LOAD-BEARING CAPACITY, BOND BEHAVIOR, ENVIRONMENTAL IMPACT AND APPLICATION OF BFRP-REINFORCEMENT IN CONCRETE

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Because of its high tensile strength, high durability and comparatively low environmental impact reinforcement made of BFRP should be investigated on its usability as structural reinforcement. Further, there is the ability to increase the life span of concrete members due to the use of BFRP-reinforcement, what can also lower the environmental impact. Due to the fact that reinforcement products made of BFRP are not generally regulated normatively in Germany, there are many characteristics that have to be investigated experimentally. At the Kiel UAS experimental and numerical investigations on the flexural and shear capacity and the bond and cracking behavior of BFRP-reinforced concrete members were carried out. Based on this, specific applications where developed. As examples a BFRP-reinforced bridge cap made of RC-concrete and a ground plate with BFRP-reinforcement can be named. In conclusion we can say that the benefit of using BFRP-reinforcement depends on the application. Especially in corrosive milieu BFRP-reinforcement can be a useful alternative to steel-reinforcement.

Keywords: Non-metallic reinforcement, Flexural capacity, Shear capacity, Crack control.

1 INTRODUCTION

Due to its high tensile strength, high durability and comparatively low environmental impact BFRP-reinforcement can be a useful alternative to steel reinforcement. Compared to the usually used carbon and glass fiber reinforcements, basalt fiber reinforcement is characterized by the fact that it is significantly cheaper, the reinforced concrete is more recyclable and the CO₂ balance is better (Görtz et al. 2023). The ability to increase the life span of a concrete member can decrease environmental impact. Furthermore, the reduction of concrete requirements can allow the use of CO₂-optimized concrete mixtures.

In North America, ACI 440 and CSA S806 are guidelines that have been tried and tested over many years. In Germany, a guideline for non-metallic reinforcement is currently being prepared by the DAfStb (2023). Due to the fact that reinforcement products made of BFRP are not generally regulated normatively in Germany, there are many characteristics that have to be investigated experimentally. At the Kiel UAS experimental investigations on the flexural and shear capacity and the bond and cracking behavior of BFRP-reinforced concrete members were performed. Additionally, the results of the experimental investigation where simulated and compared to existing design approaches. Based on the result of the experimental and numerical investigations some specific applications where developed and dimensioned. As examples a BFRP-reinforced bridge cap made of RC-concrete and a ground plate with BFRP-reinforcement can be named.
2 LOAD BEARING CAPACITY / STRUCTURAL DESIGN

2.1 Flexural Capacity

The flexural capacity of FRP reinforced concrete can be determined by iterating the strain line similar to steel reinforced members. In order to simplify the design task, a general dimensioning diagram can be evolved as shown in Fig. 1 (right). The main difference compared to steel reinforcement is the linear-elastic material behavior of the FRP bars. Due to this behavior, the FRP reinforcement must reach its maximum tensile strength in ULS to be design economical. The stresses in reinforcement in dependency of the specific moment can be compared in Fig. 1 (right).

To verify the design approach 4-point bending tests (Görtz et al. (2023)), with two girders with a cross-section of b x h = 50 x 20 cm, a length of 4.0 m and different reinforcement ratios were carried out at Kiel UAS. The results are shown in Table 1.

2.2 Shear Capacity

Regarding to the shear capacity of members with FRP-reinforcement we have to differentiate between members with and without shear reinforcement.

For structural members without shear reinforcement, the shear capacity depends among other things on the modulus of elasticity of the longitudinal reinforcement. This becomes obvious when evaluating the approach according to Eurocode 2 for members with FVK reinforcement. Especially for lower moduli of elasticity the shear capacity will be overestimated. The modification of the equation according to EC2 with the factor $E_{nm} / E_s$ leads to an improvement of the results.

![Fig. 1. General dimensioning diagram for the BFRP reinforcement DBS B32 (left); stress of BFVK-reinforcement (DBS B32) and steel reinforcement (B 500) (right).](image-url)

![Table 1. Results of 4-point bending tests.](table-url)
In case of members with shear reinforcement the specific characteristics of formed FRP-reinforcement and the lower modulus of elasticity have to be considered. The lower modulus of elasticity leads to high strains in the stirrups. This causes a possible critical crack propagation in the uncracked compression zone (see Fig. 2 right). In some cases, the maximum tensile strain of the stirrups is not reached, because a flexure-shear failure occurred before. Further the effect of aggregate interlock is reduced. This leads to a steeper inclination of the concrete struts in the truss model. High tensile strains reduce the compressive strength of the concrete struts in the truss model. The load-bearing capacity of an FRP stirrup is generally significantly lower than that of a straight FRP bar. This can be caused by the manufacturing process. The fibers are difficult to bend around the corner, so the inner fibers can buckle. Due to the tensile stress in the two stirrup legs, there is a transverse compressive stress on the bar in the area of the bend (see Fig. 2 left). Since only the polymer matrix acts in the transverse direction, the load-bearing capacity is very limited here.

![Fig. 2. Improper manufacture and transverse pressure in the area of the bend of the stirrups (left) and crack propagation in the uncracked compression zone caused by high stirrup strains (right).](image)

### 2.3 Bond Behavior and Crack Control

The significant lower modulus of elasticity of BFRP reinforcement leads to larger deformations and larger crack width in serviceable limit state. Besides the modulus of elasticity, the bond behavior has an influence on crack width and deformation. To compensate for the influence of the lower modulus of elasticity the bond behavior can be improved. This can be achieved by profiling the bars with ribs on the sides (see Fig. 3).

![Fig. 3. Profiled BFRP bar DBS B32.](image)
In order to quantify the influence of bond behavior numerical investigations were carried out. The bond behavior of reinforcement bars can be characterized by a bond-strength-slip relation which is determined by pull-out tests. Based on those tests a bond-law was defined for the BFRP-bar DBS B32. Based on this bond-law crack width can be calculated using the differential equation of bond. By calculating different configurations varying the influence of bond strength (Fig. 4 left) and modulus of elasticity (Fig. 4 right) was quantified. The influence of the modulus of elasticity can be described as under-proportional while the influence of bond strength is approx. linear.

![Graphs showing the influence of bond strength and modulus of elasticity on crack width.]

Fig. 4. Influence of bond strength (left) and modulus of elasticity (right) on crack width.

In case of the BFRP-bar B32, it can be concluded that improved bond strength can compensate for the lower modulus of elasticity. In this case the bond strength is double the bond strength of steel reinforcement according to Fédération Internationale du Béton (2013), Fib Model Code for Concrete Structures 2010. Due to that fact only 1.7 times the crack width compared to reinforced concrete can be expected for the same reinforcement cross-section.

3 APPLICATIONS

3.1 General

Basalt fiber-reinforced components are particularly suitable in chloride-containing areas, where deflections are not decisive. Accordingly, some applications were developed in the following.

3.2 Ground Plate

As part of a project on zero waste architecture, a floor slab for an info point in the city of Kiel, see Fig. 5 left, was made of concrete with recycled aggregate and basalt fiber reinforcement (Fig. 5 right) (Schlüter 2023). Due to the low static loading the reinforcement had to be designed for crack control. As the reinforcement does not corrode, the crack width can be set at 0.4mm. Furthermore, the requirements for the concrete could be reduced due to the elimination of the reinforcement-side exposure classes.
Fig. 5. Zero Waste Info Point on the Rathausplatz of the city of Kiel (left), basalt fiber reinforcement of the ground slab (right).

3.3 Bridge Cap

As the objective of a research project a bridge cap with concrete with recycled aggregates and BFVK-reinforcement was developed. Bridge caps usually wear components which have to be replaced regularly. With the use of a non-corrosive BFRP reinforcement the durability can be improved, while the larger deformations are irrelevant. The results of the research work were applied in a prototype for a large-scale test as shown in Fig. 6. The developed design model could be confirmed here.

Fig. 6. Large-scale test of a bridge cap made of recycled aggregates concrete and BFVK reinforcement.

3.4 Shore Wall

It is planned to build a prefabricated element for the facing of a seawall. Due to the use of non-metallic reinforcement, the durability of the shell can be improved while the deformation and crack control are subordinate. Currently, the design has been carried out, the construction including the load test is scheduled for spring next year.
4 CONCLUSION

The investigations show that reinforcing bars made of basalt fiber-reinforced polymer can be a suitable alternative for many applications in corrosive areas. The experimental investigations show that the load-bearing behavior can be reliably described with existing design models, considering the relevant material properties. Pre-dimensioning yields economical design results for components in which deflection is not a factor.

References

DAfStb, Richtlinie Betonbauteile mit Nichtmetallischer Bewehrung, June, 2023 (in German).