MATEC Web of Conferences **361**, 05012 (2022) https://doi.org/10.1051/matecconf/202236105012
Concrete Solutions 2022

Experimental testing of residual strain and displacement development in pretensioned BFRP reinforced concrete beams

Ana Pavlović[1*], *Ted* Donchev[1], *Diana* Petkova[1] and *Casim* Hisrattally[1]

[1]Department of Civil Engineering, Faculty of Science, Engineering and Computing, Kingston University London

Abstract. The utilisation of fibre reinforced polymers (FRPs) as reinforcement for concrete elements has attracted attention mainly due to their high tensile strength, light weight and corrosion resistance. Lately, there has been an interest in basalt FRPs as a more economically competitive and environmentally friendly option. Basalt FRP is manufactured from a widely available volcanic rock in a process which does not require any additives, giving it an edge over the currently more popular glass-fibre reinforced plastic (GFRP) reinforcement.

Pretensioning of FRP reinforcement with low longitudinal modulus of elasticity, such as GFRP and BFRP has been proposed as an effective solution to the concerns regarding the serviceability performance of flexural elements reinforced with these composite materials. In previous research it has been demonstrated that prestressing even at low levels can significantly reduce deflections and postpone cracking of BFRP reinforced concrete elements.

This research presents an experimental investigation of pretensioned BFRP reinforced concrete tested under quasi-static loading and unloading cycles at 5kN load increments until failure. A comparison with an unprestressed sample is also provided to examine the effectiveness of prestressing at improving the structural performance of the beams. The samples were equipped with internal strain gauges and linear displacement transducers to monitor the development of strains in the reinforcement, deflections and concrete surface strains during testing. Close monitoring of the anchorage zone and the development of cracks was also conducted.

Based on the experimental results it can be concluded that the prestressing of BFRP reinforced beams delays the development of residual strains and residual displacements upon unloading. Furthermore, the increase in the prestress level further reduced the residual strain and displacements.

1 Background

Fibre reinforced polymers (FRPs) have been recognised as an alternative to steel for reinforcement of concrete structures. These composite materials are made using different fibres, namely, carbon, glass, aramid and basalt, which are bound together using resins (typically thermosetting resins). These materials typically exhibit linear elastic anisotropic behaviour [1], with properties dependent on the fibre type. FRPs are generally characterised by high tensile strength, resistance to corrosion and light weight. which, among other properties, makes them attractive for structural applications.

Basalt FRP (BFRP) is the most recent addition to the FRP family. It is made from basalt fibre, an inorganic fibre made from basalt rock, which is melted at temperatures of 1400°C and extruded into continuous filaments. The fibre itself has good resistance to corrosive environments, high tensile strength and modulus, insulating properties and low moisture-absorption, to name a few advantages [2]. The resulting composite is more cost effective in comparison with CFRP, whilst being characterised by properties similar to, or better than GFRP; BFRP performs well in environments requiring chloride resistance, chemical resistance, high tensile strength and low water absorption [3]. Additionally, according to [4, 5] basalt FRP reinforcement has lower environmental impact than other reinforcement types.

The studies on the use of FRP as internal reinforcement are more limited than investigations of their strengthening applications. Nonetheless, there are a sound number of research studies demonstrating the feasibility of utilising BFRP for reinforcement of concrete structures. Due to the low longitudinal elastic modulus of BFRP, as well as GFRP, one of the main issues for their application is the early and more intensive development of cracks and deflections. Experimental investigation of a series of reinforced concrete beams [6] showed that the BFRP reinforced samples suffered from larger deflections and increased crack widths than steel reinforced samples at the same level of loading.

[1] Corresponding author: ana.pavlovic.grf@gmail.com

A possible approach to mitigate this effect is to increase the reinforcing ratio. As demonstrated by [7], increasing the concrete strength and reinforcing ratio of GFRP RC beams has a favourable effect on crack development. Similarly, [8] reported that the load bearing capacity and cracking load were increased, while the crack widths and deflections were decreased with the increase of the reinforcing ratio.

However, this approach leads to underutilisation of the material capacity of the bars and consequentially inefficient design and use of materials, which is in conflict with the principles of sustainable development. Another possible approach to improve the deformability of BFRP reinforced elements is to employ prestressing. It has been demonstrated in previous research [9,10,11,12,13,14] that prestressed BFRP reinforced concrete elements have lower deflections, delayed and less intensive cracking at prestress levels as low as 30% of the ultimate tensile capacity (f_{tu}) of the bars. However, a more limited number of studies to date [e.g., 15, 16, 17] investigated long-term performance and losses of prestress of these elements.

The aim of this research was to estimate the residual deformations and losses of prestress of BFRP reinforced beams. This paper presents the results of the experimental investigation on two prestressed and one control, unprestressed sample.

2 Methodology

The experimental programme included three reinforced concrete beams. The samples were of equal dimensions, namely, 1.2 m long, with a 130 x 180 mm rectangular cross section. All the beams were reinforced equally, with two 6 mm diameter BFRP bars as bottom main tensile reinforcement, two 6 mm diameter high-yield steel bars as top reinforcement and 6 mm mild-steel links. The shear reinforcement was not provided in the middle 300 mm of the beam, which corresponds to the theoretical zero-shear zone under the testing setup used.

Two of the beams were prestressed to 20% and 40% of the ultimate tensile capacity of the bars, and the remaining beam was not prestressed. The labelling of the samples corresponds to their prestress level, namely RCB0 for the control sample, with 0% prestress, RCB20 for the samples prestressed to 20% f_{tu}, and RCB40 for the sample prestressed to 40% f_{tu}.

The two prestressed beams were additionally equipped with bonded anchors at the ends, connecting the BFRP reinforcement to high tensile threaded steel bars which were used in the pretensioning process. The bonded anchors were prepared in accordance with the recommendations given in ASTM D7205/D7205M [19].

Figure 1 Prepared formwork and reinforcing cages in prestressing position. By Authors (2022)

Pretensioning was done using a manually controlled hydraulic ram to the required prestress level, after which the threaded bars were bolted to a steel angle, which was bolted into the strong floor. The prepared formwork and cages are shown in Figure 1. Following the pretensioning process, the beams were cast using the same concrete mix, which was poured into the prepared formwork and compacted using a poker vibrator. Two standard 150 mm cubes and cylinders were cast with each concrete batch and subjected to a compressive test. The results of the standard cube test to BS EN 12390-3:2002 [18] showed an average compressive strength of 66.3 MPa, 54.4 MPa and 69.4 MPa, for samples RCB0, RCB20 and RCB40 respectively.

The samples were cured for 28 days using water, in controlled laboratory conditions at a temperature of 20±5°C. After curing, at 28 days age, the prestressing force was transferred to the concrete by cutting of the bars.

The samples were then subjected to destructive testing. The static scheme corresponded to a simply supported beam over a span of 1000 mm, with two point loads applied symmetrically, 350 mm from the supports. The load was applied to the specified value, held for 5 min, then reduced to 0 kN. After 5 min pause, the load was again increased. The load was applied in increments of 5 kN, ranging from 0 kN to 65 kN, until failure of the samples. The loading protocol is shown in Figure 2.

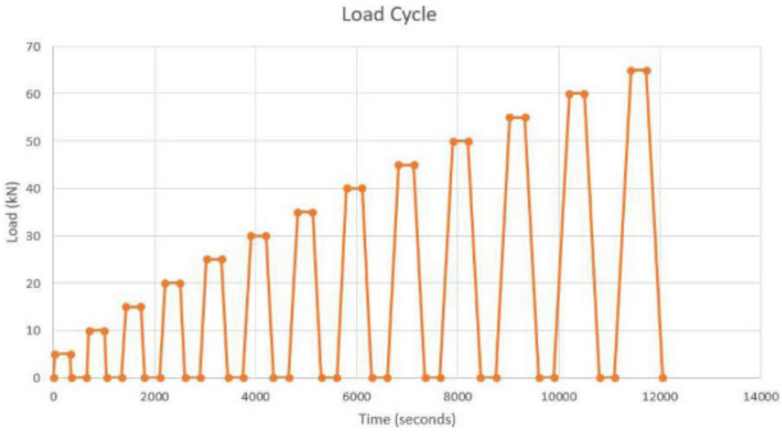

Figure 2 Loading protocol. By Authors (2022)

The samples were equipped with internal strain gauges, attached to the BFRP bars, at positions as shown in Figure 3. The strains were monitored continuously during the pretensioning process and throughout concrete curing, as well as during destructive testing. Additionally, during destructive testing LVDTs were installed at midspan and at support locations to monitor the development of deflections. All measuring equipment was connected to an electronic data logging system.

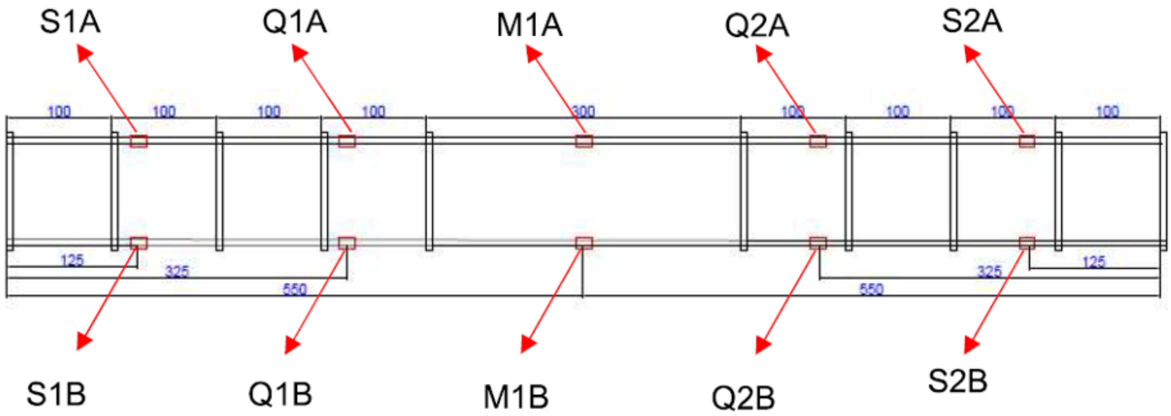

Figure 3. Layout of the internal strain gauges. By Authors (2022)

3 Results

3.1 Strain monitoring

The development of strain was monitored for all samples during all testing phases. All sensors measured a decrease in strain throughout concrete curing, up until release of prestress, for both prestressed samples, indicative of contraction of the bars, and consequentially, losses of prestress. As shown in Figure 4, the decrease in strain was most intensive in the initial 24h from prestressing, before casting of concrete. After this, the reduction in strain was much more gradual.

For both of the prestressed samples, the reduction in strain was larger at quarterspan and support locations than at midspan. Additionally, it can be noted that the loss of strain is larger for samples with higher initial prestress level, as the reduction in strain for sample RCB40 was larger than for sample RCB20. The unprestressed sample exhibited minor fluctuations of strain.

3.2 Destructive testing: Residual displacement development

The average residual displacement during destructive testing of all samples at each level of loading is shown in Figure 5. Beyond the 20 kN load, the displacement experienced by sample RCB0 was no longer in the elastic region. The change of slope corresponds to the opening of the first crack. The sample exhibited a sharper increase in the average residual displacement in comparison with the prestressed samples (RCB20 and RCB40). The maximum residual displacement measured for sample RCB0 was 8.13 mm at the 65 kN failure load.

The average residual displacement of the sample RCB20 increased approximately linearly up until 30 kN, which indicated delayed opening of the first crack in comparison with the unprestressed sample (RCB0). The maximum average residual displacement for this sample was measured at 50 kN failure load. The lower failure load for this sample can potentially be explained by somewhat lower strength concrete batched for this sample. The maximum average residual displacement was lower than for the unprestressed sample, 1.9 mm.

The cracking load for sample RCB40 was approximately 50 kN. The average residual displacements increased at a faster rate beyond the 50 kN load, up to failure load of 65 kN. The maximum average residual displacement for this sample was only 1.2 mm, which was the lowest value out of the three tested samples.

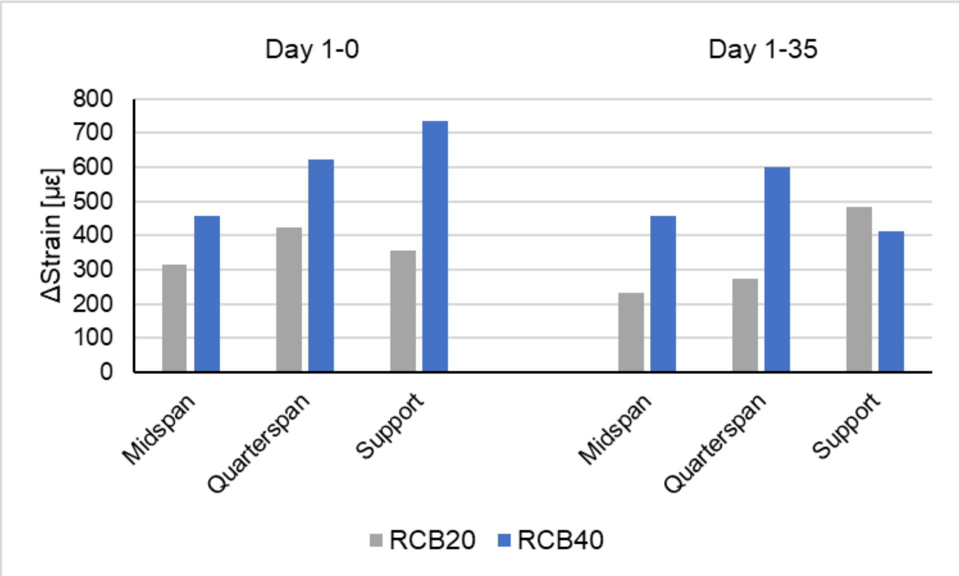

Figure 4 Comparison of strain changes during different time periods. By Authors (2022)

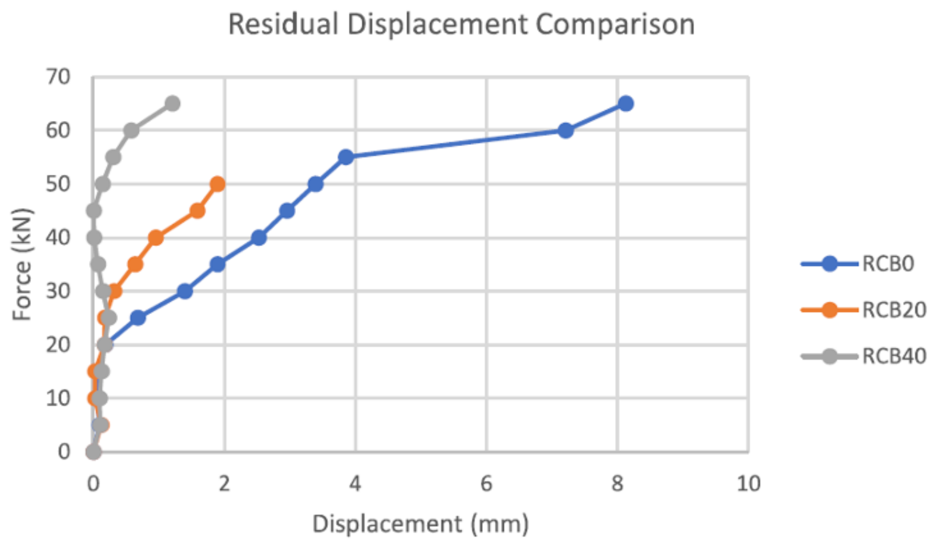

Figure 5 Average residual displacement as a function of applied load. By Authors (2022)

3.3 Destructive testing: Residual strain development

The average residual strain development during destructive testing for all samples is shown in Figure 6 as a function of the applied load. The difference in the initial strain between samples was due to the different level of prestress.

For samples RCB0, up to 20 kN, the increase in residual strain was approximately linear. Beyond this load, the slope of the tangent to the load – residual strain curve was much sharper. For sample RCB20, the change in slope occurred at approximately 30 kN, and for sample RCB40, at the highest value of 50 kN. These values correspond to the opening of the first crack for each sample. The maximum average residual strain prior to failure was also higher for higher prestress level, namely 6247 με, 7353 με and 10622 με for samples RCB0, RCB20 and RCB40 respectively.

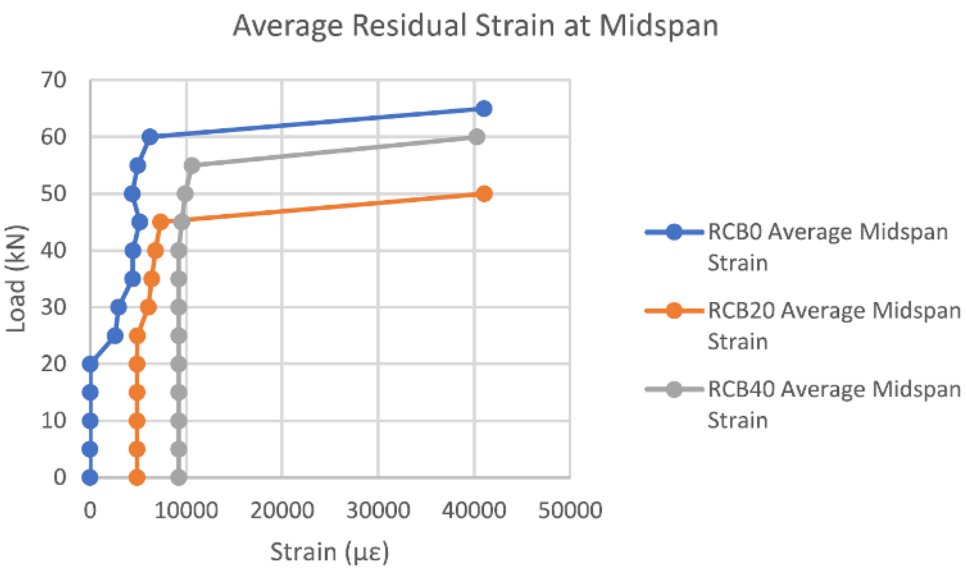

Figure 6 Average residual strain at midspan as a function of applied load. By Authors (2022)

4 Conclusions

From the previously described results obtained by testing of 3 BFRP reinforced concrete beams, the following conclusions can be made:

- The reduction in strain during curing of concrete was the largest at the supports, followed by quarterspan and finally midspan
- The development of residual deflections was delayed for prestressed samples. Higher prestress level resulted in more delayed development of residual deflections.
- The average residual strain development at midspan increased with increasing prestress level
- The ultimate load bearing capacity of all samples was similar, regardless of the prestress level

The conclusions reflect the observations based on the experimental programme on a limited number of samples and are hence applicable to the described testing conditions, materials and geometry. Further investigation of the influence of different parameters, such as bar size effect, overall geometry and material properties would be beneficial.

5 Acknowledgements

The authors would like to express their gratitude to Magmatech Ltd. For providing the basalt FRP bars which were used in this research.

References

[1] Solyom, S. and Balasz, G.L. (2020) Bond of FRP bars with different surface characteristics. *Construction and Building Materials.* **264**

[2] Lopresto, V., Leone, C. and De Iorio, I. (2011) Mechanical characterisation of basalt fibre reinforced plastic. *Composites Part B: Engineering*, **42(4)**

[3] Elgabbas, F., Ahmed, E.A. and Benmokrane, B. (2015) Physical and mechanical characteristics of new basalt-FRP bars for reinforcing concrete structures. *Construction and Building Materials,* **95**

[4] Inman, M., Thorhallsson, E. R., and Azrague, K. (2017). A Mechanical and Environmental Assessment and Comparison of Basalt Fibre Reinforced Polymer (BFRP) Rebar and Steel Rebar in Concrete Beams. *Energy Procedia*

[5] Pavlović, A., Donchev, T., Petkova, D., Staletovic, N. (2022) Sustainability of alternative reinforcement for concrete structures: Life cycle assessment of basalt FRP bars. *Construction and Building Materials.* **334**

[6] Lapko, A. and Urbanski, M. (2014) Experimental and theoretical analysis of deflections of concrete beams reinforced with basalt rebar. *Archives of Civil and Mechanical Engineering Journal*, **15**

[7] Adam, M.A., Said, M., Mahmoud, A.A. and Shanour, A.S. (2015) Analytical and experimental flexural behaviour of concrete beams reinforced with glass fiber reinforced polymer bars. *Construction and Building Materials*. **84**

[8] Hua, Y., Yin, S. and Feng, L. (2020) Bearing behaviour and serviceability evaluation of seawater sea-sand concrete beams reinforced with BFRP bars. *Construction and Building Materials.* **243**

[9] Thorhallsson, E., Smari Jonsson, B., (2012). "Test of prestressed concrete beams with BFRP tendons." Proceedings of CICE 2012 – 6th International Conference on FRP Composites in Civil Engineering. 13-15 June 2012, Rome, Italy.

[10] Pearson, M., and Donchev, T. (2013.). Experimental Study on the Behavior of Prestressed Concrete Beams with Internal BFRP Reinforcement. Proceedings of FRPRCS11 – 11th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures. 26-28 June 2013, Guimaraes, Portugal.

[11] Crossett, P., Taylor, S., Robinson, D., Sonebi, M., Garcia-Taengua, E., Deegan Banagher, P., and Ferrara, L. (2015). The flexural behaviour of SCC beams pre-stressed with BFRP. NetComposites Limited

[12] Mirshekari, M., Donchev, T., Petkova, D., and Limbachiya, M. (2016). "Deformability of pretensioned PC beams with BFRP reinforcement." Proceedings of CICE 2016 – 8th International Conference on FRP Composites in Civil Engineering. 14-16 December 2016. Hong Kong, China.

[13] Dal Lago, B., Taylor, S. E., Deegan, P., Ferrara, L., Sonebi, M., Crosset, P., and Pattarini, A. (2017). "Full-scale testing and numerical analysis of a precast fibre reinforced self-compacting concrete slab pre-stressed with basalt fibre reinforced polymer bars." Composites Part B: Engineering, Elsevier Ltd, 128, 120–133.

[14] Pavlović, A., Donchev, T., Petkova, D., Limbachiya, M., and Almuhaisen, R. (2019). Pretensioned BFRP reinforced concrete beams: Flexural behaviour and estimation of initial prestress losses. MATEC Web of Conferences, EDP Sciences, 289

[15] Atutis, M., and Kawashima, S. (2020). "Analysis of flexural concrete beams prestressed with basalt composite bars. Analytical-experimental approach." Composite Structures, Elsevier Ltd, 243.

[16] Pavlović, A., Donchev, T., Petkova, D., and Limbachiya, M. (2019). Initial estimate of short and long-term prestress losses of BFRP pretensioned RC beams. Proceedings of 14th International Symposium on Fiber Reinforced Polymers for Reinforced Concrete Structures (FRPRCS-14). Belfast, June 2019.

[17] Pavlović A., Donchev T., Petkova D. (2021) Experimental Monitoring of Long-Term Structural Behaviour and Prestress Losses of BFRP Pretensioned Beams Under Sustained Loading. 10th International Conference on FRP Composites in Civil Engineering (CICE 2020/2021), Istanbul, Turkey, 8-10 December 2021. https://doi.org/10.1007/978-3-030-88166-5_31

[18] BSI (British Standards Institution). (2002). British Standard 12390-3:2002 Testing hardened concrete – Part 3: Compressive strength of test specimens

[19] ASTM D7205/D7205M Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars. USA