension steel. Two legged vertical stirrups of 8 mm diameter at spacing of 90 mm c/c were provided as shear reinforcement.

One day before the testing, the cured beams are white washed and the locations of supports; load points and the central deflection gauge are marked with a pencil. The test specimen was mounted in a UTM of 1000 kN capacity. The supports of the beam rested on an adjustable steel rollers. The effective span of the beam is 1000 mm. The load was applied on two points each 333 mm away from the support. Dial gauges of 0.01 mm least count were used for measuring the deflections under the load points and at mid span for measuring the deflections. Beams are subjected to symmetrical two-point flexural loading under strain rate control. The dial gauge readings were recorded at different loads until failure. The load was applied at the rate of 2.5 kN/sec until the first crack was observed. Subsequently, the load was applied at the rate of 5kN/sec. The behavior of the beam was observed carefully and the first crack was identified using a hand held microscope. The failure mode of the beams was also recorded. Deflections at the central point and the ultimate load carrying capacity (Peak load) are measured for M70N-UR and M70BFRP-UR beams considered. The test is continued until the load drops to 15-20% of peak load recorded, in the descending portion of load deflection curves. At that stage the testing is stopped by gradually unloading.

The experimental test set-up is shown in Figure 2.

![Figure 2. Flexural Test Set up](image)

The strain in beam was measured using vernier calipers. The beam was instrumented to record the strain profile across a length of 200 mm at midspan at the extreme top for strain in compression fibre and at the bottom for strain in tensile steel as shown in figure 2. All measurements were recorded manually. The change in length of the portion under observation is taken at every interval of load using digital vernier calipers. The behaviour of the beam was observed carefully and the first crack was identified with magnifying glass. The deflections and strain values were recorded for respective load increments until failure. The failure mode of the beams were also recorded.
4. Load-Deflection and Moment-Curvature Relations

Deflections were measured at the central point and under the load using the deflection meters to plot load-deflection curves. The values of moments and curvatures are also obtained. A sample calculation for curvature and moment is presented below. Load-deflection behavior of M70 grade of Basalt FRP rebar beams were studied using load-deflection plots. Moment curvature relationships are very important to assess out ductility of the structure and the amount of possible redistribution of stresses.

The deformations measured are divided by the gauge length (200 mm) to obtain the strains at the particular level. From the top and bottom strains, the average curvatures were calculated. From these results, M-Φ diagrams are plotted for under reinforced Basalt FRP rebar concrete beams.

Test results regarding load at first crack, ultimate load carrying capacity and deflection at maximum load of normal and basalt FRP rebar concrete beams are tabulated in Table 3 to 6.

No horizontal cracks were noticed at the level of the reinforcement indicating that there was no occurrence of bond failure. Vertical flexural cracks were observed in the middle third region (constant moment) and ultimate failure occurred due to crushing of the compression concrete with significant amount of deflection. The flexure cracks were the first to initiate in the Constant Bending moment Zone (middle third) as expected. Loads at first crack in basalt FRP rebar beams are higher than the normal steel rebar concrete beams confirming that basalt FRP rebars beams offer greater resistance to cracking. The ultimate flexural strength of basalt FRP rebar concrete beams have improved when compared to normal steel rebar concrete beams. First crack formation was delayed in basalt FRP rebar concrete beams due to which fatigue strength is increased which in turn increases the time taken for first crack occurrence and thereby increasing the load carrying capacity. The deflection at the mid span decreased in basalt FRP rebar concrete beams which indicates the improved flexural stiffness of the elements thereby reducing the structural member’s deformability, increasing strength and hence controlling deflection. Mid-span deflections at peak load reduced in basalt FRP rebar concrete beams. The ultimate deflection in case of basalt FRP rebar concrete beams is less than that of normal steel rebar concrete beams.

From the above investigations, it can be concluded that, the ultimate flexural strength of basalt FRP rebar concrete beams have improved significantly when compared with normal steel reinforced beams due to better bond strength at the interfacial zones. Mid-span deflections at ultimate load in beams incorporated with basalt FRP rebar are reduced significantly. The recovery of deflection after removal of the load was more in case of basalt FRP rebar concrete beam indicating more elastic behaviour. Thus basalt FRP rebar concrete beam are more suitable to take fatigue loads than normal steel reinforced beams. From the above investigations it is evident that the load at first crack, cracking behavior, deflection pattern, crack development pattern and ultimate load carrying capacity of basalt FRP rebar concrete beams have improved enormously.

In normal concrete beams the visible flexural cracks developed at 70% to 80% of the ultimate load of each beam and in basalt FRP rebar concrete beams they developed at 75% to 85% of the ultimate load of each beam. All the beams exhibited a tension failure which is a ductile failure. The cracks are accompanied by pronounced bulging. When the load is further increased, cracks propagated towards the top of the beam. As the beams are forced to deform further, the cracks became more pronounced and the concrete crushed at one or both the ends. With further increase in beam deflection, the load decreased, accompanied by concrete spalling. This crack pattern is observed to be same for all the normal and basalt FRP rebar concrete beams.

The differences noticed in the moment-curvature behaviour of basalt FRP rebar concrete beams are, the increase in the horizontal plateau of the moment-curvature plots and increase in ultimate moment in beams with basalt FRP rebar beams than that in normal steel rebar beams.

In basalt FRP rebar concrete beams, the bondage is more which arrests the micro cracks developed in the matrix which results in requirement of more energy. This lead to an improvement in load at first crack. In
under-reinforced beams after the multiple cracking stages, the yielding of steel was found to be more, and ultimate load corresponds to the yielding of steel and crushing of concrete. The deflection at service load is determined from load deflection plot corresponding to a load of Pu/1.5. Deflections observed from the load-deflection curves for all the specimens at service loads (Pu/1.5) are less than the maximum permissible deflection of 4mm i.e span/250 specified by IS 456-2000.

Table 3. Observations of flexural test on steel rebar concrete beam

| Load kN | Dial gauge reading | Deflection mm | Strain gauge reading | Ec | Et | 1/R | d mm | Moment kN.m |
|---------|--------------------|--------------|---------------------|----|----|-----|------|-------------|
| 0       | 0.00               | 0.00         | 0.00                | 0  | 0  | 0   | 0    | 0.00        |
| 5       | 0.06               | 199.9        | 199.34              | 5E-05 | 0.0001 | 1.21E-06 | 122 | 0.0000     |
| 10      | 0.14               | 199.9        | 199.35              | 5E-05 | 0.000151 | 1.62E-06 | 122 | 0.8333     |
| 15      | 0.23               | 199.9        | 199.36              | 0.0001 | 0.000201 | 2.43E-06 | 122 | 2.5000     |
| 20      | 0.32               | 199.9        | 199.37              | 0.0001 | 0.000251 | 2.83E-06 | 122 | 3.3333     |
| 25      | 0.41               | 199.9        | 199.38              | 0.000151 | 0.000301 | 3.64E-06 | 122 | 4.1671     |
| 30      | 0.51               | 199.9        | 199.39              | 0.000151 | 0.000301 | 3.64E-06 | 122 | 5.0000     |
| 35      | 0.61               | 199.9        | 199.41              | 0.0002 | 0.000351 | 4.45E-06 | 122 | 5.8333     |
| 40      | 0.72               | 199.9        | 199.44              | 0.00025 | 0.000452 | 5.66E-06 | 122 | 6.6667     |
| 45      | 0.83               | 199.9        | 199.47              | 0.0003 | 0.000502 | 6.47E-06 | 122 | 7.5000     |
| 50      | 0.94               | 199.9        | 199.49              | 0.00035 | 0.000602 | 7.68E-06 | 122 | 8.3333     |
| 55      | 1.05               | 199.9        | 199.51              | 0.0004 | 0.000652 | 8.69E-06 | 122 | 9.1667     |
| 60      | 1.16               | 199.9        | 199.54              | 0.00045 | 0.000702 | 9.3E-06  | 122 | 10.0000    |
| 65      | 1.28               | 199.9        | 199.57              | 0.00055 | 0.000803 | 1.09E-05 | 122 | 10.8333    |
| 70      | 1.40               | 199.9        | 199.6              | 0.00065 | 0.000903 | 1.21E-05 | 122 | 11.6667    |
| 75      | 1.53               | 199.9        | 199.62              | 0.00065 | 0.000953 | 1.29E-05 | 122 | 12.5000    |
| 80      | 1.66               | 199.9        | 199.65              | 0.00075 | 0.001054 | 1.37E-05 | 122 | 13.3333    |
| 85      | 1.79               | 199.9        | 199.68              | 0.00075 | 0.001054 | 1.45E-05 | 122 | 14.1667    |
| 90      | 1.93               | 199.9        | 199.7              | 0.00085 | 0.001104 | 1.54E-05 | 122 | 15.0000    |
| 95      | 2.06               | 199.9        | 199.73              | 0.00085 | 0.001204 | 1.62E-05 | 122 | 15.8333    |
| 100     | 2.20               | 199.9        | 199.76              | 0.00085 | 0.001304 | 1.74E-05 | 122 | 16.6667    |
| 105     | 2.34               | 199.9        | 199.8              | 0.00095 | 0.001355 | 1.82E-05 | 122 | 17.5000    |
| 110     | 2.48               | 199.9        | 199.83              | 0.00095 | 0.001405 | 1.9E-05   | 122 | 18.3333    |
| 115     | 2.63               | 199.9        | 199.86              | 0.00105 | 0.001505 | 2.02E-05 | 122 | 19.1667    |
| 120     | 2.78               | 199.9        | 199.89              | 0.00105 | 0.001605 | 2.14E-05 | 122 | 20.0000    |
| 125     | 2.93               | 199.9        | 199.92              | 0.00105 | 0.001706 | 2.26E-05 | 122 | 20.8333    |
| 130     | 3.08               | 199.9        | 199.95              | 0.00115 | 0.001806 | 2.38E-05 | 122 | 21.6667    |
| 135     | 3.28               | 199.9        | 199.97              | 0.001201 | 0.002057 | 2.63E-05 | 122 | 22.5000    |
| 140     | 3.54               | 199.9        | 199.97              | 0.001251 | 0.002208 | 2.79E-05 | 122 | 23.3333    |
| 145     | 3.80               | 199.9        | 199.97              | 0.001301 | 0.002358 | 2.95E-05 | 122 | 24.1667    |
| 150     | 4.06               | 199.9        | 199.98              | 0.001401 | 0.002609 | 3.23E-05 | 122 | 25.0000    |
| 155     | 4.32               | 199.9        | 199.99              | 0.001501 | 0.00286 | 3.52E-05 | 122 | 25.8333    |
| 160     | 4.67               | 199.9        | 199.99              | 0.001601 | 0.003111 | 3.8E-05  | 122 | 26.6667    |
| 165     | 5.02               | 199.9        | 200.01              | 0.001751 | 0.003462 | 4.2E-05  | 122 | 27.5000    |
| 170     | 5.30               | 199.9        | 201.13              | 0.002301 | 0.009081 | 9.18E-05 | 122 | 29.8333    |

M70N-UR
Table 4. Observations of flexural test on basalt FRP rebar concrete beam

| Load kN | Dial gauge reading Centre | Deflection mm | Strain gauge reading | Ec | Et | 1/R | d mm | Moment kN.m |
|--------|---------------------------|--------------|----------------------|----|----|-----|------|------------|
|        | Centre Under load        | Top Bottom   |                      |    |    |     |      |            |
| 0      | 0                         | 206.19       | 205.97               | 0  | 0  | 0   | 122  | 0.000     |
| 5      | 10                        | 206.19       | 205.99               | 0  | 9.71E-05 | 7.83E-07 | 122 | 0.833     |
| 10     | 21                        | 206.18       | 206                 | 4.83E-05 | 0.000146 | 1.57E-06 | 122 | 1.667     |
| 15     | 33                        | 206.17       | 206.01               | 9.75E-05 | 0.000194 | 2.35E-06 | 122 | 2.500     |
| 20     | 45                        | 206.16       | 206.02               | 0.000145 | 0.000243 | 3.13E-06 | 122 | 3.333     |
| 25     | 57                        | 206.15       | 206.03               | 0.000194 | 0.000291 | 3.91E-06 | 122 | 4.167     |
| 30     | 69                        | 206.15       | 206.04               | 0.000194 | 0.000343 | 4.31E-06 | 122 | 5.000     |
| 35     | 81                        | 206.14       | 206.05               | 0.000242 | 0.000388 | 5.09E-06 | 122 | 5.833     |
| 40     | 93                        | 206.13       | 206.07               | 0.000291 | 0.000486 | 6.26E-06 | 122 | 6.667     |
| 45     | 105                       | 206.12       | 206.08               | 0.000339 | 0.000534 | 7.04E-06 | 122 | 7.500     |
| 50     | 118                       | 206.11       | 206.09               | 0.000388 | 0.000583 | 7.83E-06 | 122 | 8.333     |
| 55     | 131                       | 206.10       | 206.09               | 0.000436 | 0.000676 | 8.90E-06 | 122 | 9.167     |
| 60     | 144                       | 206.09       | 206.00               | 0.000485 | 0.000727 | 1.06E-05 | 122 | 10.000    |
| 65     | 157                       | 206.08       | 206.00               | 0.000533 | 0.000793 | 1.21E-05 | 122 | 10.833    |
| 70     | 171                       | 206.07       | 206.03               | 0.000582 | 0.001028 | 1.29E-05 | 122 | 11.667    |
| 75     | 185                       | 206.06       | 206.02               | 0.000630 | 0.001117 | 1.41E-05 | 122 | 12.500    |
| 80     | 199                       | 206.05       | 206.01               | 0.000679 | 0.001165 | 1.49E-05 | 122 | 13.333    |
| 85     | 213                       | 206.04       | 206.00               | 0.000727 | 0.001214 | 1.57E-05 | 122 | 14.167    |
| 90     | 227                       | 206.03       | 206.00               | 0.000776 | 0.001262 | 1.64E-05 | 122 | 15.000    |
| 95     | 241                       | 206.02       | 206.00               | 0.000824 | 0.001311 | 1.72E-05 | 122 | 15.833    |
| 100    | 256                       | 206.01       | 206.00               | 0.000873 | 0.001359 | 1.80E-05 | 122 | 16.667    |
| 105    | 271                       | 205.99       | 206.00               | 0.000921 | 0.001408 | 1.88E-05 | 122 | 17.500    |
| 110    | 286                       | 205.98       | 206.00               | 0.000970 | 0.001457 | 1.96E-05 | 122 | 18.333    |
| 115    | 301                       | 205.97       | 206.00               | 0.001018 | 0.001505 | 2.03E-05 | 122 | 19.167    |
| 120    | 316                       | 205.96       | 206.00               | 0.001067 | 0.001554 | 2.11E-05 | 122 | 20.000    |
| 125    | 332                       | 205.95       | 206.00               | 0.001115 | 0.001602 | 2.18E-05 | 122 | 20.833    |
| 130    | 348                       | 205.94       | 206.00               | 0.001164 | 0.001649 | 2.25E-05 | 122 | 21.667    |
| 135    | 364                       | 205.93       | 206.00               | 0.001212 | 0.001704 | 2.32E-05 | 122 | 22.500    |
| 140    | 380                       | 205.92       | 206.00               | 0.001269 | 0.001759 | 2.39E-05 | 122 | 23.333    |
| 145    | 396                       | 205.91       | 206.00               | 0.001326 | 0.001814 | 2.46E-05 | 122 | 24.167    |
| 150    | 424                       | 205.89       | 206.00               | 0.001390 | 0.001870 | 2.54E-05 | 122 | 25.000    |
| 155    | 455                       | 205.88       | 206.00               | 0.001465 | 0.001926 | 2.62E-05 | 122 | 25.833    |
| 160    | 493                       | 205.86       | 206.00               | 0.001532 | 0.001979 | 2.70E-05 | 122 | 26.667    |
| 165    | 550                       | 205.83       | 206.00               | 0.001746 | 0.002031 | 2.78E-05 | 122 | 27.500    |
| 170    | 634                       | 205.79       | 206.00               | 0.00194  | 0.002353 | 2.86E-05 | 122 | 28.333    |
| 175    | 781                       | 205.73       | 207.63               | 0.002231 | 0.002659 | 3.36E-05 | 122 | 29.167    |
4.1 Model calculation of Deflection, $E_c$, $E_t$, Curvature and Moment

Deflection in mm = dial gauge reading $\times$ L.C (0.01)

$E_c = \frac{(201.46 - \text{top strain gauge reading})}{201.46}$

$E_t = \frac{(\text{bottom strain gauge reading} - 200.3)}{200.3}$

$\frac{1}{R} = \frac{(E_c + E_t)}{d}$

Support reaction = load/2

Distance of support from application of load L/3 where L is 1m.

So Maximum Moment in kN-m = \left(\frac{\text{load}}{2}\right)\left(\frac{L}{3}\right) = \frac{\text{load} \times L}{6} = \text{load} \times \text{1m}/6$

**Table 5.** Flexural features of reinforced beam made with steel rebars

| Service load kN | Load at first crack (kN) | Ultimate Flexural Strength (kN) | Deflection at service load mm | Central Deflection at Failure (mm) | Deflection Under load at failure (mm) | Maximum Crack width at failure (mm) |
|-----------------|--------------------------|---------------------------------|-----------------------------|-----------------------------------|--------------------------------------|-----------------------------------|
| 49              | 65                       | 170                             | 3.72                        | 7.34                              | 6.59                                 | 1.14                              |

**Table 6.** Flexural features of reinforced beam made with basalt FRP rebars

| Service load kN | Load at first crack (kN) | Ultimate Flexural Strength (kN) | Deflection at service load mm | Central Deflection at Failure (mm) | Deflection Under load at failure (mm) | Maximum Crack width at failure (mm) |
|-----------------|--------------------------|---------------------------------|-----------------------------|-----------------------------------|--------------------------------------|-----------------------------------|
| 49              | 70                       | 175                             | 3.69                        | 7.81                              | 7.43                                 | 1.09                              |

5. Conclusions
Based on the results reported in this research work and key findings during the experimental investigations, the following conclusions are drawn:

1. The load carrying capacity of beams was found to be increasing with the usage of basalt FRP rebars.
2. The maximum deflections of basalt FRP rebar concrete beams were more when compared to conventional steel rebar beams. This indicates increase in ductility of basalt FRP rebar beam specimens.
3. The load-deflection and moment-curvature behaviour of under reinforced basalt FRP rebar beams shows increased values of loads at ultimate and at first crack.
4. Basalt FRP rebar concrete beams control the initiation of micro cracks, improve the first crack load, the ultimate load and ductility of concrete specimens under flexure. They are also effective in resisting deformation at all stages of loading from first crack to failure.
5. The decrease in crack width and reduction in deflections at service loads is observed in under-reinforced basalt FRP rebar beams.
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