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Fiber-Reinforced Polymers Based Rebar and Stirrup Reinforcing Concrete Structures

Marco Lindner, Konrad Vanselow, Sandra Gelbrich and Lothar Kroll
Faculty of Engineering, Technische Universität Chemnitz, Chemnitz 09107, Germany

Abstract: Fiber-plastic composites offer an interesting alternative to concrete reinforcement. In order to expand the application spectrum of reinforcing elements in fiber composite construction, a new steel-free bracing system with reduced radii of curvature has been developed. An improvement in load carrying capacity could be proven in extensive investigations based on international testing methods and verified by practical tests. With the help of newly reinforced precast concrete elements from the area of waterways and traffic routes, a high potential for lightweight construction and resource efficiency can be impressively demonstrated.

Key words: FRP (fiber-reinforced polymer) stirrup, basalt reinforced plastics with lower radii of curvature, concrete reinforcement.

Nomenclature

ACI:	American Concrete Institute
BFRP:	basalt fiber-reinforced polymer
CFRP:	carbon fiber-reinforced polymer
d_{BR}:	diameter of bend in FRP reinforcement, mm
d_b:	equivalent diameter of reinforcing bar, mm
E:	modulus of elasticity, MPa
f_{ub}:	bend capacity of the FRP stirrup, MPa
FRP:	fiber-reinforced polymer
FVC:	fiber volume content, Vol.-%
GFRP:	glass fiber-reinforced polymer
lb:	bond length, mm
s:	wall thickness of concrete elements, mm
u:	cutting gap, mm
x:	distance between component corner and reinforcement, mm

Greek letters

σ:	tensile stress, MPa
τ_{max}:	bond strength, MPa
τ_u:	shear strength, MPa

1. Introduction

Compact steel reinforced concrete elements are used in the construction sector, for example in the field of traffic area construction and hydraulic engineering, e.g. in sewers and wells. For transmission of loads by traffic loads, earth and water pressures such concrete components have a corrosion-susceptible steel reinforcement. To ensure corrosion protection in the concrete permanently, however, a minimum concrete coverage of several centimeters of the reinforcing bar is required and to very thick wall thicknesses with a significant increase in weight. The transportation to the operation site as well as the montage and especially the installation is affected by the high weight of the construction components [1]. Furthermore, steel-reinforced elements influence electric and magnetic fields, requiring special and expensive precautions, e.g. in railbound traffic area systems which are regulated by induction loops.

Explicitly in the field of internal concrete reinforcement FRP (fiber-reinforced plastic) components are rated as an important alternative to steel-based concrete reinforcement elements. The current state-of-the-art shows that primarily FRP reinforcements in linear form are produced made by pultrusion in combination with thermosetting polymer systems and glass, basalt, and carbon fiber (GFRP, BFRP, CFRP). These thermosetting matrix systems cannot be deformed after their hardening without

Corresponding author: Marco Lindner, research fields: reinforcement made of basalt fibers mainly for asphalt, concrete and polymer matrix.

damage as a result of the strong connectivity of the polymer chains. Thus, a subsequent flexure of the reinforcement, e.g. with energy supply, is excluded. The FRP stirrup reinforcements differentiate clearly from their characteristics in comparison to straight bars due to their design. The curved FRP stirrup reinforcements show a noticeably different fiber architecture and surface profiling resulting in significantly reduced compartment characteristics. Furthermore, the individual radii of curvature (d_{BR}) of the FRP reinforcements is process related restricted to a minimum of seven times the value of a bar diameter ($d_{BR} \geq 7d_b$) significantly narrowing the application range and complicating the acceptance on the market (Fig. 1) [2].

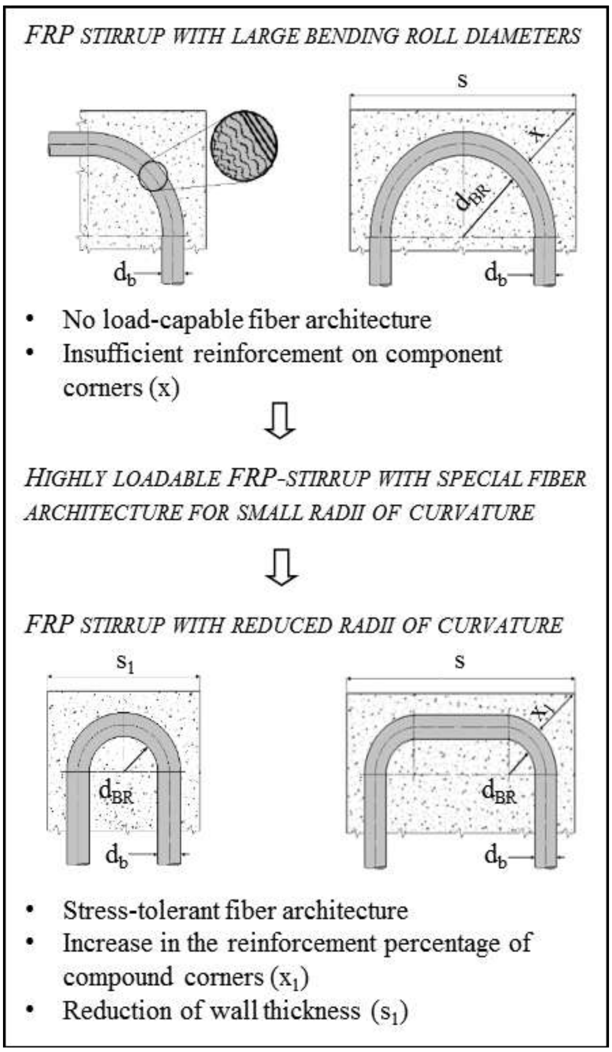

Fig. 1 State of the art and goal of the project.

In the course of the present paper FRP stirrup reinforcements with reduced radii of curvature with high load capacity as well as an extension of the calculation method for the constructive design of reinforcements were developed and subsequently validated by means of internationally accepted testing methods. These FRP stirrup reinforcements and the adjustment of the calculation method contribute to the economical manufacturing of thin-walled, highly stressable and permanent lightweight structures with mineral-bound matrixes and no influence on electromagnetic fields.

2. Experimental Setup

2.1 Raw Material

According to the state-of-the-art, aside from glass fiber (GFRP) also CFRP (carbon fiber-based reinforcement) bars were tested in concrete showing better mechanical characteristics in CFRP bars than that of GFRP bars, however, those are economically less suitable due to the comparably high semi-finish costs. The diversity of materials for FRP stirrups is only limited in glass fibers in combination with vinylester or epoxy resin.

The investigation of FRP stirrup reinforcement available on the market served as comparison to the developed highly stressable FRP stirrup reinforcements with reduced radii of curvature. The series of tests included two differently curved reinforcement profiles made of FRP as well as conventionally used concrete construction steel B500 B as reference sample. The investigated FRP stirrup reinforcements differed in their geometrical design of the image, the achievable radius of curvature, the fiber volume content, and their production technology (Fig. 2).

The manufacturer (Schöck Bauteile GmbH) of the first stirrup variant uses a production technology in which an impregnated fiber bundle is pulled through a corrugated plastic cladding tube, curved and subsequently hardened (name: GFRP cladding tube) [3].

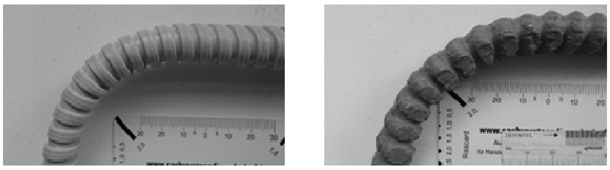

Fig. 2 Sample of FRP stirrup (left: GFRP cladding tube; right: GFRP winding.

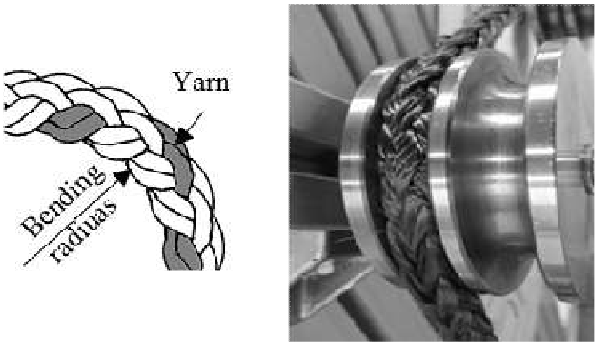

Fig. 3 Production BFRP stirrup (left: principle; right: forming process).

In this production technology formed, individual radii of curvature are limited to a minimum of seven times the value of the bar diameter [4]. A different technology is used in the second variant (FiReP Rebar Technology GmbH). In this technology the forming takes place by the entwining of a resin impregnated fiber bundle over pulleys (name: GFRP winding) [5]. The minimal bending roll diameter is eight times the value of the bar diameter ($d_{BR} \geq 8d_b$) [6].

2.2 FRP Stirrup with Structured Fiber Architecture

For the implementation of the objective and based on theoretical and numerically-supported models, a circular fiber architecture (basalt) was designed in which the inbound and external fibers lie rotationally in the bending range (Fig. 3, left).

This way of fiber arrangement theoretically provides a constant flat fiber stress in the profile crosssection, preventing for example wrinkling of the fiber layers in the inner bending range and a significantly smaller bending radius as the demanded seven times the value of the bar diameter ($d_{BR} \leq 7d_b$). This development is based on complex resin impregnation and wrapping tests in which a yarn should be generated with sufficiently good capillary action for the resin impregnation and simultaneously high crush resistance during the yarn deflection to be equipped for the beating and braiding process. In the braiding process, the twine is placed in a defined position.

The mechanical characteristics of basalt fibers in comparison to glass fibers are higher with regard to Young's modulus and tensile strength [7-9]. The fiber layer had to be rearranged in order to reduce the fibrillation and to withstand the high loads during the textile handling process. Fig. 3 shows the manufacturing process of the yarn, the semi-finish production process to the forming process (right).

After the subsequent resin impregnation and forming process (matrix epoxy resin; R & G EP L) with the help of a facility which was constructed for this purpose, the examination and quality control of the high-strength BFRP stirrups followed.

2.3 Analysis of Current Stirrup Reinforcements

The determination of the fiber volume content is one of the most important parameters for the evaluation of the mechanical characteristics of the FRP profiles. Furthermore, the FVC (fiber volume content) provides an important characteristic value and is the calculation basis for the dimensioning of the concrete elements. The determination of the FVC was reliably implemented by using the method of incineration (oxygen-reduced atmosphere). For this purpose, weighed test specimen were exposed to a temperature range (500 °C for CFRP and 625 °C for GFRP/BFRP) in which a pyrolytic decomposition of the plastic matrix took place. The resulting remains and the not decomposed fibers were weighed using a high precise scale [9]. The relation of the reinforcement fiber mass (remains) to the total mass of the fiber reinforced material results in the fiber mass portion which is then converted to the fiber volume content considering the different densities of the compound components. Additionally, for every profile a photomicrograph with a high-resolution light microscope was taken for the evaluation of the FRP reinforcement bars with regard to the fiber impregnation with the matrix system as well as for the illustration of the fiber orientation.

A tensile test with a traverse speed of 3 mm/min was performed to determine the modulus of elasticity and the tensile strength of the fiber composite (Fig. 4).

In order to ensure a meaningful measurement result, sleeves were attached to the clamping points of the sample body. These sleeves prevent the fiber from being damaged by the tensioning on the tensile testing machine and are used for the uniform transmission of force into the tensile specimen up to the specimen fracture.

2.4 Rebar-Concrete-Composite

For the application specific evaluation of the composite behavior between the FRP reinforcement elements (and conventional B500 B as reference sample) and the concrete matrix, pull-out-tests after the procedure of REHM and RILEM were chosen (Fig. 5). In addition to the determination of the characteristic value, the comparison contributes decisively to the further development of design methods with regard to the influence of the composite length.

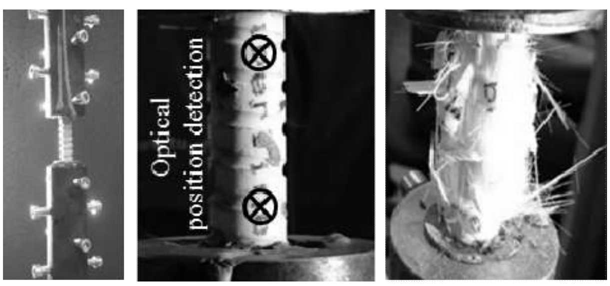

Fig. 4 Tensile test on FRP (left: sleeves for FRP-rebar; middle: detection of travel sensor; right: sample fracture).

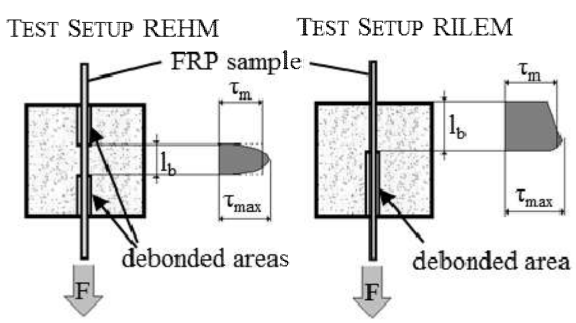

Fig. 5 Comparison of the test setups pull-out-tests (left: test setup REHM; right: test setup RILEM).

The experimental arrangement of both test procedures minimizes the unwanted influence of lateral load onto the reinforcement bar during the tensile tests. The structure of the test specimen after REHM and RILEM is basically a cubic concrete matrix with a concentric embedded reinforcement bar with a defined bonded length (REHM double bar diameter (*d*s) (Fig. 5, left); RILEM fivefold *d*s (Fig. 5, right)) [10-12]. According to REHM, by using two plastic sleeves the specimen is placed in a way that in tensile direction and in the opposing sides two debonded areas occur to the same extent. According to the experimental arrangement of RILEM, only one plastic sleeve is used at the load-absorbing side. The test ends with the reduction of force as failure criterion.

2.5 Approach to the Bending Range

Bended FRP stirrup reinforcements compared to straight profiles generally show lower tensile strengths compared to straight profiles. The tensile strengths are highly dependable on the radius of curvature (bending roller diameter d_{BR}) as in FRP reinforced concrete components the stirrup reinforcement is exposed to lateral load of the concrete matrix in its bending zones. For the determination of the stirrup tensile strength the experimental arrangement of the testing procedure is schematically shown in Fig. 6 [13, 14].

At first in the experimental procedure, the stirrup

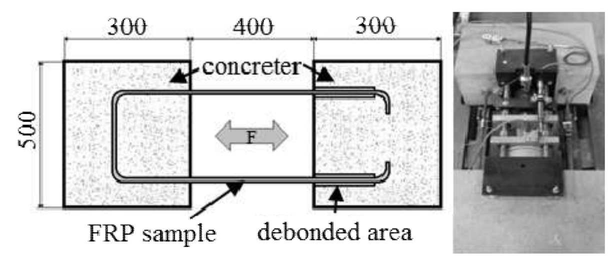

Fig. 6 Determination of stirrup tensile strength according to ACI Committee 440 Method B5 (left: test setup; right: hydraulic traverse with sensors).

ends are embedded into two concrete cubes, secondly, the tensile strengths are initiated by a hydraulic traverse. In order to minimize the unwanted influence of lateral loads onto the reinforcement stirrup, a defined bonded length is determined using sleeves. This way, the local distribution of the bond stress along the bond length can be consistently assumed. The test ends with the reduction of force as failure criterion in the bending range of the stirrup.

The test evaluation in regard to the determination of stirrup tensile showed that the stirrup test specimen failed due to a combined shear-tensile stress. Furthermore, in practice it cannot be ruled out eliminated that in the area of cracks of a concrete component a shear stress is transmitted to the FRP reinforcement could occur if a reciprocal dislocation arises due to unfavorable loads. Specifically for the determination of shear strengths a device (Fig. 7, [13]) was developed and produced simulating different crack sizes using adjustable cutting gaps. The tensile strength component will not be recorded in this shear test. For the implementation of the shear test the FRP bar specimen is put into the prism of the matrix and fixated by the downholder.

The complete cutting device is clamped into a compression-tension testing machine to determine the force-displacement curve. According to the directives of the ACI the cutting gap (*u*) was set on 0.1 mm and the measuring was realized until failure as abort criterion [14].

3. Experimental Results

3.1 Technical Characteristics

By the thermogravimetric examination, it was possible to verify that all samples of the batch BRFP stirrup have a very high fiber volumetric content of more than 55 Vol.-%. The determined fiber volume content of the samples GFRP winding was identical to that of the basalt fiber-based samples. On the other hand, the gels GFRP cladding tube showed a significant lower value of 37 Vol.-%. Furthermore, a good fiber-resin impregnation was obtained by evaluating at least 5 sample samples per sample batch.

One of the most important characteristic values for FRP reinforcement bars is the tensile strength and modulus of elasticity. In the following figure, the average values from the uniaxial tensile test are summarized (Fig. 8).

In a direct comparison between “GFRP winding” (E modulus 26.3 GPa; σ = 573 MPa) and “BFRP stirrup” (E modulus 30 GPa; σ = 634 MPa), it was shown that defined fibrous layers made of basalt lead to higher tensile strength and modulus of elasticity at the same fiber volume. The stretched fibers in the sample carrier GFRP cladding tube showed a significantly higher increase (E modulus 42 GPa) compared to the samples with an angular deviation, with a comparable tensile strength (σ = 671 MPa) of the developed basalt fiber based reinforcement stirrups.

Fig. 7 Determination of shear strength according to ACI Method B4 (left: scheme; middle: device; right: specimen after testing).

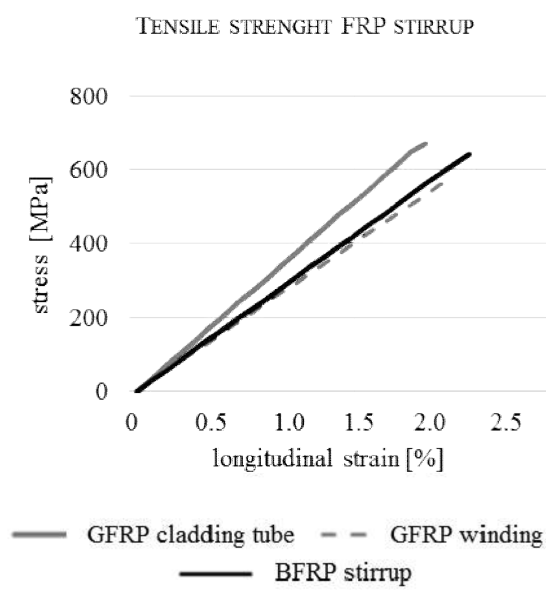

Fig. 8 Stress test FRP stirrups.

3.2 FRP Stirrup Reinforcement in Concrete Bond

The results of the investigation on the durability of the reinforcement in an alkaline environment showed that the present FRP reinforcement bars only demonstrate an extremely low change of mass (up to 1 percent of weight) during storage in the high alkaline matrix. Thus, all investigated FRP reinforcement bars can be seen as alkali-resistant.

For the application specific evaluation between FRP stirrup reinforcements and the concrete matrix conventional pull-out-tests (bond strength after REHM and RILEM) were performed (Fig. 9).

It could be verified that the scattering of the force (F_{max}) was higher in REHM (12%) as in RILEM (4%). It is to assume that in the experimental setup of REHM the existing imperfections inside the concrete or rather in the contact zone (concrete bar profiler) come into effect due to the much shorter bonding surface. Furthermore, the determined bonding stresses as well as their increase are much higher RILEM than REHM. As a result, all FRP samples showed significant differences in the determined values.

The determined failure criteria and maximum bond stress values until removal are summarized in Fig. 10

The illustrated curve shows a similar increase in the three different sample noises to the respective force drop. For the sample charge "GFRP cladding tube" a maximum bond stress of 19 MPa could be detected. Based on the exposed composite area, it could be proven that the thermoplastic resin-profiled plastic pipe was sheared off when the glass fiber-reinforced thermoset core was loaded. It is assumed that the shear strength of the thermoplastic tube is significantly involved in the GFRP cladding tube-concrete composite. The GFRP winding batch was characterized by a higher bond stress (22 MPa). The highest bond stress showed with 30 MPa the straps BFRP stirrup. In both batches a good training of the concrete consoles could be proven.

To assess the suitability as reinforcement brackets, the values determined from the tensile strength test in Fig. 11 are shown.

The stirrup tensile strength in the BFRP stirrup specimen was approx. 725 MPa (d_{BR} = 4d_b; conventional FRP stirrups up to f_{ub} = 675 MPa) with much lower bending radius.

The determined shear strength of the sample batch with inserted fiber layers in "GFRP cladding tube" (τ = 224 MPa) and the angle deviation "GFRP winding" (τ = 214 MPa) of a matrix of vinyl ester resin were in the same range of values. On the other hand, a low shear strength (BFRP stirrup τ = 160 MPa) was found for the sample batches prepared with epoxy resin for hand laminates. Thus it could be shown that the shear

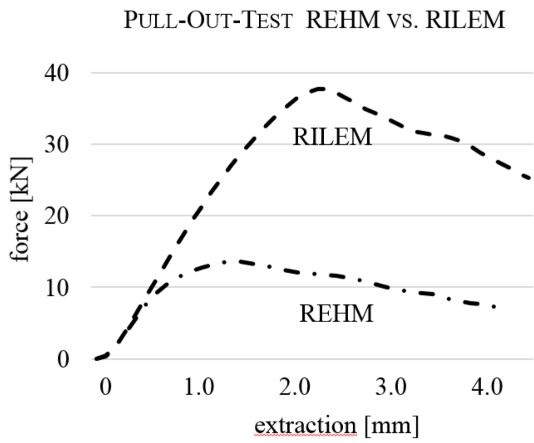

Fig. 9 Pull-out-test after REHM vs. RILEM (example B500 B).

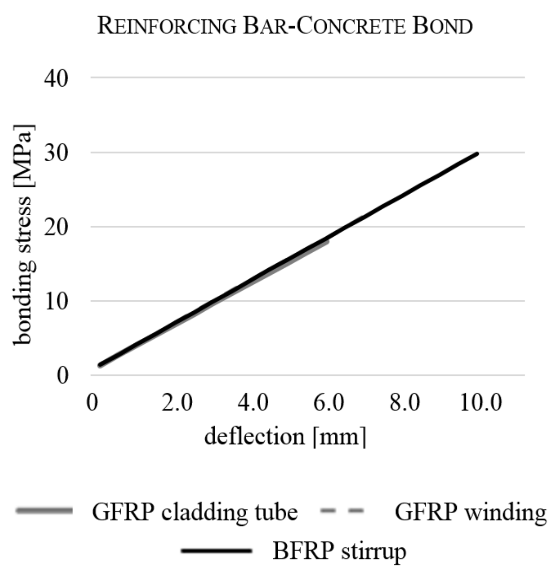

Fig. 10 Summary reinforcing bar-concrete bond.

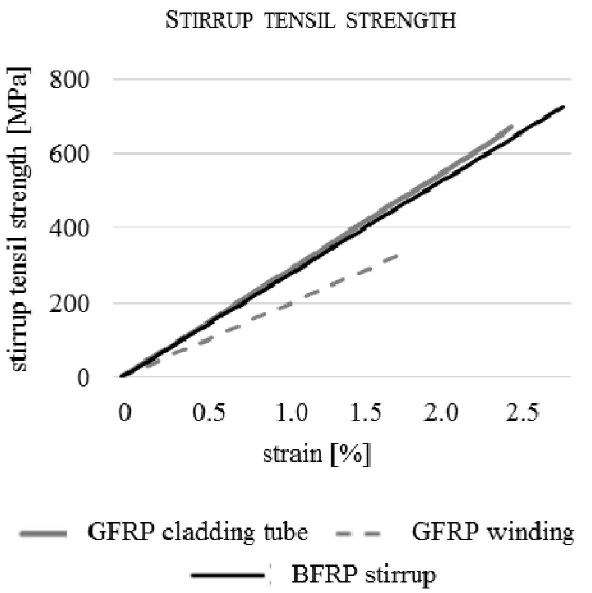

Fig. 11 Stirrup tensile strength.

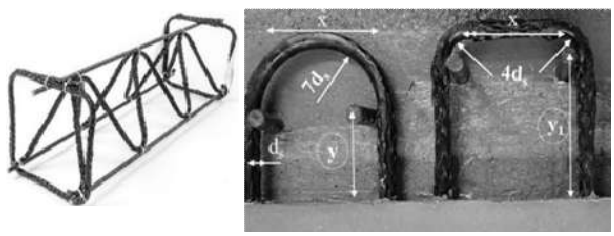

Fig. 12 BFRP stirrup (left: BFRP reinforing basket; right: comparison of FKV reinforcement with large and small radii of curvature).

behavior is decisively dependent on the resin matrix of the test specimen.

4. Conclusions

In the course of this investigation it was clearly shown that the new developed stirrup reinforcements made of basalt reinforced plastics with lower radii of curvature have in comparison to the to date FRP stirrups according to the state-of-the-art today much higher potential. This primarily concerns the reduction of radius of curvature with simultaneous significant increase of stirrup tensile strength, the increase of durability characteristics and thus an improvement of the cost- and resource-efficiency of precast concrete parts.

Another advantage of the BFRP stirrup reinforcements is that aside from the corrosive resistance there is no electronic conductivity. This makes the reinforcement especially interesting for traffic areas with induction loops as the occurrence of stray current is completely ruled out. This makes the reinforcement especially interesting for traffic areas with induction loops as the occurrence of stray current is completely ruled out. Fig. 12 (left) shows a pattern BFRP reinforcing cage. Moreover, the bending roll diameter could be reduced by half (from $7d_b$ to $4d_b$, Fig. 12 right).

This potential was verified in tests. Thus, the future application of BFRP stirrup reinforcements opens a variety of new application fields for lighter and more efficient construction.

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