A NEW APPROACH OF BONDED ANCHORAGES FOR CFRP PRESTRESSING TENDONS AND CABLES

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ABSTRACT

Due to the excellent strain- and strength properties in fibre directions, carbon fibre reinforced plastics (cfrp) offer an ideal alternative to conventional steel tendons. However, regarding the requirements given in the “European Technical Approval Guideline of Post-Tensioning Kits for Prestressing of Structures” (ETAG 013) [2] the anchorage design of CFRP-tendons must follow new approaches to meet the CFRP’s special characteristics (e.g. lack of isotropy and lack of plasticity) to prevent a premature anchorage failure prior to the ultimate strength of the tendon.

The anchorage problem has been solved by combining a clamping and bonding anchorage device thus that the anchorage presented complies with the ETAG requirements for steel tendons and cables. The use of lamella-shaped CFRP strips instead of bar-shaped members brings further advantages and allows the tendon to be directly applied and anchored on the surface of the member to be strengthened with a minimum of eccentricity. The development of the presented stressing and anchoring system for the monostrip CFRP tendon is successfully finished and the system already proved its effectiveness and its economical benefits in numerous strengthening projects some of which are described and illustrated in this paper. The General Technical Approval will be given by German Institute of Construction Technologies in Berlin.

The flat lamella-shaped tendon is excellent for external surface-posttensioning and therefore most advantageous to strengthen and upgrade existing structures. Common anchorage efficiency and quality standards which are obligatory for steel tendons can be kept, but a different anchorage design with special attention to the different material behaviour and properties is a mandatory requirement.

The presented results are part of the research and development program towards CFRP tendons and cables done by Leonhardt, Andrae and Partner, Consulting Engineers, which is financially funded by Sika Construction Germany GmbH and accompanied by German Federal Highway Research Institute (BAST).

KEYWORDS

CFRP tendon, anchorage efficiency, mechanical anchorage, bond strength

INTRODUCTION

Due to the high strength- and strain capacity, the extraordinary weight-to-performance ratio and the excellent resistance to corrosion inducing factors, the use of Fibre Reinforced Plastics (FRP) is already standard practice to add on or replace steel reinforcement in mild applications. Mild CFRP applications use mostly lamella-type CFRP strips to be externally bonded on the reinforced concrete surface of the member to be strengthened and thereby to increase flexural and/or shear resistance. Design regulations were given in the Technical Approval of the Institute of Construction Technologies, Berlin already in 1997.
The use of CFRP sheet-type material textures are mostly advantageous for strengthening actions were the forces of the external reinforcement can not be transferred to the concrete by concentrated strips but must be smeared on a larger area due to poor concrete quality.

Figure 1 shows the first application of the cooling tower in Eisenhüttenstadt, Germany which was strengthened in 2004 by ring-belt-like wrapping of endless CFRP sheets to stabilise the weakened r/c-shell due to extensively cracking and to prevent the cooling tower from demolition which was an experts witness recommendation before strengthening.

Investigations at EMPA, Zürich [1] showed, that prestressing or post-tensioning of externally bonded CFRP strips increases the efficiency of the strengthening method significantly.

Almost half a century ago even Prof. Dr.-Ing. Fritz Leonhardt mentioned the possibility of FRP-tendons when he expressed the idea and the presentiment that “……Some day, glass fibres or plastic will be used as tendons for prestressing…” in his book ‘PRESTRESSED CONCRETE – Design and Construction’ published in 1954 [2].

However, the anchorage of prestressed or post-tensioned FRP material for the use as external tendons (bonded or unbonded) results in a number of difficulties.

Early developments of GFRP (glassfibre-) tendons in Germany i.e. Polystal HLV tendon (1992) could not get established on market, although there were successful projects [3]. The casted anchorages were expensive and the anchorage efficiency was low. Further drawbacks resulted from the problems to get the glassfibres chemically stable in alkaline concrete, from the low fatigue strength and from the low elastic modulus of glass.

Carbon fibre material has nearly ideal properties for the use as tendons and cables but has only recently become economically viable with extended production capacities.

Anchorages of post-tensioning kits traditionally need to be designed such that the full strength of the tendon can be developed and that failure of the tendon at breaking load occurs outside the anchorage. These requirements are fixed in the European Technical Approvals Guideline (ETAG) of the European Organisation for Technical Approvals (EOTA). For steel tendons the effectiveness of anchor systems depends on the isotropy and plasticity of steel, which allows a redistribution of stresses in the vicinity of sharp edges, grooves, notches or threads, which are part of the anchorage mechanisms. The lack of plasticity and the totally anisotropic material texture of FRP’s however are less favourable conditions to meet the above mentioned ETAG requirement. New anchorage design approaches were required.

FORCE TRANSFER FROM CFRP TENDONS TO THE STRUCTURE

General

Prestressing or post-tensioning of CFRP strips increases the efficiency of the strengthening method significantly. It allows to exploit the full range of the strain capacity of the strips, to balance the dead load of the structure and
to compress cracked tensile zones of the structural members. To be able to use CFRP strips as prestressing tendons efficient anchorages accompanied by a site-suitable stressing systems must be developed.

Deuring [1] describes the failure modes of inefficient anchorages where the transfer of the prestressing force should solely be performed by a single-lapped adhesive joint of the tendon to the concrete member. While removing the stressing equipment, this resulted in an immediate delamination of the strip, since the shear stress peak in the adhesive at the ends of the strip exceeds by far the shear strength of the concrete cover. Delamination occurs in a zipper type shearing off of the concrete cover underneath the strip adhesive layer from the ends to the middle of the strip. Since the bond strength, which depends primarily on the tensile strength of the concrete cover, is insufficient to bear the concentrated prestressing force at the anchorage zone of a surface-mounted CFRP tendon, mechanical anchorages are to be installed to the ends of the prestressed strips. These mechanical devices provide a smooth and concrete-suitable force transfer from the strip to the anchor as well as from the anchor to the structure. The installation and the stressing and anchoring operation must at the same time be easy in handling onsite with a minimum of impact to the structure and has to meet the same qualification standards as any other system using steel wires, bars or strands.

**FRP suitable anchoring principles**

The flat shape of the strip seems to be very appropriate for friction anchors, where the strip is clamped between wedges or bolted plates. Clamping tests proved however, that simple wedge or plate clamping devices do not produce a sufficient uniformly distributed clamping pressure nor a uniform friction coefficient.

Slight deviations from a uniform pressure distribution result in anchorage slip of that parts of the strip with less friction pressure which subsequently results in longitudinal cracking of the strips. The strength of the strip matrix (i.e. epoxi resin) itself is inadequate to balance differential slip of the carbon fibres. As a result, pure friction anchors do not allow to develop the strip full tensile strength and are therefore not good for a permanent anchorage of a CFRP tendon. Optimised friction anchors however can be used as temporary anchors for the stressing operation to reach the defined stress level and hold it until final, bonded anchorages are installed and cured. These temporary anchors can then be removed and used for the next stressing operation.

Temporary anchorages need a sufficient margin of safety to develop the required tensile force in the strip. At present stage temporary friction anchors are used for the stressing operation, which provide a save stressing load of 250kN. This performance could be achieved by placing washer strips between opposite bolts to minimize clamping plates bending and thereby providing a uniform clamping pressure along the strips width. In order to guarantee a reproducible and uniform friction coefficient, special braking pads are used inside the stressing anchors.

The final permanent anchorage of the CFRP tendon is formed by a double-lapped adhered connection in between bolted steel plates (see figure 2). This final combination of both bonding and clamping proved to be a simple and foolproof method to develop the tensile strength of the strips.

The CFRP strip is generally located directly on the surface of the structure to be strengthened. In order to avoid large block outs or recesses in the concrete, the tendon force needs to be distributed on the surface of the structure over an area such that stresses resulting from force transfer actions do not exceed the concrete strength nor cause cracks in the anchor vicinity. Also, the eccentricity between the strip tendon and the anchor zone needs to be as small as possible to avoid tilt up effects of the anchor.

A steel plate inserted into a recess of the concrete cover proved to be the most practical and effective means for the force transfer into the concrete, see figure 2.

Forces are transferred by both bond of the adhesive mortar underneath the base plate and front pressure at the front face of the plate. The rather small tilt up moments are taken by a few bolts which are also used to fix the base plate during curing of the adhesive mortar.

The anchor plates are located at a distance from the ends of the strip. This means that a non stressed segment of the strip in continuity with the stressed strip segment is located directly behind the anchorage and is equally bonded to the concrete surface. These non stressed end segments are used as anchor or continuity reinforcement for the force introduction of the anchor force.
TECHNICAL REQUIREMENTS OF POST-TENSIONING KITS FOR PRESTRESSING STRUCTURES

Post-Tensioning Kits typically comprise the following components like tensile element, anchorage components, couplings, ducts, filling material etc. The technical standard and requirements of all post-tensioning or prestressing systems, the detailed methods of their verification and the assessing and judging the fitness for their use are established in the “Guideline for European Technical Approval of Post-Tensioning Kits for Prestressing of Structures” ETAG 013. Defined tests have to be carried out and defined acceptance criterias have to be achieved to prove the mechanical resistance and stability of a Post-Tensioning system.

The main requirements are as follows:

- **resistance to static load**, verified in static load tests:
  The system shall be able to develop a specified percentage of the tensile elements ultimate strength without premature failure of the anchorage components (anchorage efficiency), without undue deformations in the components and without disproportionate relative movements between tensile elements and anchorage components.

- **resistance to fatigue**, verified in fatigue tests:
  The system shall be able to withstand specified fatigue loads without exceeding a specified percentage loss of tensile element cross section.

- **safe load transfer to the structure**, verified in load transfer tests:
  The system shall be able to transfer a specified percentage of the tensile element ultimate strength from the anchorage into the concrete structure, of a defined strength class of concrete, without undue cracking of the structure and at deformations which stabilise within a given time frame.

The developed CFRP-Strip-Tendon anchorage was fully tested in static load and fatigue tests at Material Research and Testing Laboratories, University of Leipzig according ETAG 013 standards.

The “pull-apart” test set up consisted of two concrete blocks in line in a testing machine (see figure 3). The concrete blocks were symmetrically interconnected with CFRP strips at two opposite faces. This test set up allowed to test 4 anchorage units simultaneously during every test. The installation of the anchor and anchor plates mirrored identically the situation on site. The temporary stressing anchors were fixed to the anchorage baseplates. The strips were then stressed by pulling apart the concrete blocks with the testing machine. The permanent bond and clamping anchorages were installed after the design prestressing force had been applied. The stressing anchors could be removed after curing of the adhesive and the strips could subsequently stressed until failure. The anchorage is adequate if the strip fails between the anchorages at ultimate CFRP stress, In additional 2 fatigue tests with each 4 anchorages to be tested, the anchorages proved excellent resistance to dynamic and cyclic loads.

After the tendons were stressed to a prestressing force of each 220kN and after curing of the final anchorages the load subsequently was increased by the tensile testing machine up to the middle load of 500kN, then starting the pulsator at a constant frequency of 1 Hz.
After 2.1 million load-cycles at a constant upper load of 73% of the characteristic strength of the tensile element and a constant tendon’s stress amplitude of 160N/mm² the tendon was then finally loaded until fracture. Fracture of the CFRP element occurred outside the anchorages at a load level of 724kN (fatigue-test 1) respectively 763kN (fatigue-test 2). This fracture-load level means 103% respectively 108% of the characteristic strength of the CFRP tendon.

**PRACTICAL ONSITE APPLICATIONS**

The first application of the system was in 1998 [5] for the rehabilitation of a post-tensioned 4-span plate girder bridge with cracks at the bottom of the beams near the supports due to inadequate tendon profile. The CFRP monostrap tendons first generation consisted of 50mm x 1.2 mm Sika Carbodur strips which were stressed to 60 kN each.

In further development, the size of the strips and the prestressing force was subsequently increased, and a 90mm x 1.4 mm strip with 165 kN prestressing force is presently being used. This improved second generation stressing system was applied in Oct. 2001 the first time for rehabilitation reasons at the Koerschtalbridge near Stuttgart, Germany (figure 4 and 5).
In **Oct 2003** a bridge in Ravenna, Italy was strengthened by four of these CFRP Monostrip tendons, each 30m long. Due to a truck collision two of the four internal tendons of one of the prestressed concrete girders were cut and repair and strengthening works were necessary.

By applying 4 external CFRP tendons, each stressed to 165kN, the girder got back its load bearing capacity. The strengthening operation was supervised by onsite deflection measurements and a final insitu load test proved the effectiveness of the strengthening work.

In **2003**, the 585 m long approach bridge for the “Neckar Valley Highway Overpass” near Heilbronn (figure 6), Germany, built in 1965 – 1967, had to be repaired, strengthened and refurbished.

The bridge structure consists of two parallel superstructures with 15 spans of 39 m length each and was posttensioned in longitudinal and transverse direction with Dyckerhoff & Widmann (St 80/105) 32 mm diameter bars. The cross sections are double t beams with 3,00 m depth and have originally been built without diaphragms. Steel pipe diaphragms have been added later at the supports to reduce support rotations.

The bridge has been built span by span with 14 coupling joints per superstructure where all 42 bars were coupled. All coupling joints were cracked at the time of the repair which resulted in an unacceptable cyclic stress range in the bar couplers.

Additional prestressing forces are therefore needed in the coupling vicinity to reduce the live load band width of steel stresses in the couplers.

Alternative repair solutions with steel and CFRP tendons were designed for tender. The CFRP solution was finally selected for economical reasons.

![Figure 6: Six-lane Highway Bridge across river Neckar near Heilbronn, Germany strengthened by 252 CFRP Monostrip Tendons, stressing applications finished Oct. 2004](image)

The bending moment - diagram is shown in figure 7.

The governing bending moments are calculated assuming 70 % residual Prestressing Force, 12K temperature gradient and alternating live loads with +/- 50% traffic load and amount to

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\begin{align*}
M_{\text{max stress}}^{12K} &= 27600 \text{ kNm} \\
M_{\text{min stress}}^{12K} &= 20483 \text{ kNm}
\end{align*}
\]

The accompanying steel stress band width according to fig. 13 amounts to 498 N/mm² - 370 N/mm² = 128 N/mm² and exceeds the allowable stresses for couplers.

The bending moment - steel stress diagram can be shifted with the use of 9 additional cfrp tendons with 90mm x 1,4 mm cross section and 150 kN prestressing force each such that the stress band width at the couplers is reduced to 406 N/mm² - 321 N/mm² = 85 N/mm², which is below the fatigue limit of the couplers.
The strengthening of the 28 defective coupling joints with 252 cfrp tendons was successfully completed in October 2004. The stressing sequence and the arrangement of 7 tendons underneath and 2 along the faces of the webs are shown in Figures 8 and 9.

**CONCLUSIONS**

The development of efficient anchorages (anchorage failure load > tendon failure load) opens the general application of CFRP tendons in competition with steel tendons. The increasing market will reduce the CFRP cost and familiarise contractors with the new technology. Even though corrosion protection is not needed, a coating of free external CFRP tendons is needed for light and vandalism protection. The advantageous strength/weight ratio does not only facilitate handling on site but will also result in other types of structures in the near future, e.g. larger spans for cable stayed bridges.
REFERENCES