

Parametric finite element analysis to investigate flexural behavior of BFRP-FRC beams

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Abstract. Recently, most of researchers are focusing on the use of eco-friendly and natural fibers for reinforcement in concrete. One of the most recent materials that is being used is Basalt fiber due to its low cost and exceptional characteristics over glass and carbon fibers. This material is tested to be used as alternative to conventional steel reinforcement bars in reinforced concrete structures also. Basalt Fiber-Reinforced Polymer (BFRP) bars are relatively new type of FRP reinforcement material. The present paper is a parametric study for flexural behavior of concrete members reinforced using BFRP rebars using finite element analysis (FEA). FEA software – Abaqus is used for numerical simulation of selected beams. A comparison between experimentally evaluated and numerically obtained load vs midspan deflection response of beam is presented. Due to a good agreement between these two approaches, FE model was used to conduct parametric study. The parameters that were changed from experimentally tested beams are number and size (diameter) of BFRP bars to study effect of reinforcement detailing and reinforcement ratio on load vs. midspan deflection response. A comparison between experimentally determined and numerically evaluated load vs midspan deflection response was carried out and found to be consistent with mean absolute percentage error of 4.80%.

1 Introduction

The weakening of concrete over time in buildings and construction industry is a major concern being faced nowadays by structural engineers worldwide. The enormous usage of reinforced concrete in construction and corrosion with aging of reinforced concrete members results in massive economical losses and wastage of resources [1]. The aging and consequently corrosion is mainly caused due to use of steel bars for reinforcing concrete members also lead to mechanical and serviceability issues [2]. In general, reinforcement steel is susceptible to corrosion which causes both design and serviceability issues for the structural members. Besides, concrete weakening is also caused because of poor initial design and maintenance, harsh environmental conditions, construction errors and accidental

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loading situations like high intensity wind forces and earthquakes [3]. Design engineers are no longer considering increase of load specifications specified in design codes and overloading or under design of existing structures due to lack of quality control [4]. Since the repair or replacement of such defective structures requires a massive amount of money and time, researchers are searching for new materials and methods to increase the strength and durability characteristics and at the same time prolong the causes that defects the reinforced concrete. The most researched material for replacing the reinforced steel is the Fiber Reinforced Polymer (FRP). FRP has been used as an alternative reinforcement in concrete structure and gained increasingly popularity as an innovation solution to corrosion related problem of steel reinforcement. FRP is an advanced composite material made up of high strength fibers and resin matrix. Other than being non-corrosive alternative, it has several distinct advantages like high strength to weight ratio, non-conductive and non-magnetic nature [2]. It is excellent for new buildings and infrastructure works to be used structural material due to its outstanding strength and good corrosion resistance [1]. In addition, FRP also can be used for concrete members where magnetic transparency is required [5].

In present study, a parametric study to investigate flexural behavior of concrete beams reinforced using BFRP rebars through finite element analysis (FEA) is carried out. FEA software – Abaqus is used for numerical simulation of selected beams. The parameters that were changed from originally experimental tested beams are number and size (diameter) of BFRP bars. The FE analysis was also used for investigating effect of type of FRP reinforcement on load-deflection response which is an important flexure related parameter for reinforced concrete beams. The main impediment of this research is to model the beam samples through Abaqus, as there are few and limited guidelines in Abaqus for modelling Basalt FRP reinforced concrete. Hence, this study is initiated to supplement this particular dimension of FE modelling for BFRP reinforced concrete members in order to enhance research ability for BFRP reinforced concrete properties through usage of any commercial computer software. In general, it aims at exploring effective modelling techniques so that faster results in comparison to experimental results can be obtained efficiently.

2 Theoretical background

Fiber Reinforced Plastics more commonly known as Fiber Reinforced Polymers are being used as reinforcement bars as internal reinforcement for structural members. They can also be used as an externally wrapped or bonded reinforcement for the purpose of strengthening, upgrading or retrofitting concrete, masonry, steel and timber structural members. FRPs are polymer matrix reinforced with fibers. It is a composite material that mechanically enhances the stiffness and strength of a polymer matrix by using natural or synthetic fibers. FRPs are exceptionally strong, usually up to eight times stronger than conventional steel reinforcement bars. Therefore, in order to provide required tensile strength particularly along the direction of fibers, it is used as internal reinforcement as well as strengthening of structures is achieved by using artificial fibers in a polymeric matrix. As a material, FRP composites are anisotropic whereas steel and aluminium are isotropic. Therefore, fibre's properties are directional, meaning that they need to be placed in a continuous, straight and parallel arrangement within the matrix in order to achieve satisfactory mechanical characteristics in the direction of the fiber placement [6].

The first known use of FRPs as reinforcement took place in Russia in 1975. A nine meter long glued timber bridge was reinforced by prestressed tendons of glass fiber reinforced polymer (GFRP) [7]. Many researchers in Europe in the 1980s started significant studies of using FRPs as reinforcement to use it for bridge repair and strengthening as an alternative to steel plate bonding.

During the 1990s, research work on supporting structures for magnetically levitated trains in Japan provided significant support to the area of FRP reinforcements. The first design guidelines of FRP reinforced concrete was introduced by the Japanese in 1996 [8]. Since then FRP's use as main reinforcement in structural components has increased considerably. Consequently, several researchers and organizations from all over the world have authored design specifications and guidelines for using FRP as reinforcement. [6]

The newest addition to FRPs and structural composites is Basalt Fiber. Chemically it's composition is similar to glass fiber but basalt fibers have higher and better strength characteristics, it is highly resistant to acidic, alkaline, and salt attack making it a better suitor for concrete, bridge and shoreline structures than most glass fibers. Basalt compared to carbon and aramid fiber has the wider application temperature range -269°C to +650°C, higher radiation resistance, oxidation resistance, compression and shear strength. By comparing the costs of fibers, basalt price is higher than E-glass, but less than S-glass, aramid or carbon fiber. It is expected that cost of production for basalt fibers would reduce further, as worldwide production increases [9]. The cost of basalt fiber reinforced polymer (BFRP) is higher than steel because of its lack of manufacturing capacity presently.

Basalt fibers are found to perform well with a wide range of temperatures and show high resistance in high temperatures compared to other most common type of fibers. The operating range of temperatures for various common types of fibers is shown in Table 1. Many researchers have specified thermal conductivity (K) range of 0.031~0.038 W/(m•K) and coefficient of linear expansion of 6.5×10^{-6} at a temperature range of 20~300°C/°C; whereas thermal conductivity for normal strength concrete varies between 1.6~2.7 W/(m•K) depending on proportion of its ingredients.

Table 1. Operating temperature range for common types of fibers used in concrete.

Type of Fiber	ΔT (°C)
Basalt	-260 ~ +700
E-glass	-50 ~ +380
S-glass	-50 ~ +300
Carbon	-50 ~ +700

The high thermal stability of basalt fibers which is from -260~700 °C is mainly because of the material characteristics of basalt rocks that nucleate at very high temperature. In comparison with that of carbon and glass fibers basalt fibers sustain an appreciable volumetric integrity at high temperature (600°C~1200 °C). Particularly, at about 200°C basalt fibers starts thermal decomposition and it induces a mass loss of about 0.74% in the range 200°C~800 °C, while the thermal decomposition for glass fibers is in the range 160°C~850°C and it induces a mass loss of about 1.8%. Moretti E. et al. [10] found that basalt fibers exhibit relatively good sound absorption and thermal insulation properties; hence, they are best-suited materials for panels in building and construction. Tumadhir and Tumadhir [11] reported that increasing the volume fraction of basalt fibre in concrete leads to a decrease in the amount of heat conducted through the thickness of concrete specimens and hence a decrease the thermal conductivity of concrete is observed at temperature range of 0~350°C. This specific behaviour is attributed to volumetric stability of basalt fibers when they are exposed to high temperatures. This is primarily due to nucleating nature of basalt rocks at high temperatures.

3 Finite element modelling

3.1 BFRP reinforced concrete members – Experimental investigation by Shamass and Cashell (2020)[12]

Experimental investigation by Shamass and Cashell [12] included two rectangular concrete beams having dimensions as 200 mm depth $\times$ 125 mm width $\times$ 2000mm length as seen in Figure 1. In this study, beams were tested under four-point bending loading conditions over a clear span of 1800 mm and the distance between the two loading points was maintained as 500 mm. The beams were reinforced with 2T8 steel rebar as top reinforcement, while 2T10 BFRP bars were used as bottom reinforcement. Both beams included 8 mm in diameter steel shear links. They were spaced at 100 mm intervals in the shear spans and 200 mm intervals in the constant moment zone as seen in Figure 1. These beams did not include any stirrups in the constant moment zone so that confining effect of shear reinforcement on flexural behaviour can be easily minimized. A clear concrete cover at the top and bottom of beam was maintained at 25 mm and beam ends were provided with a cover of 15 mm. The test specimen in this study was designed using a reinforcement ratio larger than the balanced reinforcement ratio to fail in flexure by concrete crushing (i.e. compression controlled).

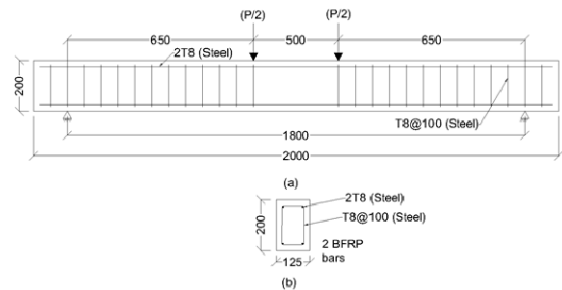


Fig. 1. Elevation (a) and cross-section of beam (b) with reinforcement details and dimensions of experimentally tested beams [10].

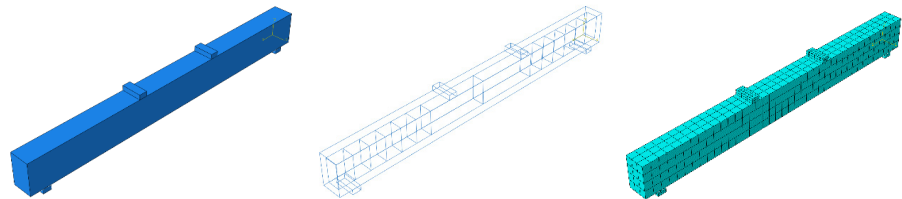


Fig. 2. FEA geometry: (a) beam (b) reinforcement cage (c) mesh configuration.

The material properties of concrete such as elastic modulus of 25.742 GPa and Poisson's ratio of 0.2 were used for FEA. The mechanical properties of BFRP and steel bars as shown in Table 2 as used by experimental study were used for modelling of beam for FEA. Model geometry of beam having a mesh size of 50 mm was considered to ensure that different materials share the same nodes in the beam. All such similar details were consistently maintained as mentioned in experimental study throughout. The geometry of beam, reinforcement cage and mesh configuration followed for FEA is shown in Figure 2.

Table 2. Mechanical properties of BFRP and steel bars used in experimental study by Shamass and Cashell [10].

Type	d_b (mm)	A_f (mm ²)	E_f (GPa)	f_{fu} (MPa)
BFRP	10	79	54	1356
Steel	8	50.3	200	621

* d_b =diameter of bar, A_f =cross-sectional area of bar, E_f =modulus of elasticity and f_{fu} =tensile strength of steel reinforcement.

The load vs midspan deflection response of first beam experimentally studied by Shamass and Cashell [12] are shown in Figure 3. A comparison between experimentally evaluated midspan deflection at various increasing load values and corresponding results obtained using FEA can be seen in Figure 3. It is generally believed that experimental results are sometimes affected by human, instrumental and random errors; and numerical models are affected by the physical model or methods adopted and selected parameters. Hence, agreement between experimentally obtained results and numerically evaluated results are verified through absolute percentage error for each of the midspan deflection values. The maximum and minimum absolute percentage error values observed for this beam specimen are 14.85% and 0.146% respectively, with mean absolute percentage error of 4.80%.

The confidence level of results obtained using numerical FE modelling were verified using unpaired t-test, which compares the mean of midspan deflection obtained experimentally and numerically using FEA. The two tailed P-value was obtained as 0.6618. The difference in mean of experimentally and numerically evaluated midspan deflection was observed to be -0.888mm indicating 95% confidence interval with this difference from -4.93mm to 3.15mm. It should be noted that experimentally and numerically evaluated midspan deflection for beam was observed to have standard deviation of 7.77 and 8.66 respectively.

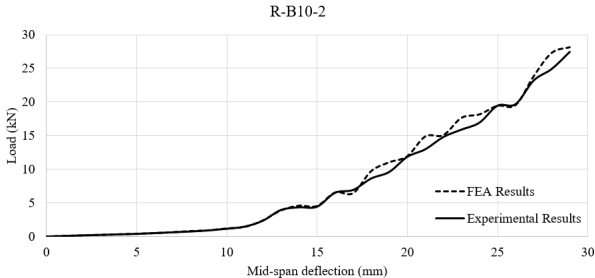


Fig. 3. Comparison between experimental and numerical load-deflection curve for beam.

3.2 Parametric study

The verified model was used to conduct parametric studies such as variation in BFRP bars ratio and detailing. These parameters were changed for FE models of beams to observe flexural behavior of the beam, which is presented in the form of load versus midspan deflection with an intention to examine effect of reinforcement ratio and reinforcement detailing.

3.2.1 The effect of reinforcement detailing

The first parametric study included addition of an extra BFRP bar as bottom reinforcement i.e. 3T10 bars instead of 2T10 BFRP bars. However, beam dimensions, loading conditions, steel shear links, material properties etc. were kept constant to study influence of increased BFRP on flexural characteristics of beam in terms of load-deflection response. Figure 4 compares the load versus midspan deflection of two FE modelled beam to understand effect of reinforcement detailing on load-deflection response. It was observed that prior to first cracking moment, both beams follow same load vs. mid-span deflection trend. Stiffer beam shows higher slope of load-deflection curve and hence results in lower value of midspan deflection.

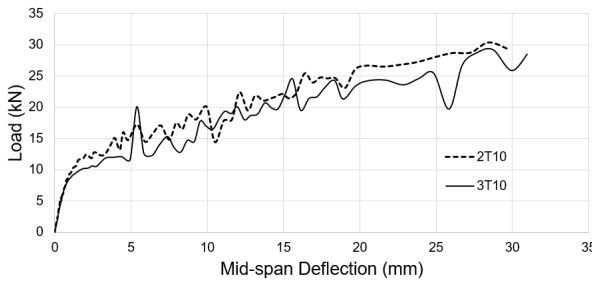


Fig. 4. Comparison of load-deflection curves for beam with varied reinforcement detailing.

Beams were observed to have almost same flexural capacity with less maximum midspan deflection for the beam with more reinforcement bars in tension zone to assess maximum deflection of beam. Beam with more reinforcement bars and marginally lower axial stiffness makes them more resistant toward deflection. The maximum midspan deflection values for FE modelled beams are shown in Table 3.

Table 3. Maximum midspan deflection with increased BFRP.

Beam	Maximum midspan deflection (mm)
2T10	28.31
3T10	28.12
2T12	30.40
2T16	30.06

3.2.2 The effect of reinforcement ratio

The second parametric study was done by increasing the diameter of BFRP bars for bottom reinforcement to 2T12 and 2T16 respectively in place of 2T10 BFRP bars. Beam dimensions and material properties were kept constant for the FE numerical model to observe the effect of reinforcement ratio on load-deflection response. Figure 5 shows load versus midspan deflection behavior of the FE modelled beams with increased reinforcement ratio along with a control beam. A slight improvement in cracking and post cracking behavior of beams along with minimal increase in load carrying capacity can be noticed with increased reinforcement. In general it is observed that addition of fibers to concrete helps to control the compression failure in case of concrete beams reinforced using fibers due to a commonly know fiber bridging effect that utilizes the high tensile strength of FRP reinforcement. Hence, increase in flexural capacity of BFRP beams can be expected with increase in reinforcement ratio. The beams show the same pre-cracking stiffness due to the fact that the behavior of the beam is controlled by concrete until the first crack. After the

first crack started, the beam with the higher reinforcement ratio started showing higher stiffness.

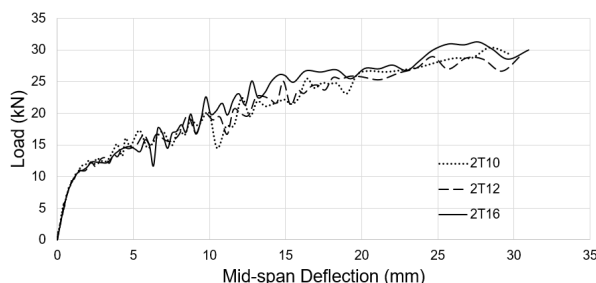


Fig. 5. Comparison of load-deflection curves for beams with varied reinforcement ratio.

4 Conclusion

The present study investigates the flexural behavior of beams reinforced with natural basalt fibers numerically using finite element analysis, via variation of the number and size (diameter) of BFRP bars. Abaqus FEA is used to carry out numerical modelling of beams. A beam from experimental study by Shamass and Cashell [12] was modelled using Abaqus FEA. A comparison between experimentally determined and numerically evaluated load vs midspan deflection response was carried out and found to be consistent with mean absolute percentage error of 4.80%. The confidence level of results obtained using numerical FE modelling were verified using unpaired t-test which produced two tailed P-value as 0.6618. It was observed that beam with more reinforcement bars and marginally lower axial stiffness makes them more resistant toward deflection. Increase in number of BFRP bars essentially produces identical load vs midspan deflection response. On the other hand increase the diameter of BFRP bars was observed to increase load-carrying capacity of the beams and decrease in ductility of beams.

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