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CFRP TENDONS IN UHPFRC – BOND BEHAVIOUR AND APPLICATIONS TO FOLDED AND CURVED SHELLS

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Abstract

In a priority programme of the German Research Foundation (DFG SPP 1542: Concrete light. Future concrete structures using bionic, mathematical and engineering form finding principles) [1] prestressed sandwich panels with thin folded and curved concrete layers will be developed and investigated.

In a first step, the bond behaviour of CFRP (Carbon Fibre Reinforced Plastics) tendons (single strut and seven-wire strands) in UHPFRC (Ultra-High Performance Fibre Reinforced Concrete), with a uniaxial compression strength $f_{cm,28d}$ of about 170 MPa, is analysed. Pull-out tests are carried out to investigate the minimum concrete cover and the local bond behaviour, namely the influence of the wedge-effect. Additionally, tests on the transfer length are performed to determine the minimum spacing of tendons as well as the minimum concrete cover in small-scale beam tests. With the information of these tests, the minimum dimensions of shells can be determined. In the future, further experimental and theoretical investigations on UHPFRC shells, prestressed with CFRP tendons, will be conducted.

Résumé

Le programme prioritaire du fonds allemand de la recherche (DFG SPP 1542 : bétons légers, structures en béton d'avenir utilisant les principes biomimétiques, mathématiques et d'optimisation pour la génération de formes) [1] prévoit l'étude et le développement de panneaux sandwichs précontraints avec des couches minces courbes et repliées en béton.

Dans une première étape, l'adhérence entre câbles (monobrin et torons 7 fils) constitués de polymères renforcés de fibres de carbone (PRFC) et bétons fibrés à ultra-hautes performances (BFUP) est analysée, le BFUP ayant une résistance moyenne en compression uniaxiale à 28 jours d'environ 170 MPa. On réalise des essais d'arrachement pour déterminer l'enrobage minimal et le comportement local d'adhérence, en particulier l'influence d'un effet d'éclatement. En outre, des essais de longueur d'ancrage sont réalisés afin de déterminer l'espacement minimum des câbles ainsi que l'enrobage minimum dans des essais de poutres à petite échelle. Sur la base de ces informations expérimentales, on détermine les dimensions minimales des couches. De futures recherches expérimentales et théoriques seront conduites à l'avenir sur les coques en BFUP précontraintes par câbles en PRFC.

1. INTRODUCTION

In a priority programme of the German Research Foundation [1] prestressed sandwich panels with thin folded and curved concrete layers will be developed and investigated. These sandwich panels are applicable as roof or façade elements with long spans, high load bearing capacity and insulation at the same time. In a first step, the concrete layers, i.e. curved or folded shells, are to be analysed. Shells and folded cross-sections mainly gain their stiffness and load carrying capacity due to the spatial load bearing behaviour of the thin-walled cross-sections. The load bearing capacity can be additionally enhanced by the use of ultra-high performance fibre reinforced concrete (UHPFRC). Nevertheless, for large spans the filigree cross-sections do not provide enough space for reinforcement, thus they have to be prestressed to prevent deformations in consequence of cracking and shrinkage, whereas not enough concrete cover for corrosion resistance can be provided. Hence non-corrosive carbon fibre reinforced polymers (CFRP) are applied as pre-tensioning members. For an economic and safe design the behaviour of CFRP members in UHPFRC has to be investigated. The dimensions of the bond anchorage zone determine the thickness of the shells since a minimum concrete cover has to be provided to avoid splitting cracks in the transmission zone.

2. MATERIALS

Pre-tensioned CFRP tendons are applicable for slender concrete structures because of a high tensile strength of about 2,500 MPa and a high corrosion resistance, which is necessary due to the lack of sufficient concrete covering. One strut and one seven-wire strand are used for pre-tensioning provided by TOKYO ROPE MFG. CO., Ltd.. The trade name is CFCC® (carbon fibre composite cable). The material properties, which are given by the manufacturer, are listed in table 1. All specimens were fabricated with the concrete mix given in table 2. The used steel fibres have lengths of 9 mm and diameters of 0.15 mm. The steel fibre-ratio in the mix was chosen to 0.9 Vol.-% leading to an enhanced ductile behaviour and good pouring quality. Higher ratios do not lead to significant better ductility as well as bond behaviour of strands [3] and ineffective pouring. The fine grained UHPFRC exhibits a uniaxial compression strength (150x150x150 mm³ cube) of about 170 - 180 MPa and a Young's Modulus of about 45,000 - 50,000 MPa after 28 days. After one day the uniaxial compression strength (150 x 150 x 150 mm³ cube) is about 60 - 65 MPa and the Young's Modulus 25,000 - 30,000 MPa. A maximum grain size of 0.5 mm provides a pourable concrete mix.

Table 1: CFCC material properties [2].

Designation [-]		Diameter [mm]	Effective cross-sectional area [mm²]	Guaranteed capacity [kN]	Young's Modulus [GPa]
●	U 5.0∅	5.0	15.2	38	167
✽	1x7 7.5∅	7.5	31.1	76	155

Table 2: Concrete mix [kg/m³].

Cement Cem I 52,5 R HS-NA	Silica fume	Quartz powder W12	Sand 0,125-0,5 mm	Steel fibres	Water	Super-plasticizer
825.0	175.0	200.0	975.0	70.7	175.0	27.5

3. BOND TESTS

3.1 General bond behaviour

The goal of prestressed folded and curved shells makes the identifications of the bond quality of CFRP tendons in UHPFRCS necessary. With data gained by the bond tests, the minimum thickness of the shells can be determined to reach a crack-free transmission zone. In general (figure 1), the bond behaviour at the end of a concrete member can be described as follows (e.g. [3]):

- a constant part, which is caused by basic friction (rigid-plastic bond behaviour),
- a stress-dependent part, which is based on the wedge effect (Hoyer-effect) and increases with the transfer of pre-tensioning,
- a slip dependent part ("lack of fit"), which is independent of the prestressing.

Along the transfer length the bond stress is not constant (figure 1). While the pre-tensioning is released, the slip and the lateral stresses rise due to the difference in tendon and concrete strain. At the end of a concrete member all three parts are activated since almost the full pre-tensioning force has to be transferred [3]. This leads to high lateral pressure between tendons and concrete.

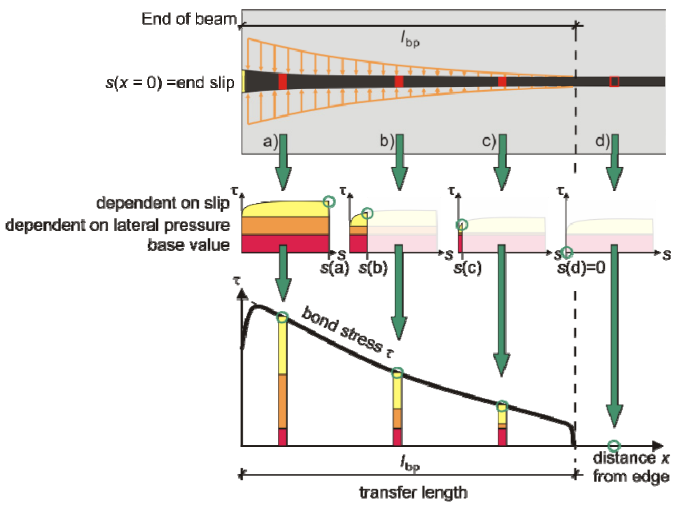
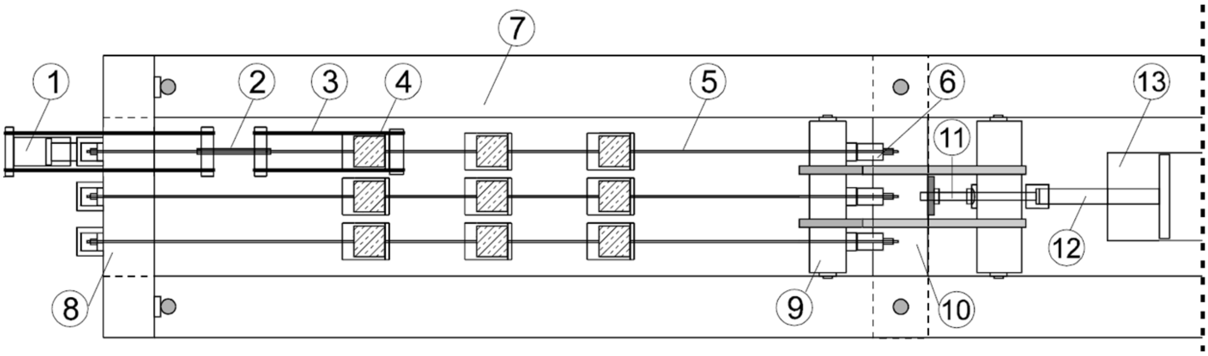


Figure 1: Schematical stress distribution along the transfer length of strands [3].

3.2 Pull-out tests

Pull-out tests are carried out to determine the influence of the concrete cover and the wedge effect (Hoyer effect) on the bond stress-slip relationships. One batch of tests comprises nine single tests (3x3), as depicted in figure 2. After the CFRP tendons are pre-tensioned in a stiff rig, nine samples are concreted. After a specified time interval, in general one day, the pull-out tests are performed. On each tendon three tests are carried out. The first three tests on the first tendon are done without a change in pre-tensioning (0 %). After the release of 50 % of the pre-tensioning the next three tests are conducted on the second tendon. The last three tests are carried out with nearly 100 % release in pre-tensioning. With this method the bond conditions along the transfer length can be represented. A release of 100 % equals the end of a concrete member, 50 % release corresponds to roughly the mid of the transfer length and 0 % release corresponds to the end of the transfer length [3].



1 Piston press
2 Tension measuring stick
3 Tension rods
4 Specimen
5 Pre-tensioned CFRP
6 Hollow load cell
7 Testing rig
8 Fixed cross beam
9 Movable cross beam
10 Cross beam to block the machine
11 Spindle for blockage
12 Tension stick for pre-tensioning
13 Main hydraulic cylinder
14 Bond length
15 Plastic pipe
16 Ball caster
17 Load plate
18 Small cross beam

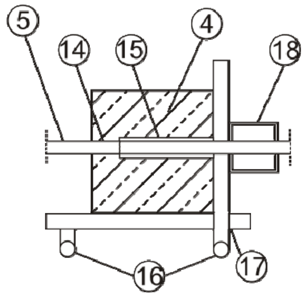


Figure 2: Test setup of pull-out tests [4]

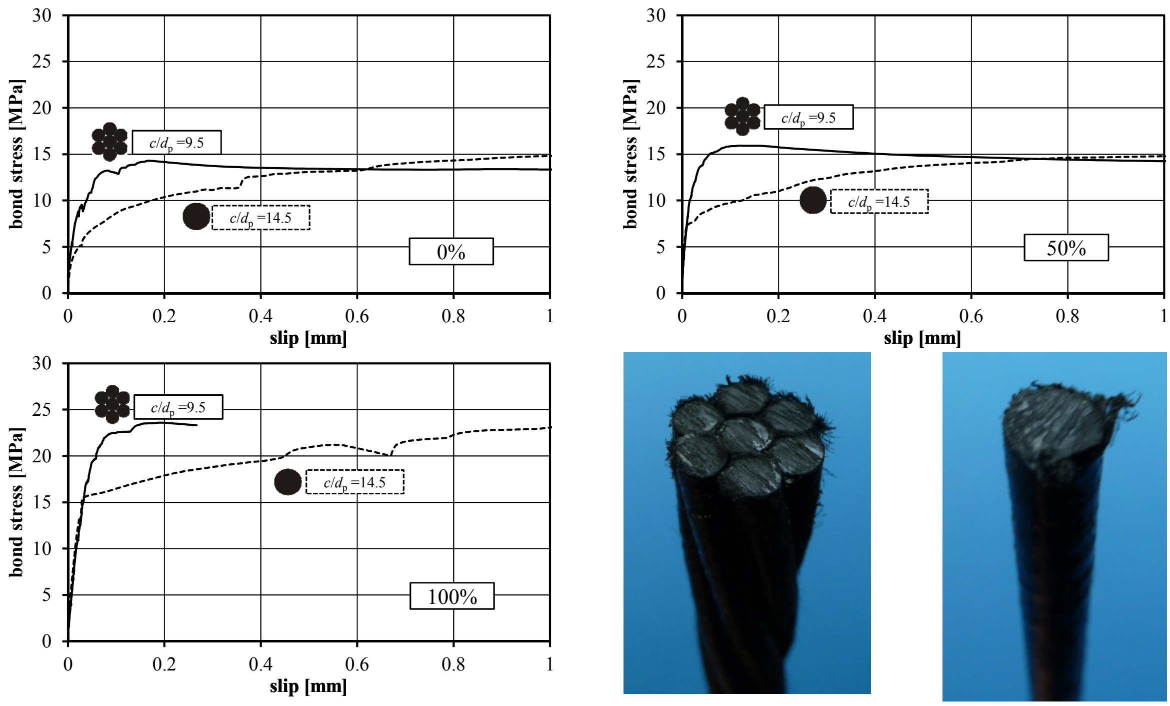


Figure 3: Test results of pull-out tests with centrically placed tendons after 1 day and saw cuts of CFRP tendons

Within the tests, which are exemplarily presented in this paper, the CFRP tendons are pre-tensioned to 1350 MPa and are centrically placed with cube dimensions of 150x150x150 mm³. The bond length of all tests is specified to $2.0 \cdot d_p$,

Figure 3 shows exemplarily the test results of pull-out tests with centrically placed tendons (c: concrete covering, d_p: tendon diameter) for the three release steps (0 %, 50 %, 100 %)

which caused no splitting cracks and hence represent the maximum possible bond stresses after one day of concrete hardening. Additionally, saw cuts of the CFRP tendons are shown.

The test results show a significant difference in the bond stress-slip relationship of the strut and the seven-wire strand. The maximum stresses are nearly equal, but the progression is different. The seven-wire strand reaches the maximum bond stress at less than 0.2 mm and the strut at approximately 1 mm. At 0 % release one can determine the constant part caused by friction to roughly 7 MPa and 4 MPa for strand and wire, respectively. The slip-dependent part is the margin between the friction part and maximum bond stress at 0 % release, which is 8 MPa for the strand and 11 MPa for the wire. At 50 % and 100 % release of the pre-tensioning the stress-dependant part (Hoyer effect) can be obtained. This effect leads to a large increase in bond stress only for 100 % release and causes a maximum bond stress of about 24 MPa, which means roughly 9 MPa caused by the Hoyer effect for either of the tendons. With the information gained by the pull-out tests, the tests on the transfer length are planned.

3.3 Tests on the transfer length

The first target of the tests is to determine the minimum concrete cover as well the minimum spacing of the CFRP tendons, i.e. the minimum dimensions of the rectangular cross-section avoiding splitting cracks in UHPFRC. The second target is to investigate the transfer lengths of these tests. The concrete age at the release of pre-tensioning is one day.

Figure 4 shows the test setup and the illustrated distribution of bond stress τ, slip δ and concrete strain ε_c along the beam. The specimens are fabricated in a stiff rig, similar to the pull-out tests. After the tendons are pre-tensioned and the formwork is set, the samples are concreted. After the hardening period of one day, the pre-tensioning force is released in five steps as described in [4]. The concrete strains are measured with extensometers. Additionally the end slip of the tendons is measured. The value c/d_p is the ratio of concrete covering and diameter of the pre-tensioning member. The value s/d_p is the ratio of spacing and diameter of the pre-tensioning member. Observations of [3] showed that the estimated ratios c/d_p from calculations and pull-out tests tend to underestimate the required concrete covering for a crack free transfer length for steel tendons in UHPFRC. In this investigations a ratio of 2.5 led to a crack-free transmission (f_{cm} = 120 N/mm²).

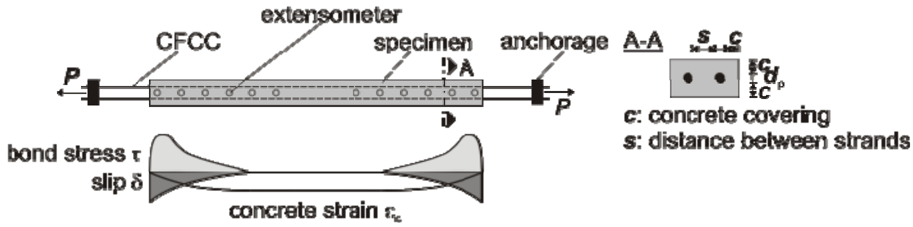


Figure 4: Test setup of tests on the transfer length and schematic bond stress, slip and concrete strain distributions

Figure 5 shows exemplarily the distributions of the end slip for the 7.5 mm seven-wire strand in respect to the induced prestressing force for two different c/d_p ratios while the spacing ratio s/d_p is 8.0 in both cases. With c/d_p = 3.0 (120x52.5 mm²) no splitting cracks were observed, which is confirmed by the progression of the end slip (figure 5, left).

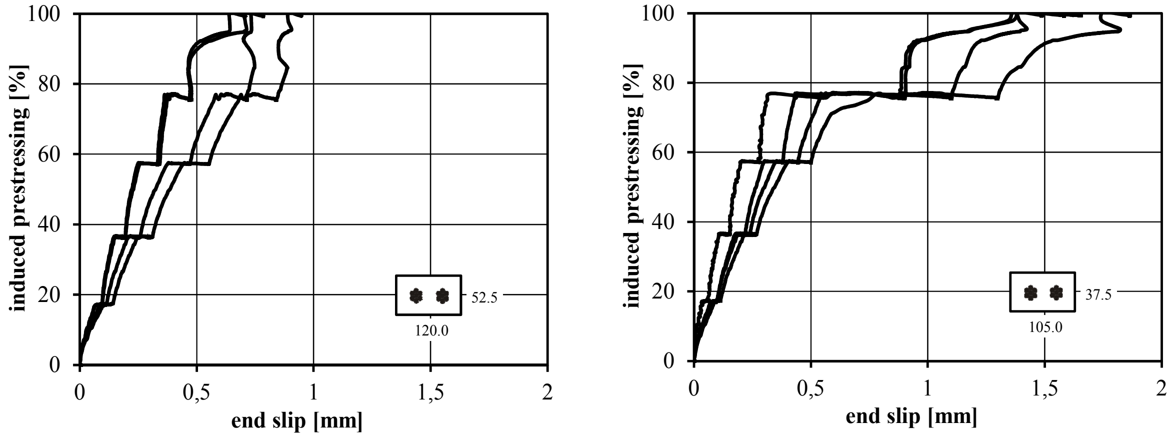


Figure 5: End slip of seven-wire strand for c/d_p = 3.0 (left) and c/d_p = 2.0 (right)

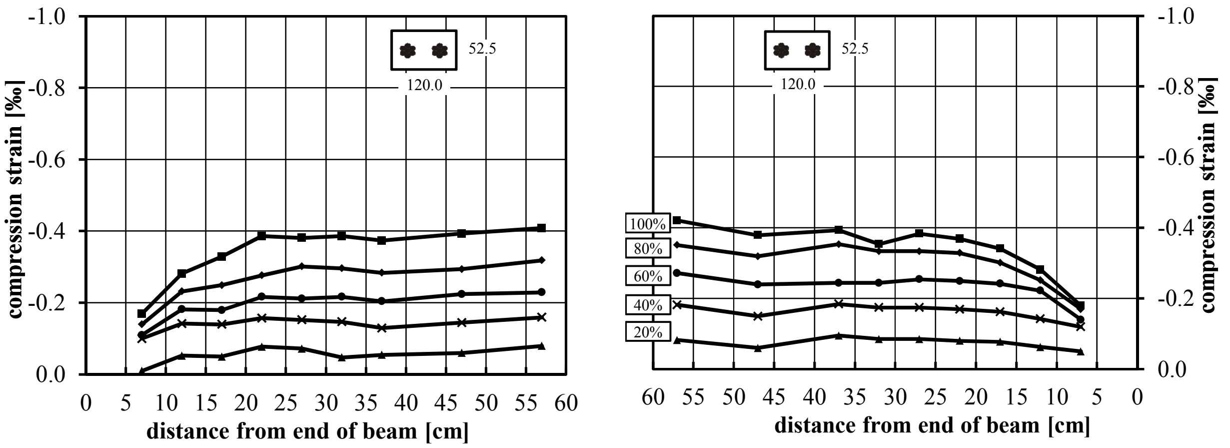


Figure 6: Concrete strains depending on the distance from the end of the beam for c/d_p = 3.0

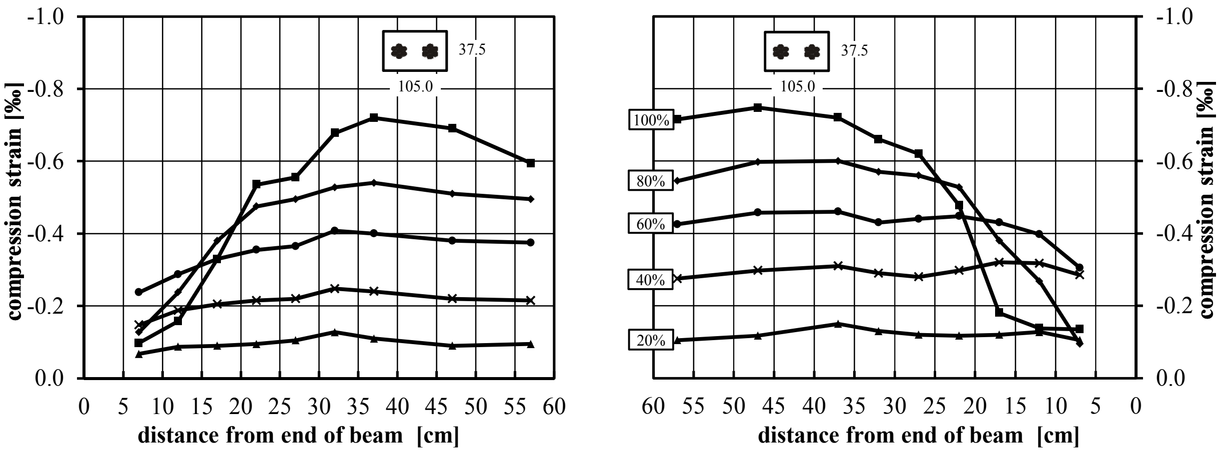


Figure 7: Concrete strains depending on the distance from the end of the beam for c/d_p = 2.0

Only small increases in end slip can be observed while the pre-tensioning is constant, which is caused by bond creep. In contrast, the beams with a ratio c/d_p =2.0 (105x37.5 mm²) showed visible splitting cracks at both ends and both sides of the beam, which were generated at 80 % release of pre-tensioning. This can be seen at the end slip progression in figure 5, right.

Figure 6 shows the measured concrete strains over the length from the end of the beam for a ratio c/d_p = 3.0 at five steps of releasing the pre-tensioning. As the end slip progression shows, there were no splitting cracks observed. The transfer length is less than 0.2 m for a prestressing stress of 1350 MPa and a concrete strength of 65 MPa.

For the beams with a c/d_p ratio of 2.0 the formation of splitting cracks is again confirmed by the measurements of the concrete strains. The visible cracks developed at a length of approximately 0.2 m from the end of the beam at the short sides of the cross-section. This observation complies with the development of the concrete strains for 80 % and 100 % induced prestressing force.

4. SHELLS

Shells provide a high load-bearing capacity compared to their thickness. The bond tests showed that it is generally possible to set up prestressed shells with approximately *d* = 50 mm thickness. Prestressed shells with folded or curved cross-sections, as depicted in figure 8, left, will be established.

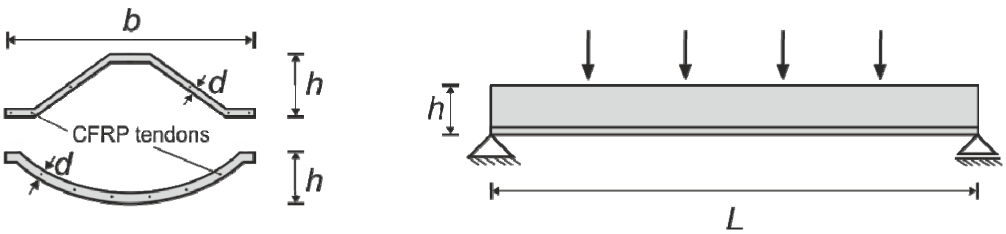


Figure 8: Folded and curved cross-sections (left) and test setup (right)

Firstly, small cross-section with heights *h* of about 0.25 m, widths *b* of 0.65 m and lengths of *L* 2.5 m and 5.0 m, respectively, will be tested under bending action (figure 8, right). The first tests will comprise three point bending tests. Afterwards more loading points will be investigated. Prior to the planned tests, nonlinear simulations were carried out to get an idea of the possible failure modes and ultimate failure loads. The concrete, the support and loading plate were modelled by volume elements with eight nodes (figure 9). The tendons were modelled as truss elements with perfect bond to the concrete. Only one quarter of the shells was modelled with appropriate symmetry conditions.

For the UHPFRC a calibrated damage plasticity law is applied, which is not explained further at this stage. Two general failure mechanisms can be observed:

- Mode A: splitting cracks at the supports
- Mode B: bending cracks in the mid part of the shell

For a three point bending test with 2.5 m span mode A is the general failure mechanism and for shells with 5 m length mode B is the failure mechanism (figure 9). Short shells provide enough stiffness and do not tend to bend, which results large cracks at the supports, since the pretensioned strands provide a discontinuity in the shell. In contrast, long shells are less stiff and are able to bend, which results in bending cracks. With data obtained by finite element modelling as well as the bond test results, the first shells are constructed and will be tested soon.

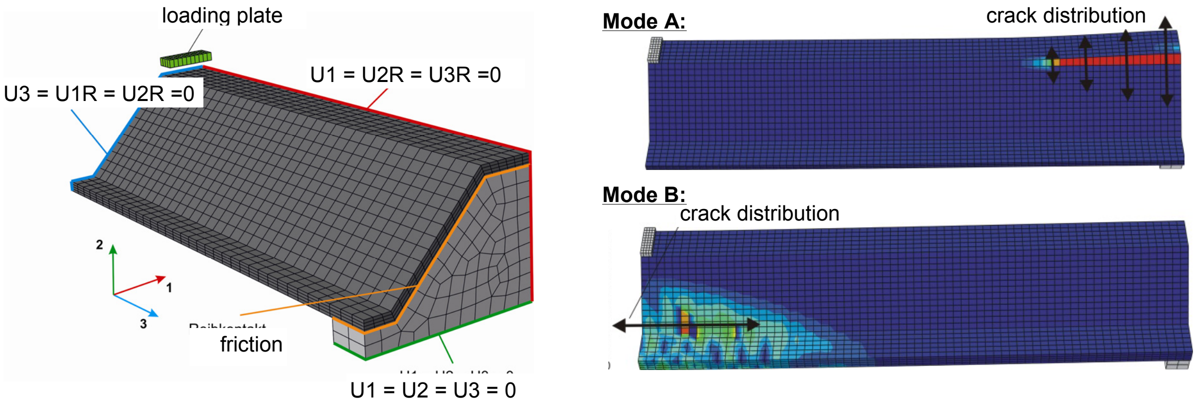


Figure 9: Loading conditions and typical failure modes of folded shells

5. CONCLUSIONS

Bond tests have been carried out to determine local bond stresses as well as transfer lengths and minimum dimensions of UHPFRC beams for a ∅5 mm CFRP strut and a ∅7.5 mm CFRP strand. Additional first finite element simulations showed possible failure modes of folded shells. The results of the experimental investigations can be summarised as follows:

- With either shapes of CFRP tendons bond stresses of about 25 MPa could be reached with full release of pre-tensioning for a concrete strength of 65 MPa.
- The slip dependent part governs the bond stress-slip relationship for the ∅5 mm CFRP strut.
- The transfer length of the ∅7.5 mm CFRP seven wire strand is less than 0.2 m for an uncracked beam.

The application to shells seems possible. The minimum concrete cover ratio c/d_p for a ∅7.5 mm CFRP strand is 3.0. Hence, thicknesses of approximately 50 mm are feasible. Due to a folded or curved cross-section the load bearing capacity will be enhanced.

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