BOND BEHAVIOR OF PRETENSIONED STRANDS UNDER CYCLIC LOADING

Stephan Gessner, Institute of Structural Concrete, RWTH Aachen University, Germany
Josef Hegger, Institute of Structural Concrete, RWTH Aachen University, Germany

ABSTRACT
In a current research project 12 large-scale bending tests are performed on prestressed girders. Within the test program, the influence of concrete strength, bond length and different loads on the tendon slip and transfer length under cyclic loading are investigated. The results enable the calibration of a finite-element model to perform systematical analytics and numerical analysis of the influence of cyclic loads on bond behavior. The aim of the investigation is an assured description of the change in bond behavior due to service conditions based on the performed analyses and the derivation of a design approach for bond anchorage with cyclic loadings.

This paper gives general information about bond mechanisms of strands in pretensioned girders under static and cyclic loadings. Dealing with this topic, a former research program is specified. At last, the currently conducted test program is described and selected results are presented.

Keywords: Pretensioning, Bond, Transfer length, Cyclic loading

INTRODUCTION

Prestressing is required for long spans, innovative floor systems and economic girder designs. Usually pretensioning is used for prefabricated concrete sections. For pretensioning, no anchorage devices are required as in post-tensioned members. Thus, the use of prestressing strands can be very cost-effective.
For the prestressing procedure, first the required strands will be pretensioned in a prestressing bed. After casting and hardening of the concrete the pretensioning is released and transferred from the strand into the concrete. Hereby, no anchorage device is used and the stress is transferred by bond. For this reason not only do the moment and shear carrying capacity of pretensioned beams have to be considered in the design but the bond also has to be guaranteed in order to prevent a premature failure.
The bond behavior of tendons in pretensioned concrete members under static loading was analyzed extensively in the past. The importance of service conditions is increasing because of the use of slender elements in industrial construction as well as an increase in the traffic volume of bridges. Due to limited knowledge of the influence of cyclic loadings on bond anchorages of pretensioned concrete elements, their application under cyclic loadings is not generally accepted in all codes and guidelines[3].

In the past, the Institute of Structural Concrete at RWTH Aachen University investigated the influence of cyclic loading on the bond behavior of pretensioned concrete thoroughly and developed first design models. The current project addresses in order to continue this work.

BOND MECHANISMS

STATIC LOADING

The bond mechanisms of prestressed tendons differ from those of conventional ribbed bars, where the bond is mainly based on the forces between the concrete and the ribs. The bond of tendons as used for prestressing is established by adhesion and friction. In order to obtain friction forces, lateral stresses between tendon and concrete are required. At the time when prestressing is released, the tendon tries to return to its unstressed state. The hardened concrete however counteracts this expansion. Thus, lateral pressure is generated. This so-called "Hoyer-effect", also known as wedge-action, governs the bond strength of strands (Fig. 1).

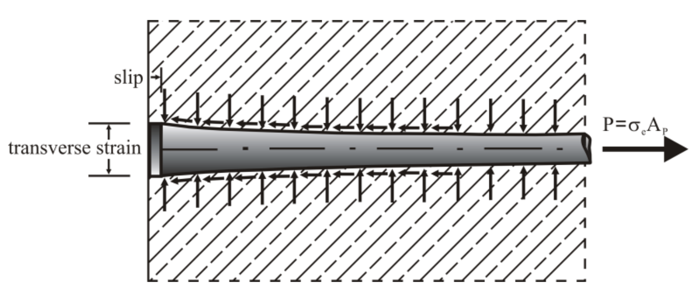


Fig. 1 Hoyer-effect[2]

Of course the radial stresses also lead to tensile stresses in the surrounding concrete. If these stresses exceed the tensile strength, longitudinal cracks arise in the anchorage zone and the Hoyer-effect disappears. For this reason, a sufficient concrete quality and concrete cover has to be maintained and lateral reinforcement may need to be applied accordingly to the circumstances.

Generally, the bond strength can be divided into three parts:

- a constant part caused by the basic friction, also called the rigid-plastic bond behavior;
- a stress-dependent part which is based on the Hoyer-effect and which increases with the degree of prestressing;
- and a slip-dependent part which is also independent of the prestressing. This effect can be explained by the "lack of fit" which results from the geometry of the strands which is not completely uniform.

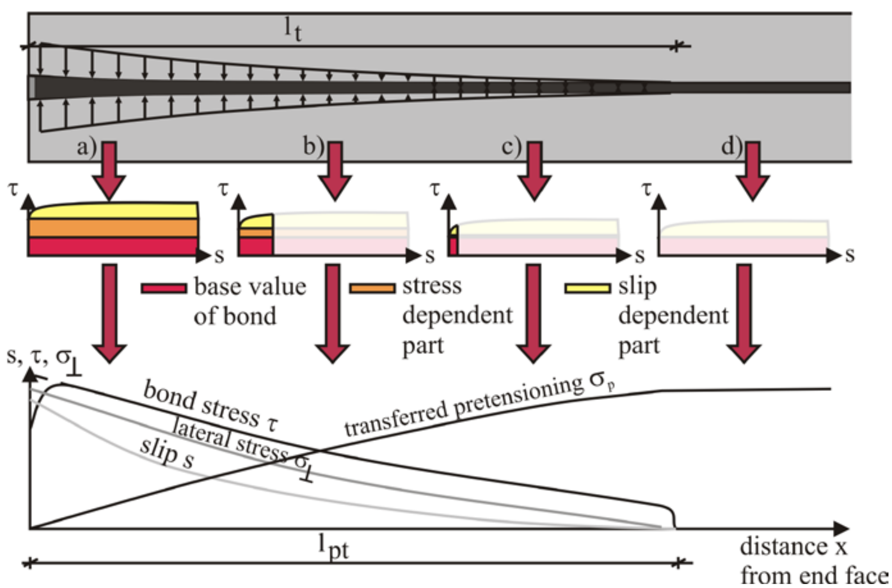


Fig. 2 Transfer of prestressing[2]

Figure 2 illustrates the transfer of pretensioning. Both, the lateral pressure and the slip, decrease along the transfer length l_{pt} according to the pretensioning of the strand which has to be transferred into the concrete. Close to the concrete end face, almost full pretensioning has to be transferred leading to high lateral pressure between steel and concrete. All three bond parts are fully activated. The prestressing of the concrete increases along the transfer length and thus, the stress which has to be transferred decreases. At the end of the transfer length, most stresses already have been transferred from steel to concrete. Here, the lateral stresses and the slip are very small, the bond is mainly established by the base value of the bond. Outside the transfer length there is neither bond nor lateral stresses nor slip due to prestressing.

CYCLIC LOADING

For the understanding of bond under cyclic behavior, the theoretical stress development of the strand is very important (Figs 3-4).
The model of stress development assumes cracked girders are in the tension zone. In the service limit state (SLS) prestressed members are generally supposed to remain uncracked by limiting the tensile stress in the precompressed zone under a defined load combination. Resulting from material deterioration over time, changed utilization and singular overloading this cannot be assured and cracks may develop.
Due to release of the pretensioning, the stresses are transferred continuously from the strand into the beam. When the full prestressing is applied, the stress remains constant (Fig. 3a). Due to the loading of the beam, elastic deformation of the beam occurs as long no cracks occur. This leads to a slight elongation of the concrete around the strand and therefore also to a slight stress increase in the strand. Due to equilibrium, no stress transfer arises (outside transfer length) (Fig. 3b).
The loading is increased and first cracks develop. The strand is stretched in the debonded length. A constant but increased stress level arises, which acts at the transition to the embedment length. This increase also has to be anchored in the concrete (Fig. 3c). The length for the transmission of stresses due to external loads is called flexural bond length ($l_{\Delta\sigma p}$).

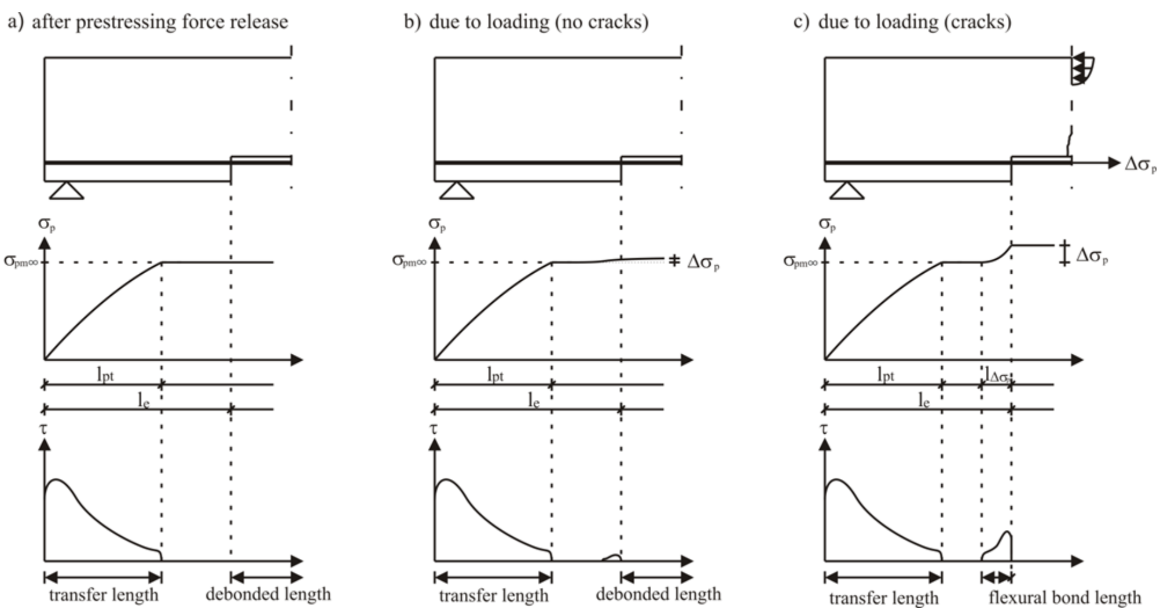


Fig. 3 Bond under cyclic loading (a), (b), (c)

Cyclic loading does not affect the stress level in the debonded length significantly. However, the transmission of the stresses resulting from the loading in the strand proceeds more slowly due to cyclic bond creep. The bond is reduced and the flexural bond length is increased (Fig. 4d).

The cyclic bond creep continues until the flexural bond length overlaps the transfer length which of course remains unchanged. An overlapping of the bond length and the transfer length results in an anchorage failure (Fig. 4f), which has to be prevented.

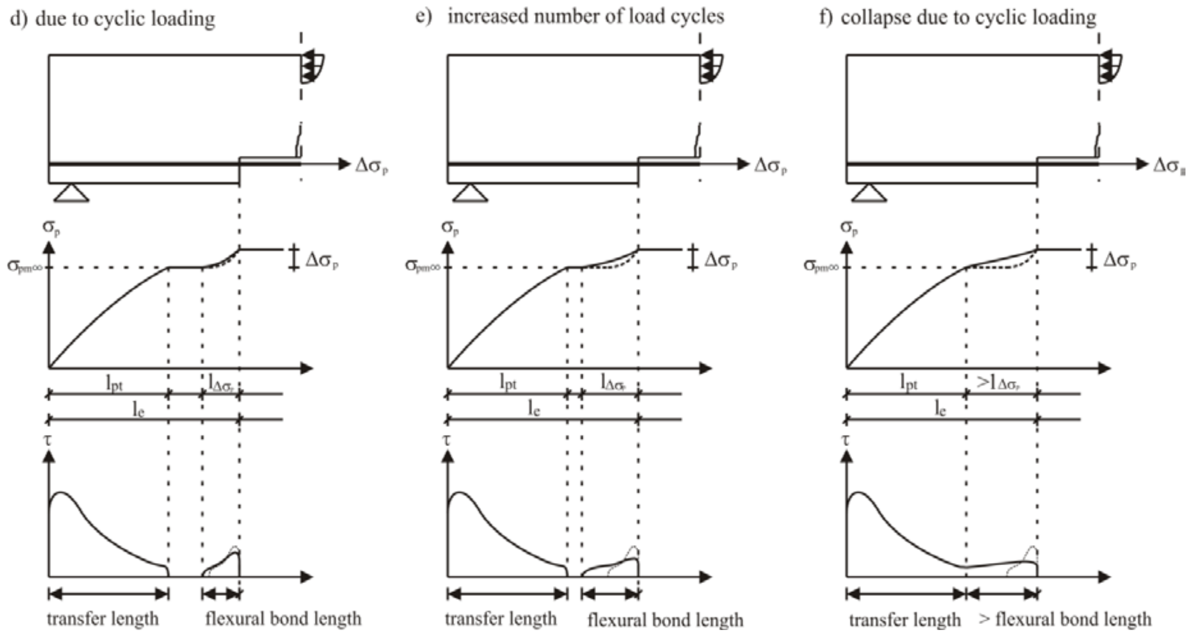


Fig. 4 Bond under cyclic loading (d), (e), (f)

PREVIOUS TESTS

The influence of cyclic loading on the bond behavior of pretensioned concrete has been investigated thoroughly at the Institute of Structural Concrete at RWTH Aachen in the past. A full overview of the research program is given in BÜLTE[2].

CYCLIC PULL-OUT TESTS

In order to determine the local bond behavior under cyclic loading and the residual bond capacity along the transfer length, 60 pull-out tests were performed. The specimens, consisting of concrete cubes (150 × 150 mm) (5.9 in. × 5.9 in.), were tested with varying transfer of prestressing forces.
The specimens are produced with prestressed strands in the testing frame. Before starting the tests, a defined part of the prestressing force is transferred to the concrete cubes. By the variation of the transferred forces, different areas of the anchorage zone can be simulated. Tests on specimens after almost the full release of pretensioning (1100 MPa) (159.5 klbf) described the bond behavior at the beginning of the transfer length (Fig. 2, area a). A medium change in the state of stress (550 MPa) (79.8 klbf) represents the middle segment of the transfer length (Fig. 2, area b) and specimens without any release of the prestressing represent the bond capacity close to the end of the transfer length (Fig.

2, area c-d). The procedure allows the determination of the influence of the Hoyer-effect. The static bond strength (τ_{max}) was determined by two pull-out specimens. For the cyclic examinations, a cyclic load was applied to four corresponding specimens (Fig. 5). The upper (τ_u) and lower (τ_0) load levels were based on the static reference value (τ_{max}). After two million load cycles, the residual bond strength was examined and compared to the reference value.

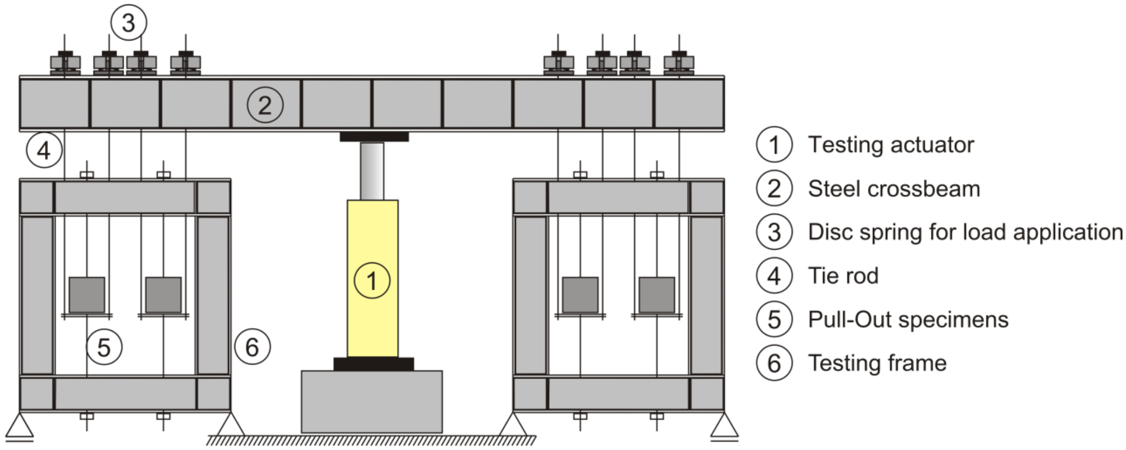
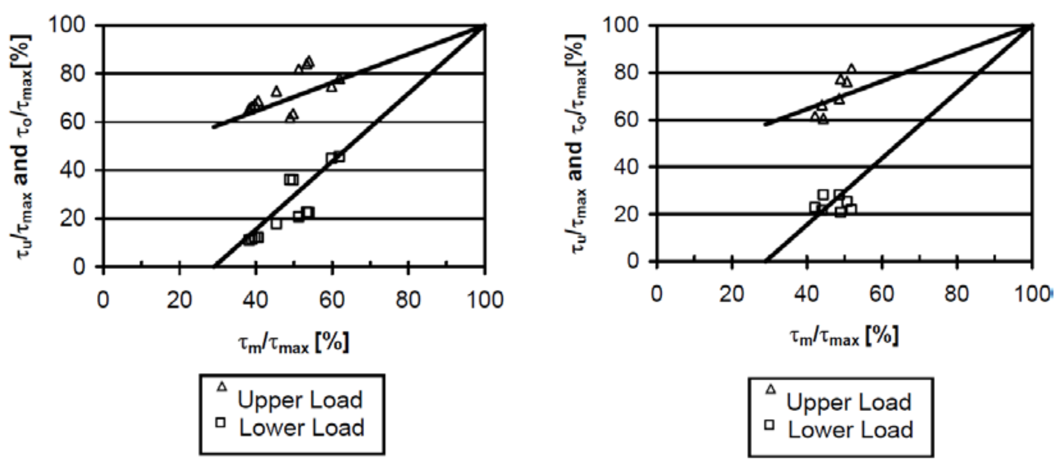


Fig. 5 Experimental set-up of the cyclic pull-out-tests[2]

Previous investigations revealed that the Smith-diagram evaluation of the concrete compressive strength under cyclic loading is also valid for the bond of reinforcing bars under tension[6]. The performed pull-out tests with pretensioned strands, which resisted the cyclic loading, are shown and matched with the boundaries of the Smith-diagram in Fig. 6. Here, the ratios of the upper load level to the static reference (τ_u/τ_{max}) and the lower load level to the static reference (τ_o/τ_{max}) are plotted as a function of the ratio of the mean stress to the static value (τ_m/τ_{max}).



a) With full pretensioning release b) Without pretensioning release

Fig. 6 Loading of tests, which resisted two million cycles, compared to the Smith diagram for concrete compressive strength under cyclic loading[2]

As the results showed, the bond of strands is able to withstand load ranges that lie out of the limits of the Smith-diagram. This is justified because the cyclic loading of the bond of strands does not cause any damage in concrete as long as no considerable slip occurs, i.e. the upper load level is lower than the rigid-plastic bond behavior. In this case the stress range has no recognizable influence for the high fatigue strength of bond. Only after the loosening of the adhesive effect due to cyclic loading, deterioration occurs. This is significantly influenced by the level of the upper load. Thus, the cyclic bond strength of pretensioned strands cannot be expressed as a function of the number of load cycles, as proposed for reinforcement bars. While enduring the cyclic loading, the residual bond strength showed no difference to the static reference values.
The overall result is that a cycling loading with an upper load of up to 80% of the static bond strength does not affect the bond of the strand significantly.

CYCLIC GIRDER TESTS

Based on the results of the pull-out tests the bond behavior along the anchorage length was tested on eight prestressed beams.
Beams 1–6 used PVC-pipes to ensure a debonded length in the middle of the beam. In beams 7 and 8, the debonded area was achieved by boxing out the concrete around the strands in a defined area. This allowed measuring the slip at the inner end of the embedded length. Furthermore, the cross section was also enlarged to prevent shear force failure and the concrete cover was raised up to $3.9 \cdot d_p$, compared to beam 6 ($3.5 \cdot d_p$) due to a longitudinal cracking.
The test enabled the examination of the global structural behavior of the anchorage area. After two million load cycles or alternatively at the time of bond failure, which was established as an excessive slip of the strands, the cyclic loading was stopped. Finally, the residual bond strength was tested.
Only the two final specimens had the design, which allowed a systematic analysis. A detailed specification of the specimen and the testing program can be found in the description of the current test program.

NUMERICAL SIMULATIONS

Since neither the flexural bond length nor the bond stresses can be measured explicitly, a FE-simulation was developed to analyze the behavior. The calibration of the finite element model with the test results gives an estimation of the increase in transfer length due to cyclic loading.

The program uses the isochrone method from FRANKE[4], which can be applied on the differential equation of bond. The program separates the slip between strand and concrete into a load-dependent part and a creep-dependent part. This allows a better simulation for the non-linear bond-slip relationship. To take into account the constitutive equations for bond, which involve the transferred prestressing force due to the Hoyer-effect, an element was developed which represents concrete and steel as well as the appropriate bond layer

(Fig. 7). This 1D-element with two joints and four degrees of freedom is used to simulate the displacements and forces between concrete and strand. The degree of freedom between strand and concrete is modeled by a second longitudinal degree of freedom (bond layer). The calibration of the finite element model with the test results gives an estimation of the increase in the flexural bond length due to cyclic loading.

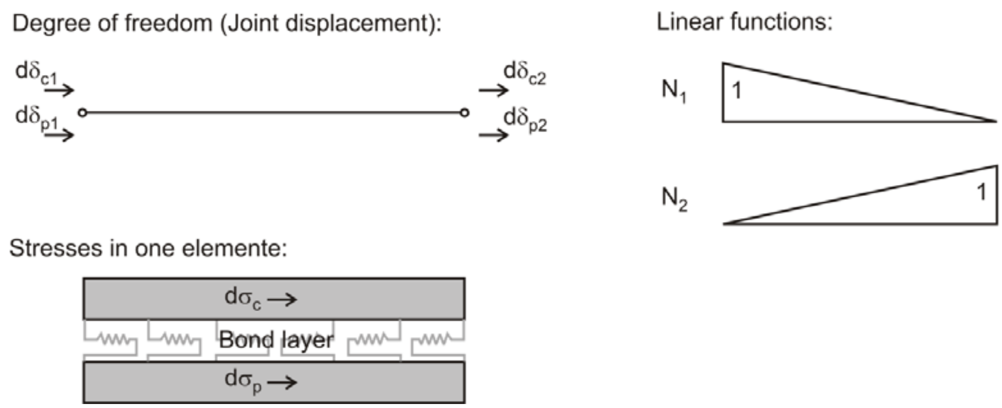
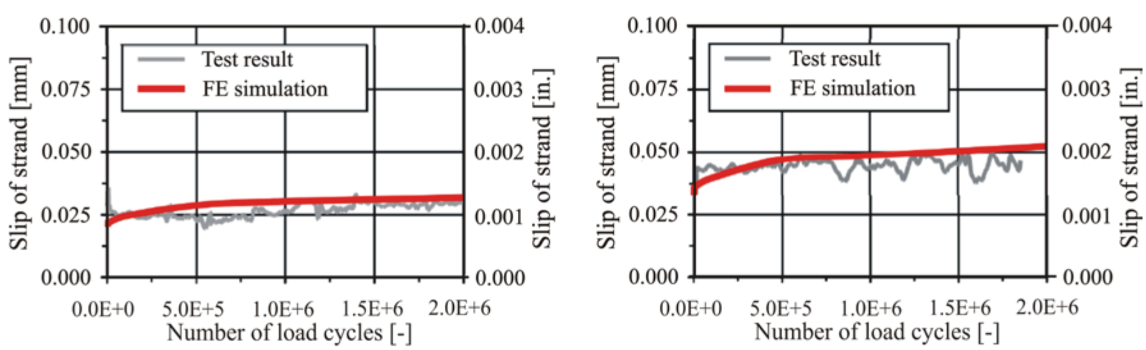


Fig. 7. Selected element with its degrees of freedom and form functions[2]

The results of the numeric simulation showed that these simulations are helpful to estimate the bond behavior of pretensioned strands due to cyclic loading. As Figure 8 shows for beam 7 (f_{ck} = 49.6 MPa (7.2 klbf); $\Delta\sigma_p$ = 160 MPa (23.2 klbf)) and for beam 8 (f_{ck} = 49.6 MPa (7.2 klbf); $\Delta\sigma_p$ = 210 MPa (30.5 klbf)), the result of the finite element model accurately illustrates the slip increase of the strands under cyclic loading.



a) Beam 7 b) Beam 8

Fig. 8 Development of the strand-slip in anchorage-zone under cyclic loadings for beam 7 and beam 8[2]

The first assessment showed that 2.0 Mio. load cycles result in an increase of 30% of the corresponding flexural bond length. After 10.0 Mio load cycles a prolongation of 40 % can be expected. Thus, the existing design approaches[3] for the static bond anchorage have to be adjusted.

However, the calibration of the finite element model considered only the data of two tests. The limited test data is going to be enhanced in the current program in order to allow a better simulation of the bond behavior under cyclic loading.

TEST PROGRAM

The current research project is based on the research program, described above. The aim of the investigation is the description of the change in bond behavior due to service conditions and the derivation of a design approach for bond anchorage with cyclic loadings.

TEST SPECIMEN

In order to investigate the influence of cyclic loading on the anchorage of strands regarding cracks and their location, a total of twelve four-point bending tests on prestressed beams with a debonded length at midspan are performed. The design of the test specimens derives from former tests[2].
The aim of the investigation is to measure the slip at the end of the beam due to transmission of prestressing force and in the bending crack next to the anchorage as a result of the number of cycles.
By providing a defined embedment length, specified stresses on a defined anchorage length can be tested. This way, cracks at a specified location are simulated. A direct measurement of the required anchorage length is not possible. However, by measuring the slip in the area of the load transmission zone, a conclusion of the influence of cyclic loading on the bond can be drawn.
The embedment length l_e of the strands varies between 500 mm (19.7 in.) and 600 mm (23.6 in.) to simulate the uncracked anchorage zone. The debonded zone at midspan of the beam is accomplished by omitting the concrete in the tensile zone. All test specimens have the same dimensions (Fig. 9). The location of the bending crack in the anchorage zone is varied by the length of the debonded zone l_2 in the middle of the beam.

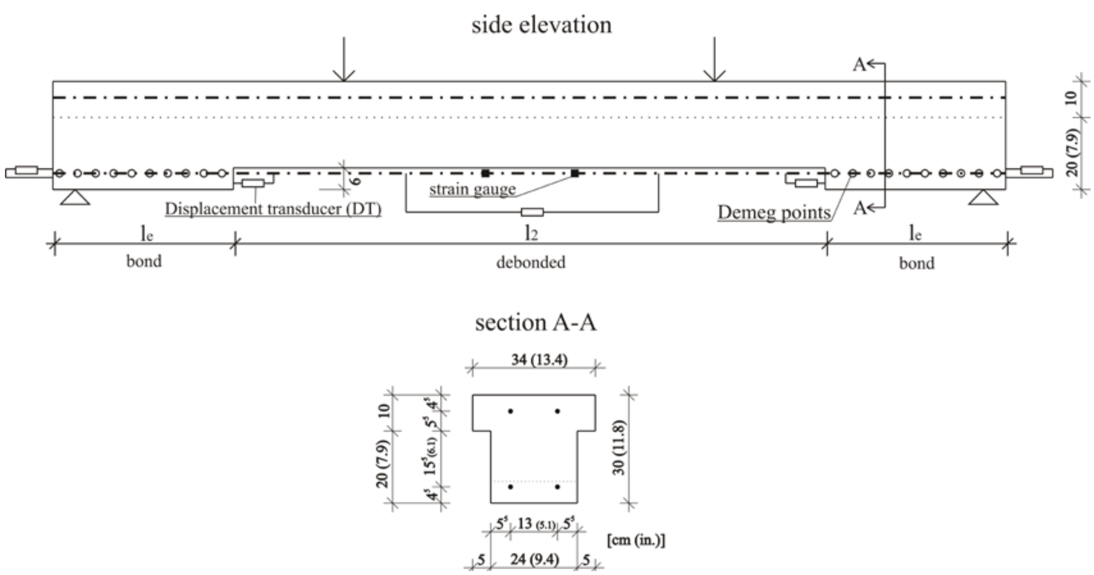


Fig. 9 Test specimen

The compressive strength of the planned cube amounts to 50 MPa (7.3 klbf/in²) and 85 MPa (12.3 klbf/in²) for high-strength concrete, respectively. All specimens are prestressed with 1275 MPa (184.9 klbf/in²) without losses (σ_{pm0}), respectively 1100 MPa (159.5 klbf/in²) with time-dependent losses ($\sigma_{pm\infty}$). The strived for mode of failure is a failure of bond. A premature failure due to shear or bending failure is excluded by the chosen geometry.

Table 1: Test specimen – dimensions and testing parameter

Specimen	7*	8*	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Concrete strength	C 40/50								C 70/85					
l_e	50 (19.7)	60 (23.6)	50 (19.7)				55 (21.7)				60 (23.6)			
l_2 [cm (in.)]	164 (64.6)	144 (56.7)	164 (64.6)				154 (60.6)				144 (56.7)			
Upper Load [kN (klbf)]	134 (30.1)	134 (30.1) 142** (32.9)	-	130 (29.2)	140 (31.5)	150 (33.7)	140 (31.5)	150 (33.7)	150 (33.7)	150 (33.7)	140 (31.5)	140 (31.5)	160 (31.5)	160 (31.5)
Lower Load [kN (klbf)]	50 (11.2)	50 (11.2)	-	70 (15.7)	60 (13.5)	50 (11.2)	70 (15.7)	70 (15.7)	60 (13.5)	50 (11.2)	30 (6.7)	20 (4.5)	50 (11.2)	40 (9.0)

* Specimens from former testing program

** Upper load increased after 590.000 cycles

TEST PROCEDURE

After pretensioning the strands as well as casting and hardening the concrete, the pretensioning force is gradually released. To ascertain the transfer length, the concrete strains are determined with Demeg points. The interpretation is done equivalent to RUSSEL & BURNS[7] and WÖLFEL & KRÜGER[8]. Alternatively the transfer length is measured with the method described in BRUGGELING[1], using the slip at the end of the beam measured during the releasing of the force in predefined steps. The calculated transfer lengths can be used to recalculate realistic mean bond stresses. Hereby, the flexural bond length can be calculated.

Thereafter, a four-point bending test is set up to determine the increase of the flexural bond length by measuring the slip at the transition points at the ends of the bonded length. The main testing parameters are given in Table 1. The upper load level of the cyclic loading is defined by a stress increase in the strands of approximately 150 – 210 MPa (21.8 – 30.5 klbf/in²) ($\Delta\sigma_p$), which corresponds to the stress increase in strands of prestressed girders due to cracking[5]. The lower load level is chosen below the decompression of the beams, but – due to an irreversible crack opening – an additional steel stress of approximately 50 MPa (7.3 klbf/in²) remains. The cyclic loading is stopped after two million load cycles or at the time of bond failure, which is determined by an excessive slip of the strands. Finally, the residual bond strength can be tested.

TEST RESULTS

Altogether 10 tests of the test program have been performed so far. This paper presents the results of three selected tests (I, VI, IX).

Beam I was tested statically to failure to determine the static capacity of the beam. For this purpose the beam was loaded with a force of 100 kN (22.5 klbf). Subsequently five slow loading/unloading cycles were applied. Slip occurred already at a relatively low load level. During the loading/unloading cycles, the slip increased continuously and finally stabilised with a slip of 0.065 mm (0.0026 in.). Thereafter the force was increased in steps of 10 kN (2.2 klbf). At a load level of 125 kN (28.1 klbf), a sudden increase of slip occurred in the anchorage of one strand. In the other anchorage zones, the slip increased after a low increasing of the force, too. Nevertheless, no total failure of bond occurred. The strands were able to anchor again, the slip and the loss of tensioning force were high. At a load level of 190 kN (42.7 klbf) compressive failure occurred in the compression zone.

Generally the bond strength of the specimen with a concrete strength of 50 MPa (7.3 klbf/in²) was lower than expected compared to BÜLTE[2]. Slip occurred already at relatively low loads. In response, the manufacturing method was improved for beam V and VI. Before the placing of concrete, the strands were polished and the framework was sealed with silicone.

For beam VI, the first visible cracks were detected at a load of 110 kN (24.7 klbf). During the initial loading, slip occurred in one anchorage zone at a level of 120 kN (27.0 klbf) and stabilized afterwards; the other anchorage zones stayed stable. After approximately 1,828,000 cycles, the slip increased suddenly (Fig. 10). A continuous rising of slip followed. After 3,818,637 cycles the test was stopped due to a stabilization of the bond. The prestressing forces were still 96.8 kN (21.8 klbf) in the strand with the noticeable slip and 109.3 kN (24.6 klbf) in the other strand. Finally the remaining capacity was tested. The slip increased in all anchorage zones. The mode of failure was a failure of compression zone with a load of 192 kN (43.2 klbf) (Fig. 11).

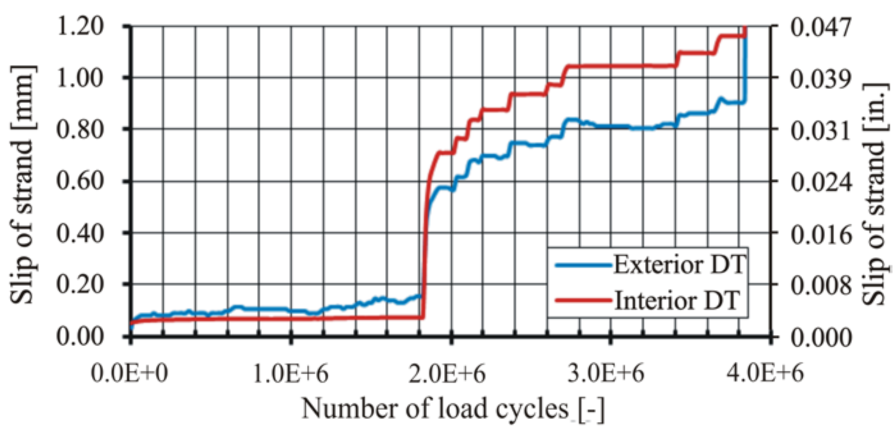


Fig. 10 Slip-development of beam VI

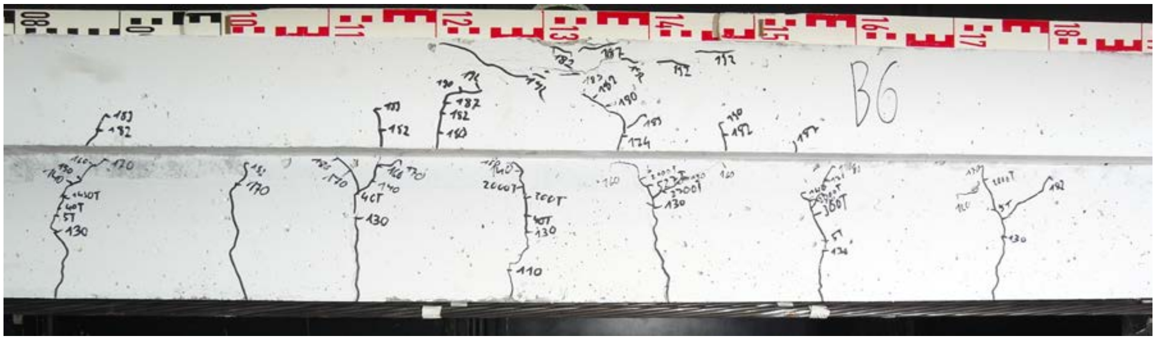
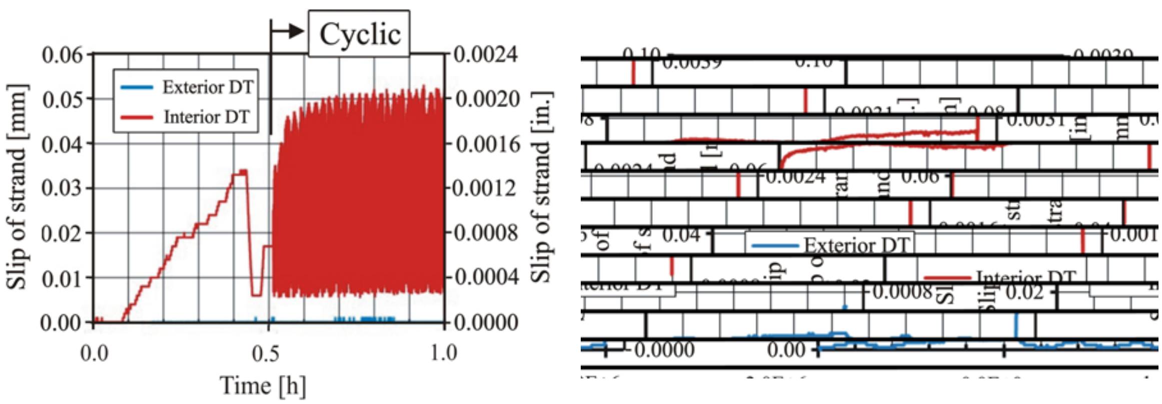


Fig. 11 Final crack pattern of beam VI

The behavior of the specimen with high-performance concrete is presented exemplarily at beam IX. At the initial loading 4, visible cracks occurred at a load level of 140 kN (31.5 klbf). These bending cracks were located at the bottom of the beam, close to the center. The cracks had a distance to each other of about one girder depth.
At the beginning of the cyclic loading, the beam suffered some material injury leading to an increase in slip, but crack growth stabilized soon. The beam resisted the cyclic loading without any appreciable change in its load-deflection characteristic. The level of slip was very low and stayed at a constant level for 2.0 Mio Cycles (Fig. 12).



a) Initial loading b) Cyclic loading

Fig. 12 Slip-development of beam IX

After the cyclic loading, the remaining capacity was tested. With increasing load, the ncracks grew and branched. The slip stayed at a very low level. No bond failure occurred. At a loading level of approximately 200 kN (45.0 klbf) inclined cracks in the compression chord clarified (Fig. 13) and the strands also yielded. Finally the test was aborted at a load level of approximately 220 kN (49.5 klbf), before the breaking of the strands in the middle of the beam.

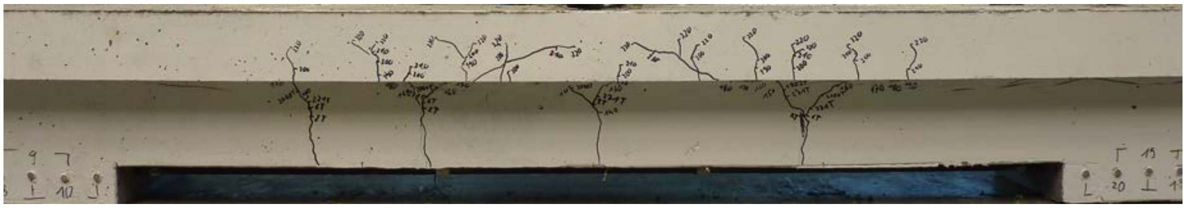


Fig. 13 Final crack pattern of beam IX

CONCLUSIONS AND OUTLOOK

Altogether 10 tests of the test program have been performed so far but the research program is still ongoing. For this reason, this paper cannot present final results.
In reference to the previous program it can be maintained that the anchorage length has to be increased to consider the influence of cyclic loading. To design the anchorage zone of a prestressed member, current codes require the definition of the anchorage capacity curve. At each point the anchorage capacity has to be higher than the tensile forces, otherwise a premature failure occurs. The anchorage capacity consists of the transfer length, which remains unchanged, and the flexural bond length, which has to be adjusted. Based on the performed tests a prolongation of 50% is proposed, which corresponds to a factor of 2/3, according to BÜLTE[2].

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