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A REVIVAL IN FAÇADES: TEXTILE REINFORCED CONCRETE PANELS ARE LIGHT, SAFE AND AESTHETICALLY PLEASING

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Abstract.
Textile reinforced concrete was developed in recent years into a construction technique that has its benefits and advantages in applications where conventional types of reinforcement have their limits. The current, minimum slab thickness for steel-reinforced concrete façade slabs is 7.0 cm; this is due to the minimum, required concrete cover to ensure adequate corrosion protection. Façade slab anchors for these slab thicknesses are building authority approved. As corrosion protection is not an issue for textile reinforced concrete, the minimum thickness for the concrete cover can be significantly reduced. The requirement for component thickness is now determined by the load-bearing capacity and by production-related boundary conditions. For practical building reasons, panel thicknesses of 3.0 cm have proven to be the best choice. Compared to steel-reinforced façade panels, this is a weight and thickness reduction of almost 60%. Thin concrete elements are of great interest in cases when the thickness or the weight of the panels is largely limited e.g. because of adjoining concrete elements in renovation or upgrade projects, retrofitting or improvements. Compared to other building materials, concrete has characteristic advantages in building physics and fire protection properties, irrespective of the thickness. Obviously, minimal thicknesses place extra demands on planning and construction. Especially effects on concrete, punching, splitting and concrete breakout must be examined in experiments. This is an overview of calculation and test methods. Results are provided to show the bearing behaviour of fixings in thin, textile reinforced concrete slabs. The design rules are explained and the results are illustrated.

Keywords: Building innovation, carbon reinforced concrete façades, fixings, new materials, textile reinforced concrete.

1. Introduction

Currently, more than half of the world's population lives in cities. In 2050, this figure is expected to rise to two thirds. This will lead to a strong increase in the density of urban spaces, which in turn will lead to a high demand for façade constructions that are efficient in terms of raw materials and space. The general availability of raw materials, sufficient load-bearing capacity and durability, as well as the ease of production have made reinforced concrete the building material of the 20th and the beginning 21st century. In 2017, approximately 4.3 billion tonnes of cement, 28.6 billion tonnes of aggregates and 2.85 billion tonnes of water were used to produce concrete [1]. And this is the other side of the coin of the universal building material concrete: no other material is responsible for greater raw material extraction and higher CO_2 emissions. The huge quantities of concrete used worldwide are particularly problematic. If it were possible to achieve a leaner design through a new type of construction, considerable savings could be achieved - carbon concrete offers this potential. Reinforcing structures (grids) made of carbon fibers can already be used today to replace some steel reinforced concrete applications in new buildings, i.e. to achieve greater resource and energy efficiency [2]. In addition, it is possible to repair solid structures in need of renovation by means of reinforcing layers of carbon concrete, thereby increasing their service life. For architects and designers, carbon concrete and other types of textile-reinforced concrete offer great design freedom, as they can be used to produce any shape, format, surface structure and colour in high quality. Furthermore, additional functions such as heating, lighting or building automation can be integrated into the components. Due to the arrangement of the reinforcement according to the force distribution, components made of textile concrete also require less reinforcement than conventional, fibre-reinforced concrete, in which cut short fibres made of glass, plastic or carbon fibre are introduced into the concrete mix in a non-directional manner.

In Germany, experiments with reinforcement made of technical textiles were already being carried out in the 1980s. The first joint research projects in Dresden, Chemnitz and Aachen followed in the mid-1990s. They formed the basis for two DFG-funded Collab-

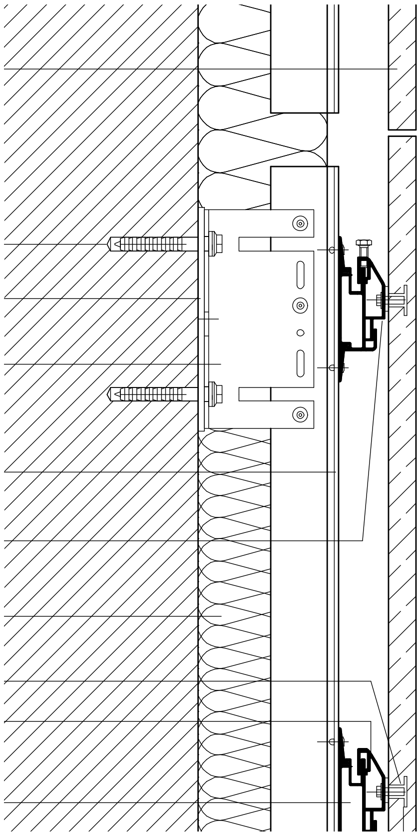


Figure 1. Principle cross-section curtain wall façade.

Figure 2. Carbon reinf. concrete façade white concrete - curtain wall.

orative Research Centres in Dresden [3] and Aachen [4], in which basic research in the field of non-metallic reinforcements was advanced between 1999 and 2011. In what is currently the largest German construction research project C3 - Carbon Concrete Composite - more than 150 partners from science and industry are working on the development and market launch of carbon concrete.

Carbon concrete will change the construction world, the technology is already there and is gradually being used in more and more areas of construction due to its advantages. The first applications have been realized in the field of façades, in addition to the repair of reinforced concrete structures. Through the further development of the components concrete matrix and carbon reinforcement of the composite material, further fields of application can now be opened up. Carbon concrete offers the possibility to rethink old approaches in the building industry.

2. Carbon reinforced concrete

In reinforced concrete, the concrete primarily absorbs the compressive forces occurring in the component and the reinforcing steel compensates for tensile stresses. In addition, the concrete cover protects the steel against corrosion, corrosion-promoting media (e.g. de-icing salts) and fire. Depending on the paving situation, the concrete cover course must be up to 5 cm thick. In the case of carbon concrete, carbon, as the equivalent of steel reinforcement, ensures the tensile strength of the composite material. The principles and design bases are very similar to those of reinforced concrete. Since carbon is about six times more load-bearing (3000 instead of 500 N/mm^2 tensile strength) and four times lighter (1.8 instead of 7.8 g/cm^3) than steel and also does not corrode, this reinforcement allows a much freer design. Since the corrosion protection for the reinforcement is no longer required, concrete slabs for façade cladding, for example, can be produced with a thickness of 2 cm instead of the previous minimum of 7 to 10 cm [5]. Even thinner layers are sufficient for reinforcing existing reinforced concrete components. Currently, filigree mat-like structures made of one or more layers of multifilament yarns (rovings) are used for reinforcement. Rovings in turn consist of several thousand individual filaments (fibres). Since the fabrics are relatively soft, they can be used to produce almost any shape. However, for entire structures, rod-shaped reinforcements will be required in the future. Various research institutes and industrial companies in Germany are currently working on the development of suitable carbon rods. In addition to carbon, fibers made of AR glass are becoming increasingly important for multifunctional applications. These are somewhat less load-bearing (1500 N/mm^2) and durable than carbon fibers, but are significantly less expensive. Furthermore, unlike carbon, they do not conduct electricity, but are good light guides. Up to now, normal-strength or high-strength fine concrete with a grain size of 1 to 8 mm was used as concrete - depending on the component and application. This is also a difference to steel reinforced concrete, where grains up to 32 mm in diameter are common. This concrete matrix is particularly suitable for thin building components such as façade panels [6].

3. Carbon concrete façades

For façade construction, carbon-reinforced concrete elements offer the advantage that they have very uniform, fine-pored and sharp-edged surfaces and can be produced much slimmer and lighter than steel re-

Figure 3. Storey-high façade element with new fixing system for carbon reinforced concrete.

Figure 4. Construction of the façade in Dormettingen (GER).

inforced concrete elements. The reduction in weight leads to greater economic efficiency in production and transport and reduces environmental pollution. The elements are mainly used for curtain wall rear ventilated façades (Figure 1). Furthermore, the panels are suitable for the production of particularly slim sandwich façades. The first office and commercial building with a curtain-wall ventilated façade made of carbon concrete was completed in Neumarkt in 2016. The 2.88 * 4.48 m large façade elements here are only 30 mm thick. A reinforced concrete facing layer would have been around three times as thick at this point. The white concrete façade elements on a modular single-family house in Leipzig are also only 30 mm thick and reinforced with a carbon fiber fabric (Fig. 2). The panels are up to 0.75 × 3.00 m in size and are held in place by a clasp system. An office building in Essen shows the possibilities of three-dimensional surface design. Here, too, a curtain-wall, rear-ventilated façade was realized, whereby the concrete slabs are anthracite-colored throughout and provided with a binary code with the help of a formwork matrix. A fair-faced concrete façade element only 11 cm thick with passive house insulation standard (0.15 W/m^{2}K) was developed within the framework of the research project "vakutex - vacuum-insulated façade elements made of textile concrete" in Leipzig [7]. The non-load-bearing sandwich element has similar physical properties as a four times thicker reinforced concrete element. This results in floor space gains of up to 15 % for the same building cubature. For the implementation of the first projects in the façade area, approvals were required in individual cases. In order to make this easier, general building authority approvals were obtained, which allow the approved component to be used throughout Germany. Façade elements have also been used in non-European countries. The pylons of the new Bosporus Bridge Yavuz-Sultan-Selim were clad with textile and carbon concrete façade elements at a height of 326m.

For the further practical suitability of the technology, a façade anchor system was developed which is particularly suitable for large-format thin (min. $d = 3$ cm) concrete elements. With this system, concrete façade panels and ventilated façades made of textile and carbon reinforced concrete can be easily installed and adjusted. This technology has already been implemented in a practical project, the Schiefererlebnis in Dormettingen (Germany). (Figure 3 and 4) This shows that carbon-reinforced concrete technology has arrived in practice.

4. Fixtures in concrete

After the bearing construction is erected, the façade panels will be fixed. Inserts are necessary for handling and support to provide a safe connection between the bearing construction and the panels. The general approach to calculate anchors in concrete is the CC (Concrete Capacity) method [8, 9]. The mechanisms of load-transfer from a steel anchor into the concrete are either mechanical interlock, friction or bond. Anchors can be cast-in-place or post installed. Usually, cast-in anchors are fixed by mechanical interlock whereas post installed anchors, such as dowels placed in a drilled hole introduce a load by friction or bond. Raising the load and assuming the anchor material is strong enough to carry the tensile load, the fixing fails because the tensile capacity of the concrete is exceeded. This failure mode has a shape of a cone with a slope of approximately 35° from the horizontal. The concrete cone failure load is proportional to $h_{ef}^{1,5}$, where h_{ef} is the effective anchorage depth, the depth where the anchor introduces the load into the concrete. The concrete capacity method is based on calculation of this failure cone. The cone capacity can be influenced by geometry of the concrete member, by reinforcement or by additional cracks.

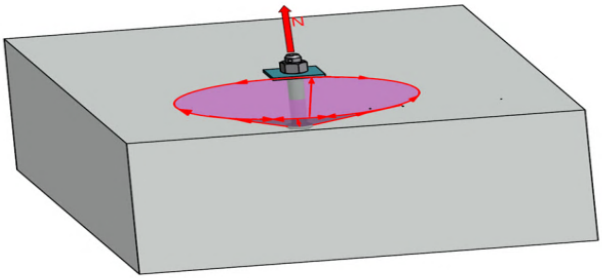


Figure 5. Stress distribution in uncracked concrete.

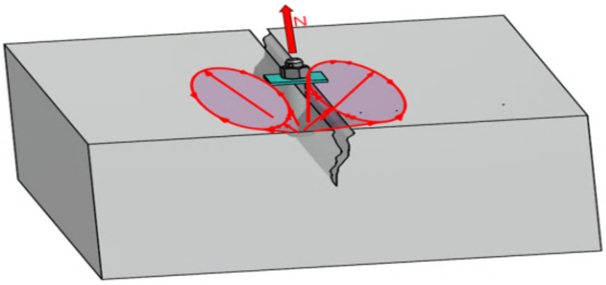


Figure 6. Stress distribution in cracked concrete due to splitting.

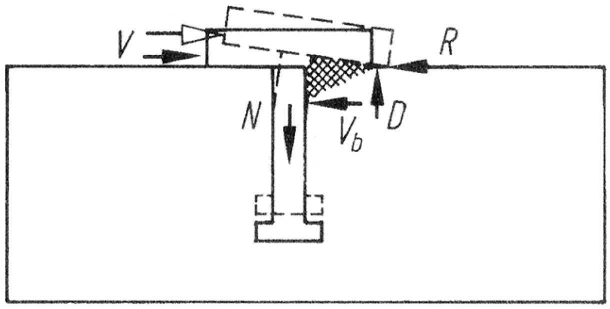


Figure 7. Supporting mechanism of a head bolt anchorage due to shear load (Eligehausen, Mallée & Silva 2006)

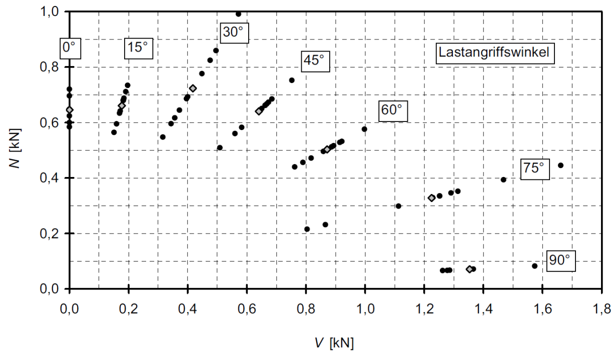


Figure 8. Load capacity depending on the relation between axial / lateral load, (DAfStb 2008).

5. Experimental approach

Tests have been carried out to investigate the support behaviour of fixings in thin concrete slabs: calculations according to the CC-Method set the minimum depth of anchorage at $h_{ef} \geq 25$ mm. This minimum anchor depth is not feasible for applications with CARBON REINFORCED CONCRETE and the calculation method should be reviewed for the use case of thin slabs. Tests were carried out to extend the effective range of the anchors for short depths. These tests were carried out on thin concrete panels, with and without reinforcement.

5.0.1. Punctual fixings

Additionally to [10], tests with headed bolts installed in 30 mm thick concrete plates were carried out to investigate the bearing behaviour of anchors installed in thin plates.

Bolts were installed at the maximum feasible anchorage depth and the shaft diameters and different head sizes varied. All bolts were tested in tension. First results were published in [11], additional test series followed. Unexpectedly large scatterings of the test results were observed in all test series. These results were not sufficiently reliable due to a coefficient of variation well in excess of 20 %. Despite the observed tendency for the resistance of concrete fracture bodies to depend directly on the lateral area, it was not possible to derive a practically applicable mathematical rule for this dependence. The cause of these large scatterings can be attributed to the fracture mechanism itself. The order of crack initiation was assessed, and it was found that the initial surface cracks occurred during the test. The final failure of the anchor is almost always due to splitting rather than the expected failure of the concrete. The failure mechanism of splitting is shown in Figure 6. The compressive load introduced into the concrete by the anchor head results in tensile stresses near the surface of the concrete member, as shown in Figure 5. If initial cracking occurs near the anchor due to bending stress in the concrete, further splitting stresses will open the cracks and reduce their resistance.

Therefore, fixtures which are sensitive to splitting failures will have a lower resistance value and a higher variability of test results.

If a fixture is sensitive to splitting, a corresponding coefficient should be introduced [12]:

$$\Psi_{h,\,sp} = \left(\frac{h}{2 \cdot h_{ef}}\right)^{2/3} \leq 1.0 \qquad (1)$$

This factor reduces the basic resistance $N_{Rk,c}$ in case when $h < 2\,h_{ef}$.

When additional shear forces are applied to the concrete, the tensile load component of the headed anchor increases (see Figure 7). This additional load component can lead to so-called prying failure, which also leads to a reduction in the overall tensile resistance.

This effect is investigated in Figure 8 [10]. Loads were applied to the anchors at large distances and at different angles towards the edge of the panel. The resulting crack diagrams in the report show additional

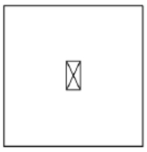
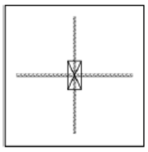
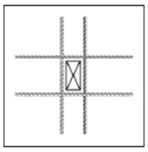
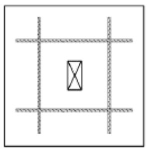
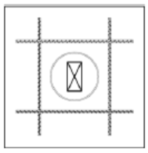
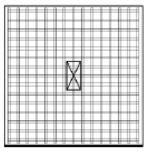
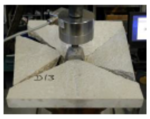
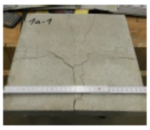
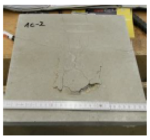
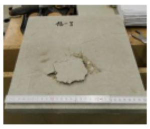
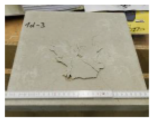
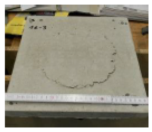
Reinforcement	-	Rebar (2 pcs)	Rebar (4 pcs) *Narrow*	Rebar (4 pcs) *Wide*	Rebar (4 pcs) *Wide* + Spiral wire	Carbon mesh (2 layers)
Arrangement						
Failure Appearance						
Load Factor	1,00	1,06	1,67	1,35	1,40	2,12

Figure 9. Tests with additional reinforcement. The resistance of the unreinforced concrete forms the reference value. It can be seen from the pictures that the load-bearing capacity is significantly influenced by the crack development. The inserted carbon meshes prevented cracks and a concrete breakout cone could form.

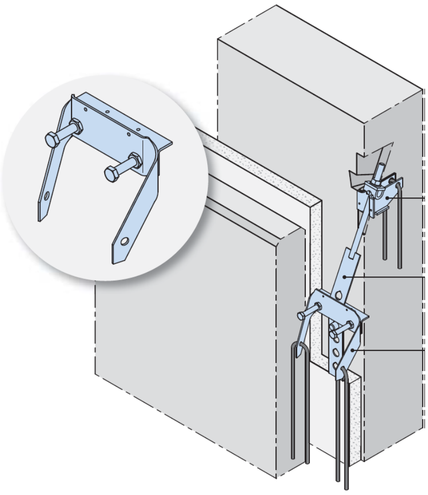


Figure 10. Fixing system for façade panels.

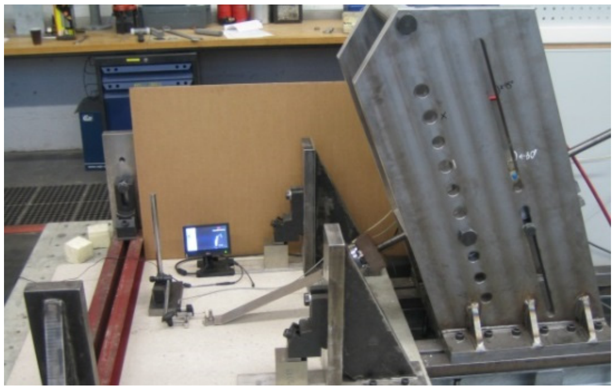


Figure 11. Test setup for shear/tension.

splitting and fracture of the concrete cone, in addition to the overlapping of the cracks due to prying failure. This may lead to a further increase in scattering (see Figure 8).

Finally, it can be said that timed fixings are not very suitable for applying large loads to thin fibre-reinforced panels, especially when the loads contain a large shear component or when $h < 2 - h_{ef}$. Depending on the size of the panel, the resistance of the fixings may not be sufficient to support the façade panel.

6. Methods to reduce the influence of splitting

To increase the load-bearing capacity of an anchorage and to reduce the scattering of the test results, various measures can be taken. Two measures are described in more detail below, on the one hand the use of reinforcement and on the other hand the distribution of the load to be introduced over several load-bearing components.

6.1. Use of additional reinforcement

Additional reinforcement can be arranged in several ways. In addition, different types of reinforcement were considered in tests, namely bar-shaped reinforcement and reinforcement mats. In the case of bar-shaped reinforcement, it must have its own corrosion protection due to the low concrete cover, i.e. it should consist of e.g. stainless steel or carbon. The same reinforcement was used as mat-shaped additional reinforcement, which is also used as slab reinforcement.

The results of the tests with additional reinforcement are shown in Figure 9

6.2. Multi directional fixings

Special anchoring systems with suitable insert elements are required to fix concrete facades. To prevent eccentricity of the supporting structure, it is advantageous that the insert can be loaded in different directions. It is convenient to equip this type of insert element with several components to introduce loads independently into the concrete. An example of this is shown in Figure 10. Headed anchors carry the loads

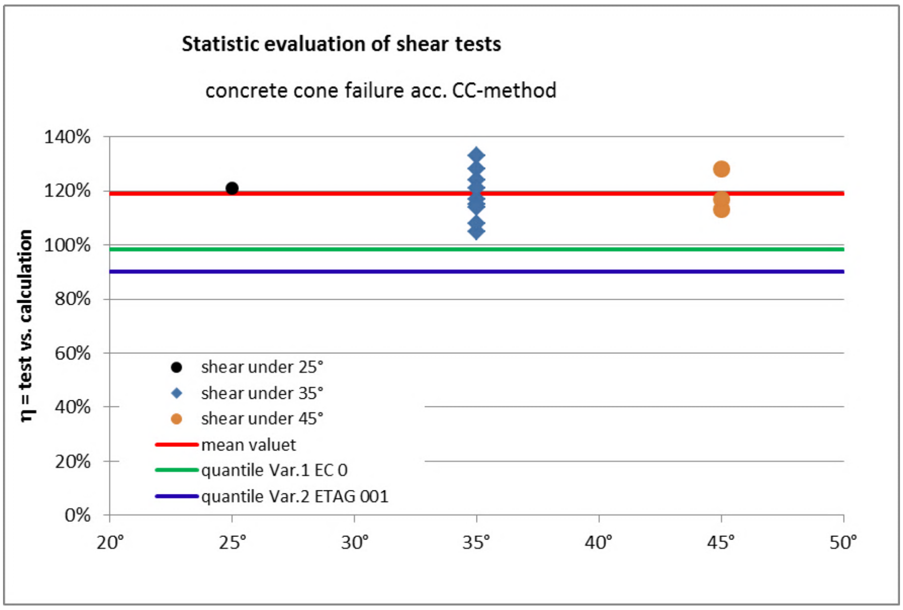


Figure 12. Test results vs. calculation results of multidirectional fixing.

perpendicular to the surface of the facade, i.e. tensile loads, while reinforcement bars, for example, support the shear direction.

These inserts were subjected to tensile tests at different angles. The test set-up is shown in Figure 11. The concrete panels were fixed to a special test rig and loaded at different angles. The insert system was designed to accommodate loading angles of between 25° and 45°. This range was used for the tests.

It was found that even when relatively large loads were introduced into the concrete, the loads did not depend significantly on the loading angle. The final fractures were of sufficient size to achieve a noticeably higher resistance than the time-fixed ones; for values below 10%, the scatter was well within acceptable limits. These findings demonstrate that multidirectional fixings have significantly better load-bearing properties than the fixings.

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The results of the test are shown in Figure 12. To describe this interaction, a computational model has been developed according to [8, 9]. The test results are presented together with the relevant safety levels according to [13, 14]; the difference between the safety levels in [13, 14] is based on the difference in confidence levels (the confidence factor in [13] is 75% and in [14] it is 90%). In the case of reinforced concrete structures, [13] is the restraining force and in the case of fixed structures, [14] is the restraining force.

Tests have shown sufficient safety and a good correlation with the calculated values. The inserts have been specially developed for thin carbon-reinforced concrete panels and have been approved by the general building authority.

For the horizontal load component due to wind loads, a spacer such as a compression element is usually installed. This compression element can take the horizontal load without affecting the load-bearing equipment.

The thinner plates are more sensitive to wind loads, as they carry less dead load than thicker concrete façade panels. Depending on the shape of the slab, the weight of the slab and the expected wind loads, horizontal anchors (e.g. compression bolts or restraint anchors) may need to be additionally fixed for wind suction.

In stacked, suspended façade slabs, the lower spacer bolts are replaced by dowels for aligning the elements. These elements are also included in the general building approval.

7. Numerical investigations

Numerical investigations of the effects observed in the experiment are in progress. Based on the undisturbed concrete failure cone, i.e. concrete breakout without edge and thickness influence, the resulting resistances are currently to be determined, which occur if the influencing factors are guided to the limits of applicability.

As can already be seen from the test results, the influence of the splitting coefficient $\Psi_{h,sp}$, for example, is considerably greater than stated in current publications. The influence of the reinforcement is currently being investigated.

8. Summary / Outlook

The construction of carbon reinforced concrete can be described as a mega-trend, as this technology will be used in many areas of the construction industry. Façade construction in particular has been one of the first areas of application to show the advantages of carbon reinforced concrete. Above all, the savings of resources is an essential aspect which, in addition to the many technically advantageous properties, has benefits for society as a whole. Of course, not all design methods known from reinforced concrete can be transferred to carbon concrete. Therefore, new design methods are being developed at the universities in Dresden and Aachen (Germany). In addition, the current technical specifications for fastening techniques developed for conventional steel-reinforced structures must be adapted to the specific boundary conditions of carbon concrete construction. For this purpose it is necessary to adapt the relevant parameters to the specific properties of the fabrics (reinforcement), which is usually done by tests. Although the effective anchorage depth and the edge distance of an anchor according to the formula should have the greatest influence on the load bearing behaviour, the influence of cracking of the concrete dominates. In further investigations - by means of tests and numerical analysis - further special features of carbon reinforced concrete are to be analysed, such as the influence of the special bond behaviour or the reduced shear resistance compared to steel reinforcement, in order to derive efficient systems for practical use.

Acknowledgements

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