Strengthening with a carbon fiber composite cable. A new possibility?
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Abstract

CFRPs have proved as outstanding engineering materials in the aircraft / aerospace industry. This enables them to become an alternative material for the use in reinforced concrete structures. Experimental and numerical investigations on different anchoring systems for a stranded CFRP-cable used as a prestressing element are presented. Clamping and potting systems have been developed for single cables. They were tested and optimized under static and cyclic tension loading. The results of the finite element analysis help to give a better understanding of the complex stress distribution in the anchoring zone in order to optimize it. The comparison between experimental results and FE analysis of a clamping system showed good agreement. The behavior of the optimized clamping system under static and cyclic loading encourage practical field tests and further investigations.

1 Introduction

Main advantages of carbon fiber reinforced polymers (CFRPs) in comparison to steel are their high specific strength and modulus, outstanding corrosion and fatigue resistance, excellent damping characteristics and low creep behavior. With this property-profile CFRP can fullfil requirements in civil engineering, for instance as prestressing elements in bridge constructions\textsuperscript{1-3} and possibly as reinforcement elements in the restoration and maintenance of historical buildings.
The composite cable used in this research project is a stranded CFRP-cable. It consists, like a steel rope, of seven single wires twisted left-handed. The biggest engineering challenge using the CFRP-cable is the question of how to transfer the axial load from the long, slender cable into the anchoring zone. The economy and reliability of such a strengthening system depends heavily on the function and construction of the anchoring device.

After a brief overview of the material properties of the CFRP-cable and different end fixing methods, investigations of experimental and theoretical work on clamping and potted end-fitting systems are presented.

2 Material Properties

The composite cable used in our tests was developed by two Japanese companies. The seven wires of the standard stranded CFRP-cable are twisted left-handed with an angle of $\alpha = 9.7^\circ$. Unlike a single steel wire, the wires of the cable consist of 15 UD-prepreg rovings which are twisted right-handed with an angle of $\gamma = 7.9^\circ$. Each prepreg roving consists of endless carbon fibers (type HT) which are arranged in parallel and embedded in an epoxy resin system of 60 vol.-% fiber fraction. A polymeric yarn is twisted around each wire as a protection against abrasion and other mechanical damage which may occur either during processing or during manufacturing of the cables.

Table 1 gives an overview of the matrix properties, the carbon fibers, one single wire and the standard stranded CFRP-cable with a diameter of 12.5 mm. The breaking load of a steel rope with the same diameter amounts to 180 kN. The specific strength of the stranded CFRP-cable is four times higher than that of a steel rope. The bending modulus is much smaller than the tensile modulus due to the stranded CFRP-cable construction. As a result, the standard cables can be wound and transported on drums with a diameter of only one meter.

<table>
<thead>
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<th>Table 1: Material properties of different CFRP-products</th>
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<tr>
<td><strong>Matrix</strong></td>
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<td>Standard-EP-resin</td>
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<td>C-fibers (Besfight HTA)</td>
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<td>Single CFRP-wire (60 vol.-% fibres)</td>
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<td>Stranded CFRP-cable (1x7 12.5)</td>
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3 End fixing methods

In general anchoring systems for fiber reinforced polymer cables can be classified in potted end-fittings with a resin or potting mortar and metallic compression systems with clamps or wedges.

The existing combined die casting-compression-anchoring system of the stranded CFRP-cable is an expensive metallic die casting system in a tube which must be manufactured in advance in the factory. In order to manufacture the die casting system, the exact length of the cable must be known. On the site, the tube is finally clamped with conventional wedges.

Within the scope of an internal research project, a variety of different end fixing methods have been developed to find anchoring systems which are simple and compatible with the material. With the help of a previously established table of requirements, containing the issue of mounting on the site, etc., a compression and a potting system have been chosen and will be evaluated in the following investigations.

4 Investigations of clamping systems

The small transverse compressive and shear strength of the stranded CFRP-cable in comparison to steel ropes leads to immense problems using the conventional compression systems with clamps or wedges. Due to the low material strength normal to the cable, an early failure will result. Moreover, the teeth of the wedges will damage the stranded CFRP-cable. Thus, the principal goal of the development of new end fixing methods is a reduction of the transverse compressive stresses so that failure takes place outside the anchoring zone. Experimental investigations on compression systems with clamps, which are easier to manufacture than wedges, have been carried out for principal examinations. The understanding of this mechanism can be transferred to the wedge system later.

Figure 1: Geometry of the clamping system for experimental investigations
Numerous experimental tests with different intermediate layers between cable and clamping elements were performed to produce a "soft transition" from the stranded CFRP-cable to the clamping elements with a clamping system shown in Figure 1. With a suitable intermediate layer the small compression surface, resulting from the cable construction, is enlarged, while at the same time protecting the stranded CFRP-cable against high local loads, and also increasing the adhesive friction. By applying a low torque on the clamping screws at the beginning of the load transfer of the anchoring zone, small transverse compressive loads of the cable were reached to achieve a "softer load-transfer". The intermediate layer can be applied to both, clamps and cable. The application on the clamps is much simpler than on the cable, however, investigations from Dreesen\(^1\) showed poor results so that this technique was abandoned here. Extensive investigations with intermediate layers mounted on the cable finally lead to the use of abrasive-coated paper. With a surface treatment of the clamps and an optimized torque on the clamping screws 95% of the cable breaking load could be transferred with a clamping length of 200 mm under a static load. In earlier tests the cable had frequently been pulled out of the clamps. An optimization led to a cable breaking outside the anchoring zone.

Figure 2 shows the effect of the clamp surface condition on the anchoring loads for two differently treated cables. The very small anchoring loads of the stranded CFRP-cable clamped without a layer could be improved with the optimized abrasive-intermediate layer. The clamping length for these tests was 200 mm.

![Figure 2: Anchoring loads of clamping systems](image)

Pulsating tension tests with a stress amplitude of 30 - 50 N/mm\(^2\) to a stress level of 1345 N/mm\(^2\), which is equivalent to 65% of the cable breaking load,
places high demands on the clamping system. The clamping system optimized under static load leads to a cable pullout out of the clamping elements in the pulsating tension tests before reaching 2 million load-cycles. Therefore the clamping length was increased to 250 mm and additionally the torque of the clamping screws was raised. After this optimization under cyclic loading more than 2 million load-cycles could be performed with the clamping system without a cable pullout or a cable fatigue failure.

In addition to the experimental investigations, a finite element analysis was performed for a better understanding of the complex stress distribution inside the clamping system. Because of the stranded construction of the CFRP-cable a full three dimensional model was developed and analyzed with a finite element program (ANSYS®). With a special contact-element the friction behavior of the clamping system could be simulated. The numerically calculated anchorage slip showed good agreement with the experimentally measured slip values. So the finite element model could be used to vary parameters in order to assess the effect of design modifications and to conduct the numerical optimization.

Some of the most important results contain information on the tensile and shear stress distribution in the CFRP-cable of the calculated experimental model in comparison to the optimized model after numerical optimization. Figure 3 showed that the tensile and shear stress distribution $\sigma_z$ and $\tau_{xz}$ could obviously be improved. Both, the tensile peak at the beginning of the clamping length and the shear peak within the first-third of the clamping length, could be reduced.

**Figure 3:** Distribution of tensile and shear stress $\sigma_z$ and $\tau_{xz}$ in the CFRP-cable along the clamping length for the experimental and optimized model
5 Investigations of conical potting systems

With potted end-fittings, the load transfer from the stranded CFRP-cable to the anchor body is a combination of a bonding and a locking mechanism. However, a simple bonding/locking joint is unable to transfer the cable breaking load, so that a conical-shaped anchor is used in addition. Under axial cable load, the potting body is pulled into the cone, which causes a well-defined, transverse compressive stress on the cable. In earlier tests the existing systems showed a flaw in strength and strain between cable and anchor. With an optimized cone-geometry and a careful composition, cone-stiffness and stiffness of the potting body these flaws could be reduced. For the conical potting system various parameters (cone angle $\omega$, cone shape $(d, h, R)$, potting length $L_V$, and preliminary treatment of the stranded CFRP-cable), have been examined in numerous experimental investigations under static load (s. Figure 4).

![Parameters of experimental investigations](image)

**Figure 4:** Geometry of the potting system for experimental investigations

The potting material was a standard epoxy resin. By untwisting the stranded cable, the adhesion surface was enlarged, which was expected to lead to an increase of the transferable load. In first tests with cone A (s. Fig.5) and a short potting length this effect could in fact be observed and the obtained pullout forces of the untwisted cable were higher than those of the normal potted cable. By increasing the potting length $L_w$ the difference became smaller and the normal potted cable was pulled out, whereas the untwisted cable broke at the entrance of the potting length far below the cable breaking load. With the untwisting of the cable, a failure was encouraged at the entrance of the potting body as a result of fiber damage during untwisting the cable. Thus, untwisting of the stranded cable was abandoned in all following experiments. By experimentally optimizing the cone angle and inner cone shape, 85% of the cable breaking
load of the existing system could be reached. This second version (cone B) had a potting length of 120 mm and a cone angle of $\omega = 5^\circ$.

A failure now occurred due to a combination of shearing failure between the potting resin and the polymeric yarn, shearing failure between yarn and the composite itself and compression failure of the potting resin. In Figure 5, the measured anchoring loads of the two mentioned cones A and B are presented for different potting lengths and for an untwisted and a normal potted cable.

Figure 5: Anchoring loads of conical potting systems

In comparison to the anchoring loads reached with the clamping system, further investigations of the potting system will be necessary to reach the cable breaking load under static load before pulsating tension investigations will be performed. Numerical analysis for a better understanding of the stress distribution in the potting body are conducted now. The aim of a numerical optimization is to design the cone geometry in such a way that the ultimate strength of the potting material is not exceeded. Shear and transverse compressive stresses in the potting material at the entrance of the anchor have to be reduced by further variations of the cone parameters. The detailed parameter analysis of the potting system is being performed in a 2-D analysis on a cross section of the system in order to reduce the calculation time.

Several simplifying assumptions must be made in developing the potting model: The interface between stranded CFRP-cable and potting material and also between potting material and anchor cone is assumed to be an adhesive bonding. The results of calculations shall be used mainly as a qualitative tool to guide the decisions for improving the design. In a future step the bonding beha-
Behavior between potting material and cable shall be simulated with a special finite element which enables to simulate the load-slip behavior.

6 Conclusion and outlook

Stranded CFRP-cables offer a significant potential for the use as reinforcement elements in civil engineering. The load transfer in the anchoring zone might be difficult and certain prerequisites will have to be fulfilled before an acceptance can take place and their use - which is at present still extreme limited - may increase. The acceptance is principally associated with changes in the design philosophy of today. The biggest barrier seems to be the existing reluctance in the industry to introduce new techniques. Most of these can be tackle sucessfully in an academic context, as shown in the present investigations on different anchoring systems. But tests are necessary in the field where steel cables are replaced by CFRP-cables in existing structures and monitored over the time to convince. This technology has to be mature when the doors are open for a widespread use of CFRPs in civil engineering. Before this will happen, the CFRP-cable may contribute to the preservation and the extension of the useability of historical buildings.

References