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Fibre-reinforced polymer stirrup for reinforcing concrete structures

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Keywords

Basalt Fibre, Concrete Reinforcement, FRP Stirrup, Rebar, Reduced Radii of Curvature

Abstract

Fibre-plastic composites offer an interesting alternative to concrete reinforcement. In order to expand the application spectrum of reinforcing elements in fibre composite construction, a new steel-free bracing system with reduced radii of curvature was 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.

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 the transmission of loads by traffic loads, earth and water pressures, such concrete components have a corrosion-prone steel reinforcement. To ensure long-term corrosion protection in the concrete, however, a minimum concrete covering of several centimetres of the reinforcing bar is required, which leads 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 are 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 rail-bound traffic area systems which are regulated by induction loops.

Especially in the field of internal concrete reinforcement, fibre-reinforced plastic (FRP) components are rated as an important alternative to steel-based concrete reinforcement elements. The current state of the art shows that FRP reinforcements in linear form in particular are produced by pultrusion in combination with thermoset polymer systems and glass, basalt, and carbon fibres (GFRP, BFRP, CFRP). These thermoset matrix systems cannot be deformed without damage after curing as a result of the strong connectivity of the polymer chains. Thus a subsequent bending of the reinforcement, e.g. during energy supply, is excluded. The FRP stirrup reinforcements differ clearly in their characteristics in comparison to straight bars due to their design. The curved FRP stirrup reinforcements show a noticeably different fibre architecture and surface profiling resulting in significantly reduced compartment characteristics. Furthermore, the individual radii of curvature (d_{BR}) of the FRP reinforcements are 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 (figure 1, [2]).

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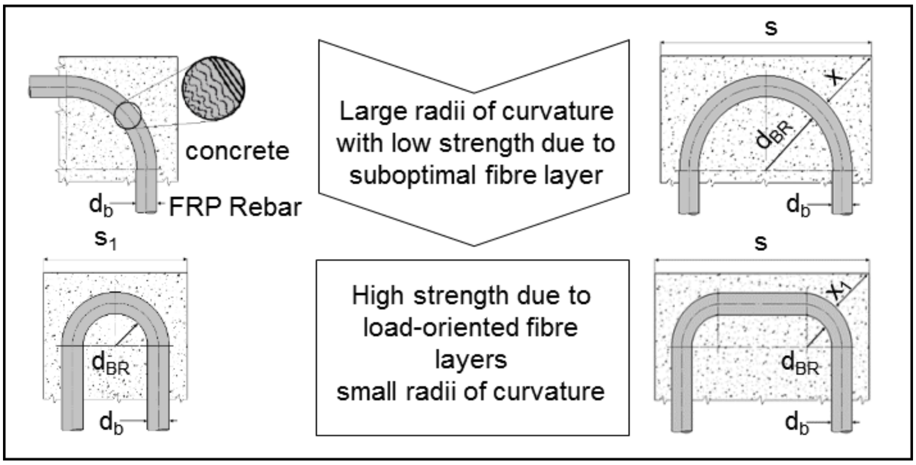

Figure 1: State of the art and goal of the project

In the course of the present paper, FRP stirrup reinforcements with reduced radii of curvature at high load-bearing capacity as well as an extension of the calculation method for the structural 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 durable lightweight structures with mineral-bound matrixes and no influence on electromagnetic fields.

2 Experimental Setup

2.1 Reference Material

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 samples. The investigated FRP stirrup reinforcements differed in their geometric design of the image, the achievable radius of curvature, the fibre volume content, and their production technology (figure 2).

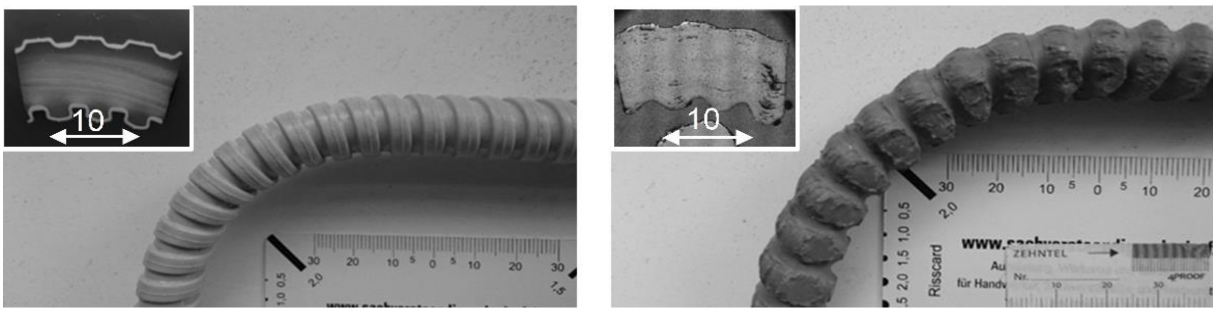

Figure 2: Sample of FRP stirrup (left: GFRP cladding tube, right: GFRP winding)

The manufacturer of the first stirrup variant uses a production technology in which an impregnated fibre bundle is pulled through a corrugated plastic cladding tube, bent and subsequently hardened (name: GFRP cladding tube, [3]). The individual radii of curvature formed in this production technology are limited to a minimum of seven times the value of the bar diameter [4]. A different technology is used in the second variant. With this technology, forming takes place by the interweaving a fibre bundle impregnated with resin (vinyl ester resin [5]) via pulleys (name: GFRP winding, [5]). The minimum bending roll diameter is eight times the value of the bar diameter ($d_{BR} \geq 8d_b$, [6]).

2.2 FRP stirrup with structured fibre architecture

To realise the objective and based on theoretical and numerically supported models, a circular fibre architecture (basalt) was designed in which the inbound and external fibres lie rotationally in the bending range (figure 3, left).

This way of fibre arrangement theoretically provides a constant flat fibre stress in the profile cross-section preventing for example wrinkling of the fibre layers in the inner bending range and a significantly smaller bending radius than the required sevenfold 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 is to be generated which has a sufficiently good capillary action for the resin impregnation and simultaneously a high crush resistance during the yarn deflection in order 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 fibres in comparison to glass fibres are higher with regard to young's modulus and tensile strength [7, 8, 9]. The fibre layer had to be rearranged in order to reduce the fibrillation and to withstand the high loads during the textile handling process. Figure 3 shows the manufacturing process of the yarn, the semi-finish production process (centre) as well as the forming process (right).

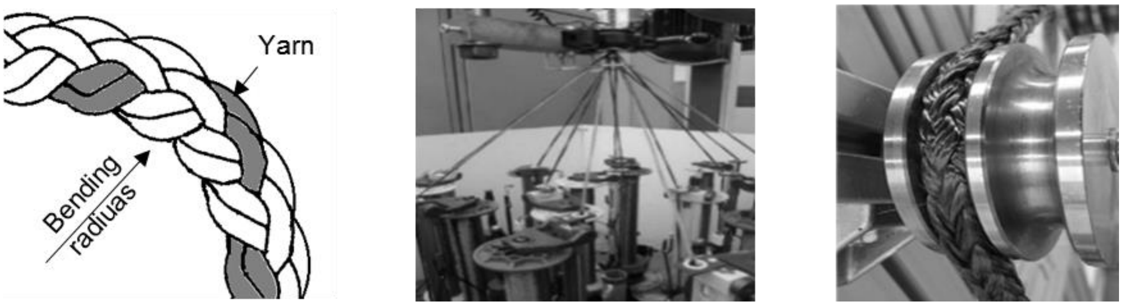

Figure 3: Production (left: principle, centre: semi-finish production, right: forming process)

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 fibre volume content is one of the most important parameters for the evaluation of the mechanical characteristics of the FRP profiles. Furthermore, the fibre volume content (FVC) provides an important characteristic value and is the calculation basis for the dimensioning of the concrete elements. The FVC was reliably determined 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 takes place. The resulting remains and the undecomposed fibres were weighed using a high-precision scale [9]. The ratio of the reinforcing fibre mass (remains) to the total mass of the fibre-reinforced material yields the fibre mass fraction, which is then converted into the fibre volume content taking into account the different densities of the composite components. Additionally, for every profile a photomicrograph was taken with a high-resolution light microscope for the evaluation of the FRP reinforcement bars with regard to the fibre impregnation with the matrix system and to visualise the fibre orientation.

A tensile test on bars with a traverse speed of 3 mm/min was performed to determine the modulus of elasticity and the tensile strength of the fibre composite [10]. In order to ensure meaningful measurement results, sleeves were attached to the clamping points of the sample body. These sleeves prevent the fibre from being damaged by the tension on the tensile testing machine and are used for the uniform transmission of force into the tensile specimen until the specimen fractures.

An investigation of the accelerated aging of the FRP reinforcement bar elements in an alkaline environment was performed for the evaluation of the steel-free bars in concrete as well as the long-term FRP concrete composite behaviour. The alkali resistance of the FRP reinforcement bars was tested using a molar sodium hydroxide solution in which the test specimen lay for 28 days at 40°C. In order to determine the alkali resistance, the loss of mass was investigated during the tests [10, 11, 12].

2.5 Approach to the bending range

Curved FRP stirrup reinforcements generally exhibit lower tensile strengths compared to straight profiles. The tensile strengths are highly dependent on the radius of curvature (bending roll diameter d_{BR}) as in FRP-reinforced concrete components the stirrup reinforcement is exposed to the lateral load of the concrete matrix in its bending zones. The experimental arrangement of the testing procedure for the determination of the stirrup tensile strength is schematically shown in figure 4 [13, 14].

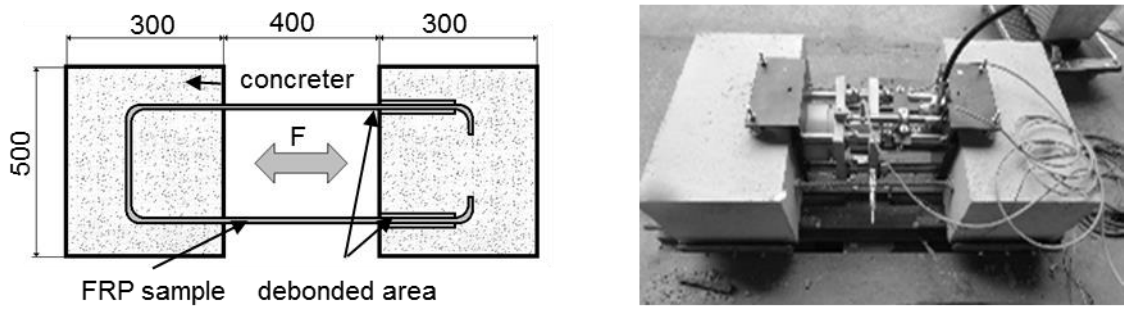

Figure 4: Determination of the stirrup tensile strength according to ACI Committee 440 Method B5 (left: test setup, right: hydraulic cross beam with sensors)

First in the experimental procedure, the stirrup ends are embedded into two concrete cubes, then the tensile stresses are initiated by a hydraulic cross beam. In order to minimise the unwanted influence of lateral loads on the reinforcement stirrup, a defined bond length is determined using sleeves. In this way, the local distribution of the bond stress over the bond length can be consistently assumed. The test ends with the reduction of force as a failure criterion in the bending range of the stirrup.

The test evaluation in regard to the determination of the stirrup tensile strength showed that the stirrup test specimen failed due to a combined shear-tensile stress. Furthermore, in practice it cannot be ruled out that in the area of cracks in a concrete component a shear stress will be transmitted to the FRP reinforcement if a mutual displacement occurs due to unfavourable loads. A device (figure 5, [14]) was developed and produced especially for the determination of shear strengths and the simulation of different crack sizes using adjustable cutting gaps. The tensile strength component is not recorded in this shear test. To perform the shear test, the FRP bar specimen is put in the prism of the matrix and fixated by the hold-down device.

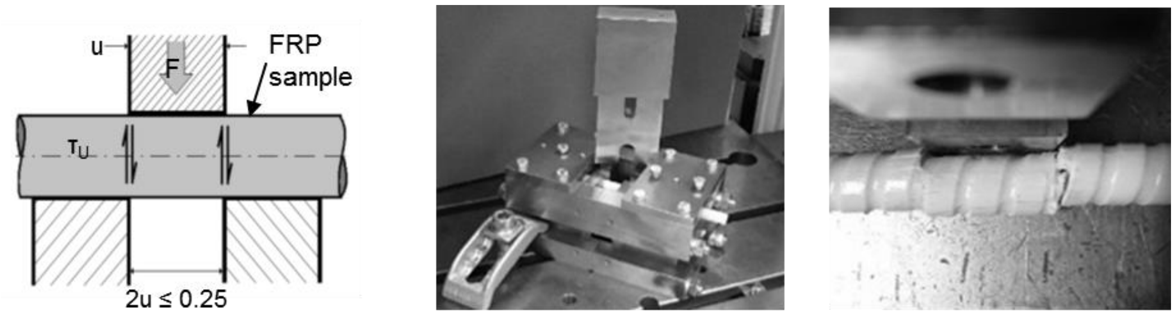

Figure 5: Determination of shear strength according to ACI Method B4 (left: diagramme, centre: device, right: specimen after testing)

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 measurement was carried out until failure as a break-off criterion [14].

3 Experimental Results

3.1 Technical characteristics

Through the thermogravimetric examination, it was possible to verify that all samples of the batch of BRFP stirrups had a very high fibre content of more than 55 Vol.-%. The determined fibre volume content of the GFRP winding samples was identical to that of the basalt fibre-based samples. On the other hand, the gels GFRP cladding tube showed a significantly lower value of 37 Vol.-%. Furthermore, a good fibre-resin impregnation was obtained by optically (microscopically) 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 the modulus of elasticity. In the following figure, the average values from the uniaxial tensile test are summarised (figure 6).

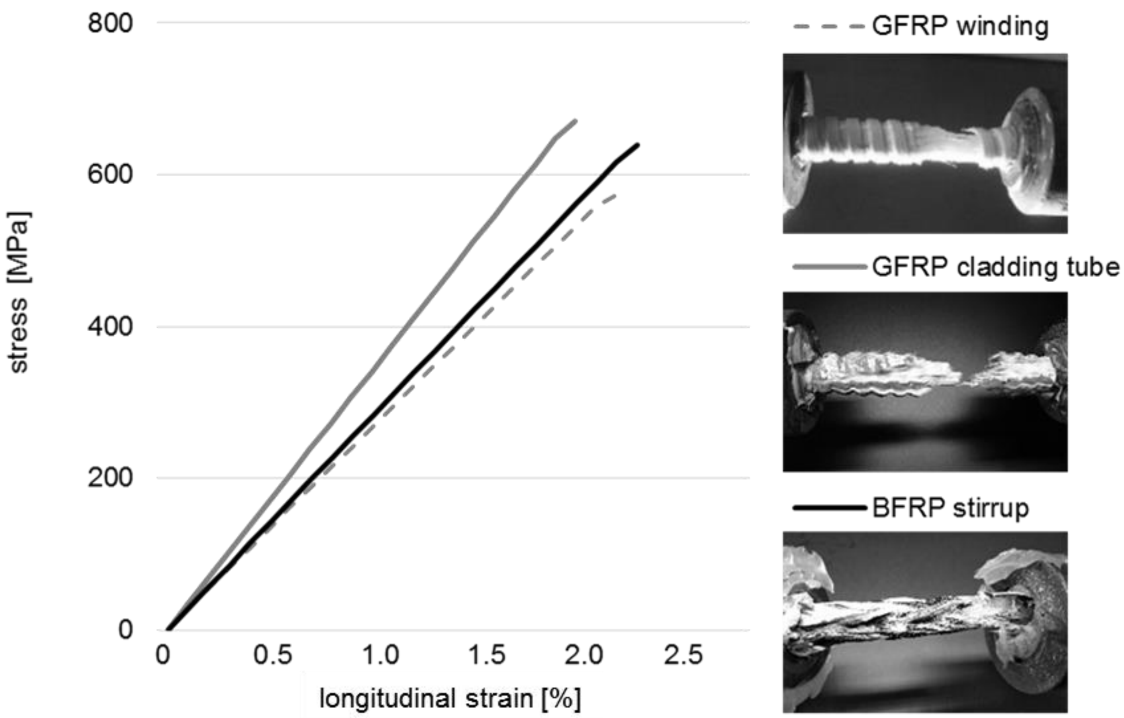

Figure 6: Uniaxial tensile test

Two of the most important characteristic values for FRP reinforcement bars are the tensile strength and the modulus of elasticity. 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 fibre volume. The stretched fibres in the sample carrier GFRP cladding tube showed a significantly higher increase (E modulus 42 GPa) compared to the samples with angular deviations, with a comparable tensile strength (σ = 671 MPa) of the developed basalt fibre-based reinforcement 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 existing FRP reinforcement bars only demonstrate an extremely low change of mass (up to 1 percent of weight) during storage in the highly alkaline matrix. Thus, all investigated FRP reinforcement bars can be regarded as alkali-resistant.

To assess the suitability as reinforcement brackets, the values determined from the tensile strength test are shown in figure 7.

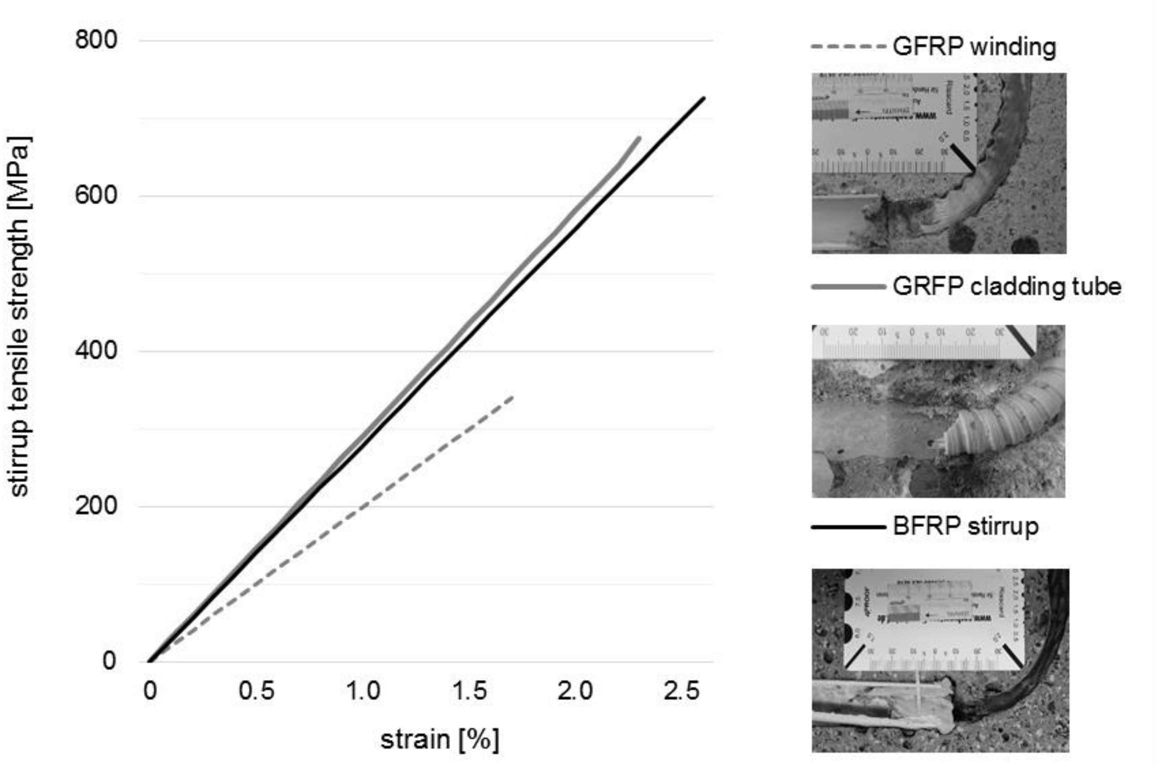

Figure 7: Tensile strengths in the curve area

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 a much lower bending radius.

The determined shear strength of the sample batch with inserted fibre layers in the "GFRP cladding tube" (τ = 224 MPa) and the angular deviation "GFRP winding" (τ = 214 MPa) of a matrix made 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 behaviour is decisively dependent on the resin matrix of the test specimen.

3.3 Reference

On the basis of the successful investigations on a laboratory scale, the construction of reference objects for practicable assessments followed. In this case, an angle support element (ASE) for rail-bound traffic surface constructions with the new BFRP bar reinforcement was created as a reference object (figure 8).

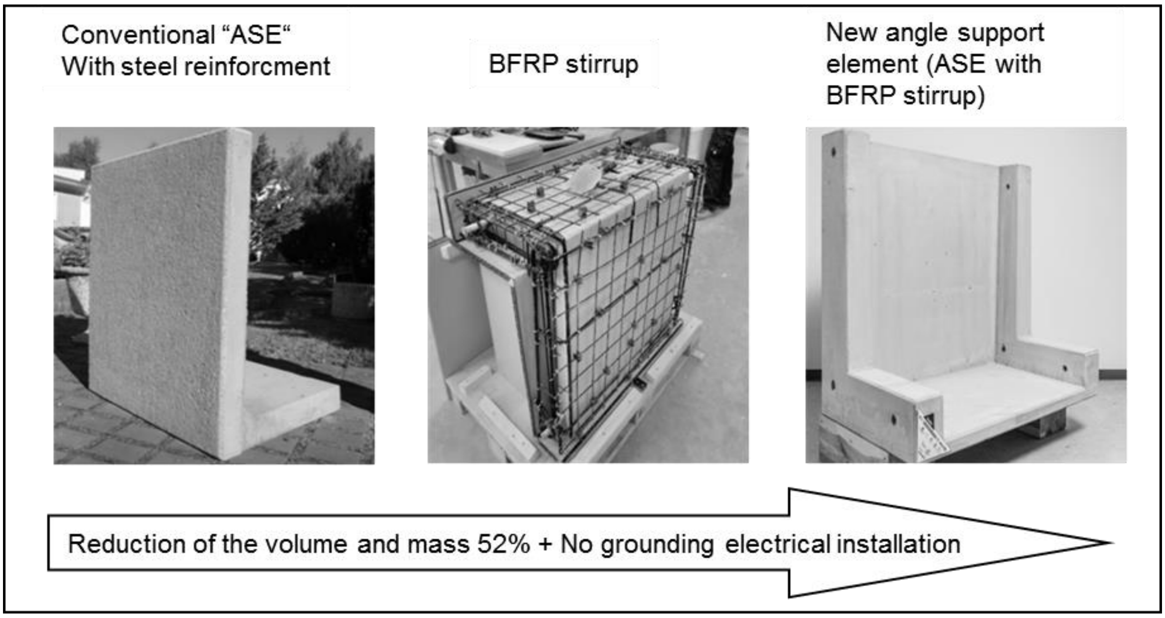

Figure 8: Reference

In summary, it can be shown that the newly developed ASE has a significantly more filigree component structure due to the special arrangement of the basalt fibre rod deflection with the same load-bearing capacity properties. Thus, the vertical and horizontal mirror surface can be reduced to a maximum thickness of d = 35 mm depending on the largest grain in the concrete matrix due to the low concrete coverage. Compared to conventional ASE with the same basic dimensions, this results in a volume and mass savings of approx. 52%.

4 Conclusions

In the course of this investigation it was clearly shown that the newly developed stirrup reinforcements made of basalt-reinforced plastics with lower radii of curvature have a much greater potential in comparison to the FRP stirrups according to the current state-of-the-art. This applies primarily to the reduction of the radius of curvature with a simultaneous significant increase of stirrup tensile strength, an increase in 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. Figure 9 (left) shows a pattern of a BFRP reinforcement cage. Moreover, the bending roll diameter could be reduced by half (from $7d_b$ to $4d_b$, figure 9 right).

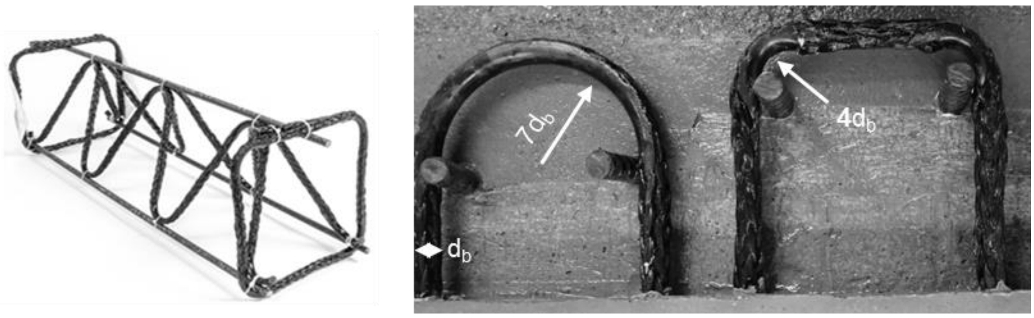

Figure 9: Comparison of FKV reinforcement with large and small radii of curvature

This lightweight potential has been verified in tests. Thus, the future use of BFRP stirrup reinforcements opens a variety of new application fields for lighter and more efficient constructions.

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