EXPERIMENTAL AND NUMERICAL STUDY ON STRESS TRANSFER CHARACTERISTIC OF FULLY-BONDED AND SHEATHED STRAND IN PRESTRESSED BEAMS

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ABSTRACT

Strand debonding is a common approach used to reduce cracking at the ends of pre-tensioned concrete beams. While the method has been successful to a large extent, end cracking of pre-tensioned beam ends continues to be a problem. Yet, only limited studies have been conducted to investigate the stress transfer performance of debonded (sheathed) strand. Twenty-four small-scale prestressed concrete beam units with fully-bonded and sheathed strand were tested and their stress transfer characteristics were evaluated. The effects of strand release method, debonding material, and debonded length were considered. Three-dimensional non-linear finite element models were established and calibrated to obtain further understanding of the effect of strand debonding. Experiment results verified that the use of rigid (oversized) debonding material will generally lead to longer transfer lengths compared to soft (tight) sheathing. Numerical simulations demonstrated that the lack of bond strength along the debonded region maximizes strand dilation after release and that this may cause concrete damage if there is tight contact between the strand and concrete, which can be eliminated if enough room is provided for the strand dilation. Thus, the use of rigid or oversized debonding material is recommended for strand debonding practice to prevent beam end damage caused by strand dilation.

Keywords: Strand, Debonding, Sheathed, Prestresss, Transfer length, Finite Element Method.

INTRODUCTION

Understanding the stress transfer characteristics between prestressing strand and concrete is an important element in the design of pre-tensioned concrete products. The ends of prestressing beams are highly stressed due to the strand-concrete stress transfer, which may lead to beam end cracking. There are many factors that can contribute to beam-end cracking. Mirza and Tawfik[1]studied the vertical cracks that appear in the end regions of pre-tensioned members during detensioning and found that such problem can be reduced by providing longer strand free length. Kannel et al.[2] evaluated the effect of strand release sequence on prestressed concrete beam end cracking and recommended approaches to reduce it. One of the methods to minimize cracking at the ends of prestressed beams is strand debonding, which to a large extent has proved to be successful. However, damage in the anchorage zone of beams with unbonded strands during the production of box beams[3] and U-beams[4] for bridges in Michigan and Indiana, respectively, has brought to question the bond behavior of sheathed strand. Unfortunately, only limited studies have been conducted on the performance of debonded strand and the relation between bond-slip response and dilation of tensioned strand during release, which is a potential source of damage, has been generally overlooked. For example, both of the noted prior studies assumed perfect bond between the strand and concrete, and the models by Kannel et al. used one dimensional (truss) elements to simulate the strands.

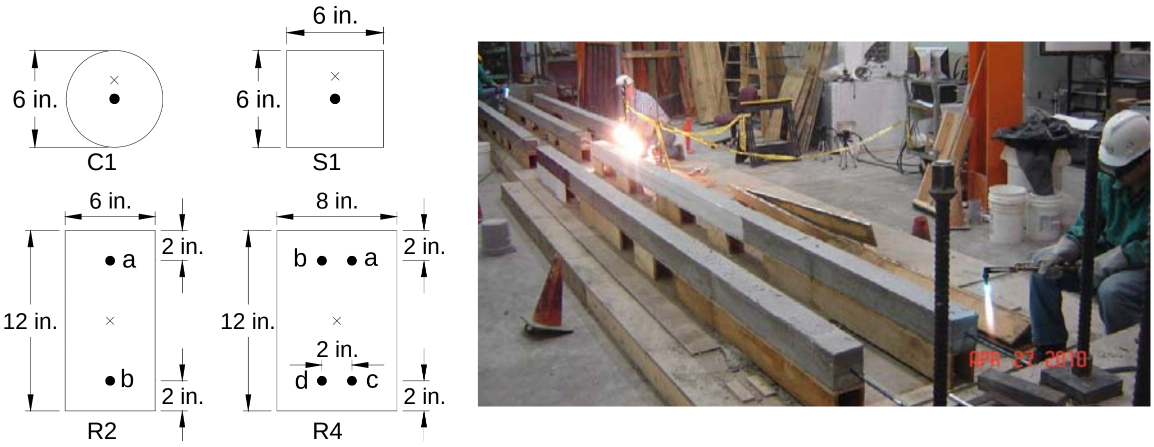
Strand debonding is normally achieved by placing plastic sheathing around the strand. Two different options are typically available for strand debonding, namely: flexible split-sheathing with a tight fit around the strand, or a more rigid preformed plastic tube with an inside diameter greater than the strand (Fig. 1). These debonding options are intuitively thought to have different efficiency. Specifically, the flexible (softer) debonding material with a tight fit to the strand is thought to have lower debonding efficiency as mechanical interlock shear resistance may develop and bond may not be completely eliminated. Some stress may thus be transferred within the debonded region through residual bond and as a consequence the transfer length beyond the debonded region is reduced. On the contrary, stress transfer will not occur within the debonded region if an oversized preformed tube is used since the strand is physically separated from the concrete.

Fig. 1 Photos of two different debonding options: (a) a tight-fitting flexible split-sheathing, and (b) an oversized rigid preformed tube.

The aim of the research summarized herein was focused on gaining basic understanding on the stress transfer characteristics of fully-bonded and sheathed strand and to evaluate potential damaging mechanisms when using shielded strand. The investigation had experimental and numerical tasks based on the testing of 24 small-scale prestressing concrete beams[5,6]. The effects of strand release method, debonding material and debonded length were considered. The numerical study examined the lateral behavior of strand after release and the resulting internal stress state in the concrete.

EXPERIMENTAL STUDY

The effects of debonding option, release method, debonded length, and strand free length on the stress transfer characteristics of prestressing strand were studied through a test program composed of 24 small-scale prestressed concrete beams with fully-bonded and sheathed strand. Conventional concrete and seven-wire 0.6-in. (15 mm) diameter low-relaxation strands were used. The beams were divided in four groups according to their cross-section and prestressing layout, see Fig. 2(a), and each beam was assigned with a unique configuration of test parameters. The test matrix is given in Table 1, where the identification (ID) name follows from the cross section type as shown in Fig. 2. Two types of strand blanketing options were evaluated, namely, (1) sheathing with a flexible (or “soft”) polymer plastic tubing (Concrete Accessories, Inc., Norcross, GA) and (2) sheathing with oversized closed plastic tubing (outside diameter of 0.725 inches [18.4 mm] and wall thickness of 0.04 inches [1 mm].) The flexible slit sheathing was implemented by using two overlapping layers with the slit opening in opposite directions. The concrete compressive strength at the day of test (~ 2 days after casting) ranged from 5,700 psi (37 MPa) to 7,400 psi (51 MPa).



(a) (b)

Fig. 2 (a) Cross-sections of the beam test units (Dark dots represent strands and the cross (x) represents the location of the strain gage instrumented rod. Strand cutting sequence is shown in letters next to the strands.) (b) Strand release process. Note: 1 in. = 25.4 mm

The test setup was the casting bed for the pre-tensioned beams. The testing process was the release of the prestressing strand. The strands were stressed to $0.75f_{pu}$ and were simultaneously released from both ends of the beams, typically two days after casting; see Fig. 2(b). Two release methods were used: sudden release by flame cutting and gradual release by slowly annealing (heating) the prestressing strand. Sudden release took only a few seconds per strand. The annealing process took approximately 15 minutes per strand. Stress transfer behavior was studied by comparing the transfer lengths of the different beams. Transfer length was the parameter used to evaluate stress transfer behavior since it is relatively simple to measure. However, the aim was not to identify new transfer length expressions but to use this parameter to assess the relative effect of different parameters on stress transfer and for calibrating the numerical models. Transfer length was determined by measuring the longitudinal compressive strains on the beams and locating the point at which it became constant. Concrete internal strains (CISM) were measured with an instrumented (strain gages) rod embedded in the beam. The location of instrumented rod is shown with a cross marks ("x") in Fig. 2(a).

Table 1. Test Matrix

Beam ID	*L* (ft)	*Lu/Lb* (%)	Debonding Material	Release	Beam ID	*L* (ft)	*Lu/Lb* (%)	Debonding Material	Release
C1-1	20	0	NA	Gradual	R2-1	20	0	NA	Sudden
C1-2	20	0	NA	Sudden	R2-2	20	7.5	Soft	Sudden
C1-3	20	7.5	Soft	Gradual	R2-3	44	0	NA	Gradual
C1-4	20	7.5	Soft	Sudden	R2-4	44	0	NA	Sudden
C1-5	20	7.5	Rigid	Gradual	R2-5	20	15	Soft	Sudden
C1-6	20	7.5	Rigid	Sudden	R2-6	20	25	Soft	Sudden
S1-1	20	0	NA	Gradual	R4-1	20	0	NA	Sudden
S1-2	20	0	NA	Sudden	R4-2	20	7.5	Soft	Sudden
S1-3	20	15	Soft	Gradual	R4-3	20	15	Soft	Sudden
S1-4	20	15	Soft	Sudden	R4-4	20	25	Soft	Sudden
S1-5	20	25	Soft	Gradual	R4-5	20	15	Rigid	Sudden
S1-6	20	25	Soft	Sudden	R4-6	20	25	Rigid	Sudden

Note: *L* = Beam length; *Lb* = Length of bonded region; *Lu* = Length of unbonded region. 1 ft = 0.3 m.

Since multiple parameters were considered in the study the aim was to evaluate general performance rather than to provide statistically significant evidence for certain parameter. Further, only partial details and results from the study are presented in this paper as manuscripts for archived publications have been submitted. The full study is documented in the report by Burgueño and Sun[5] and the thesis by Sun[6].

EXPERIMENTAL RESULTS

Effect of Strand Release Method

Fig. 3 shows the comparison of transfer lengths for beams with different release methods. It can be seen that beams released suddenly had a longer transfer length than those that were gradually released. This is consistent with expectations since sudden release leads to a higher kinetic energy upon release compared to the gradual process and the additional energy needs to be dissipated in a larger region, thus resulting in a longer transfer length. It should be noted that the transfer length of the sudden released beams C1-2 and C1-4 were much higher compared to the corresponding gradually released beams C1-1 and C1-3. However, such effect was not as significant in the comparison between beams R2-3 (gradual release) and R2-4 (sudden release). The reason may be that the effect of release rate is related to the beam mass and the effect is likely higher in beams with smaller cross section (i.e., less mass). The strand in beam C1-5 was inadvertently cut from overheating during the annealing process. Thus, beam C1-5 was essentially released in a sudden manner and had a similar transfer length as beam C1-6.

Effect of Debonding Material and Debonded Length

Transfer lengths for the R4 beams are shown in Fig. 4. The labels on top of the data bars indicate the debonded length in feet and the letters represent the debonding option (“S” for soft debonding and “R” for rigid debonding.) The figure shows that beams with debonded strand using a rigid debonding material (R4-5 and R4-6) generally had longer transfer lengths than beams using a soft debonding material (R4-2, 3 and 4) and beams with fully bonded strands (R4-1). Comparing the results for beams R4-5 and R4-6 it can be seen that a longer debonded length led to a longer transfer length when rigid debonded material was used. This result was consistent with others from the test matrix in Table 1. The increase in transfer length is attributed to two reasons: i) the debonded strand has more stored strain energy; and ii) concrete-strand debonding is fully achieved when rigid debonding material is used and no stress is transferred within the debonded region.

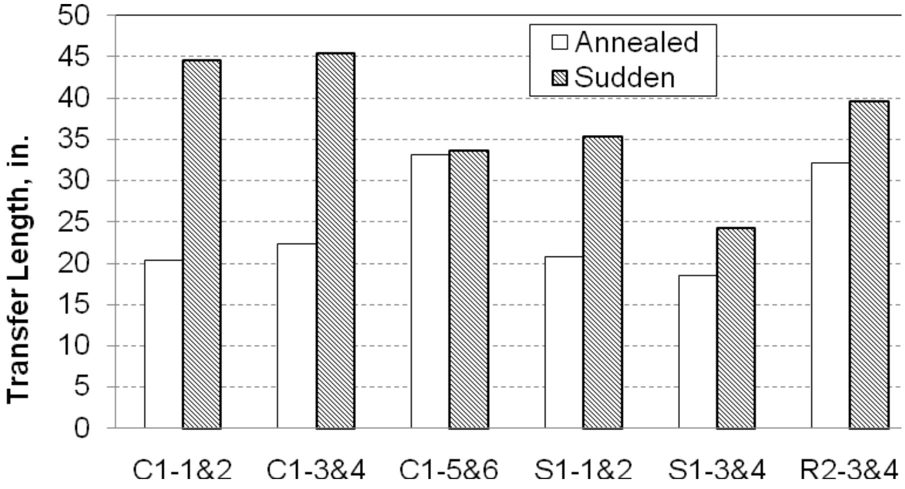


Fig. 3 Effect of strand release option on transfer lengths. Note: 1 in.=25.4mm

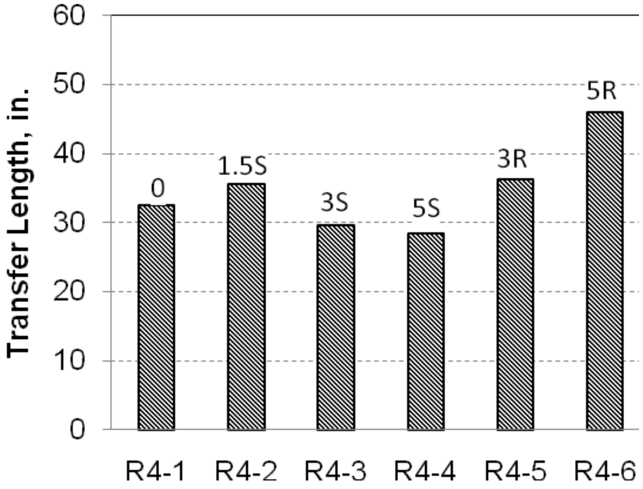


Fig. 4 Effect of debonding/blanketing material on transfer lengths based on concrete internal strain measurement (CISM). Note: 1 in. = 25.4 mm.

The beams with debonded strand using soft sheathing had similar or shorter transfer lengths compared to those with fully bonded strands. This is attributed to the fact that, even though more strain energy is also stored in strands, part of the pre-tension force is actually transferred within the debonded region. The effect of additional strain energy in the unbonded strand is also reduced due to the partial bond resistance along the debonded length. Thus, the stress transfer region changes depending on the relative significance of the two noted phenomena. It can be observed form Fig. 4 that beam R4-2 had a slightly longer transfer length than the fully bonded beam (R4-1). However, with the increased debonded length the effect of partial prestress transfer in the debonded region starts to dominate and thus beams R4-3 and R4-4 had shorter transfer lengths than beam R4-1.

NUMERICAL STUDY

Numerical models were established using the finite element program Abaqus[7]. Models for all beams (24) in the test matrix (Table 1) were developed and calibrated with the experimental data. Material properties for the model were based on test data for the different beam test units. A concrete damage plasticity model was used for the concrete material model while the strand was assumed to be elastic.

Three-dimensional continuum elements were used to model both the concrete and strand parts. The strand was modeled as a cylindrical rod with an equivalent cross-sectional area equal to the actual strand. The prestress in the strand was introduced in the model by defining an initial stress condition so that the strand was stressed at the beginning of the analysis. The equivalent diameter of the rod was 0.5245 in. (13.32 mm) after considering the initial stress due to pre-tensioning. The bond between the strand and concrete along fully bonded regions was simulated with a surface-based contact definition such that the strand and the surrounding concrete surfaces could not penetrate each other in the normal direction. A non-linear friction model, which was controlled by the contact pressure and a friction coefficient, was defined between the two surfaces in the tangential direction. After release, the strand dilates due to its Poisson’s ratio and pressure is generated between the strand surface and the surrounding concrete. This pressure was used as the normal pressure needed for the friction model. Friction coefficient values were determined by calibrating the model with experimental data, namely the longitudinal concrete strain profile after transfer. The transfer of the pre-applied stress in the strand to the concrete after release was the only load in the numerical model.

Strand-concrete interaction in the strand debonded region when the strand was to be simulated as shielded with a soft (flexible) material was similar to the fully bonded case with one key difference a zero friction coefficient was defined to simulate the eliminated bond strength. However, the prestressing strand and concrete had a tight fit, thus a normal pressure was still generated after release. This approach was used to represent the easily-deformable characteristic of the soft slit sheathing material. On the other hand, oversized holes were defined around strand parts that were to be simulated as shielded with an oversized rigid debonding material. Thus the bond mechanism was completely eliminated and there was no interaction between the strand and the concrete even after release.

SIMULATION RESULTS

Effect of debonding material

Models for the C1 beam series (see Table 1) were used to assess the effect of debonding material. Beam C1-2 had a fully bonded strand, while the strand in beams C1-4 and C1-6 was debonded for 1.5 ft (0.46 m) with soft and rigid debonding material, respectively. Fig. 5 shows contours of the maximum principal stresses in the vertical mid plane of the beam and Fig. 6(a) shows a plot of the principal tensile stress along a path on top of the beam. It can be seen that a region of high tensile stresses is generated close to the strand. For beam C1-2 (fully bonded), high tensile stresses concentrate in a region close to the beam end and decrease rapidly along the beam length. For beam C1-6, in which the strand is ideally debonded (rigid oversized debonding), the principal tensile stresses in the debonded area are essentially eliminated, while the stress level beyond the debonded region is also reduced. However, it can be observed that the C1-4 model predicts high tensile stresses all along the debonded region and that the trend of tensile stress beyond debonded length is similar to the end region of the fully bonded beam unit (C1-2). These results show that debonding with close-fitting soft material delays the decrease of principal tensile stresses and that high stresses remain throughout the debonded region.

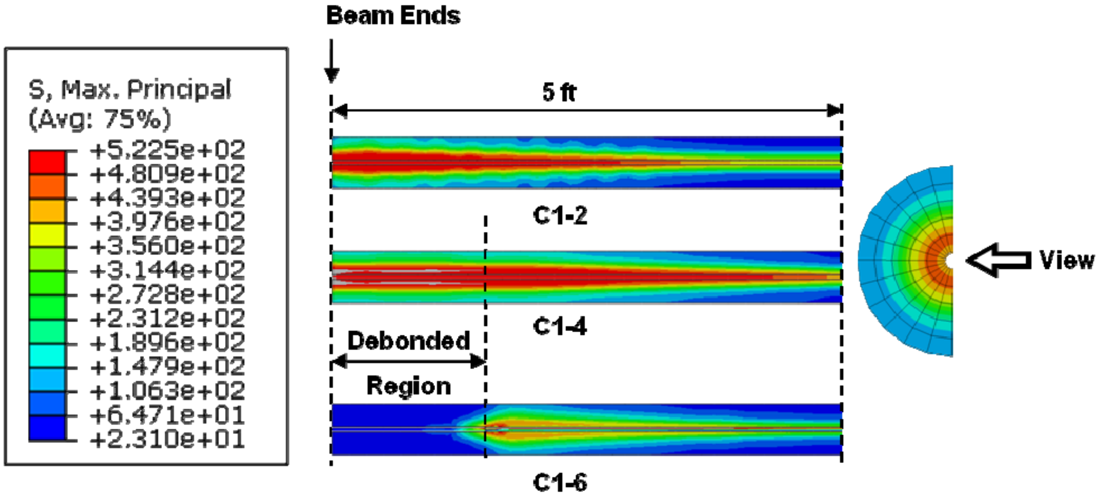
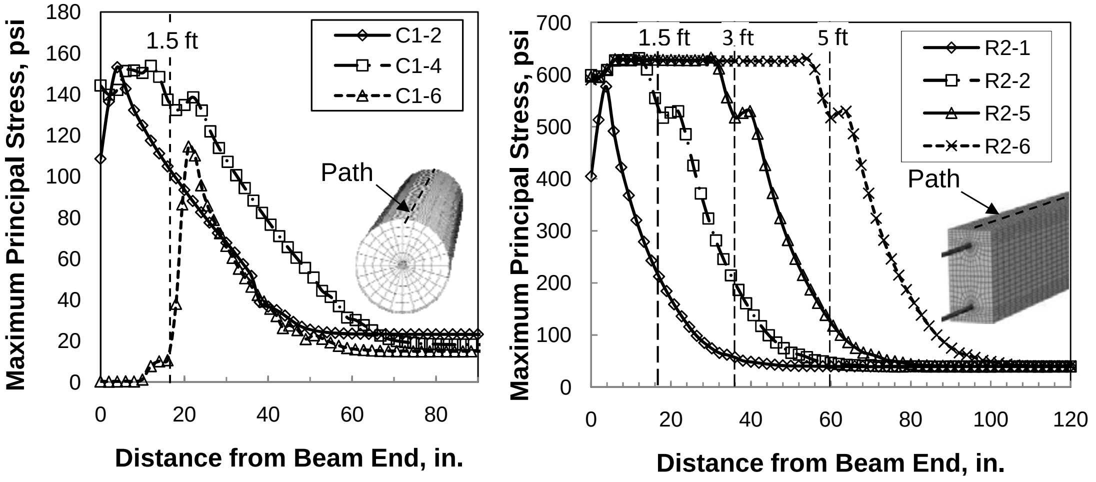


Fig. 5 Maximum principal stresses (psi) in the vertical mid-plane for the C1 beam models. Note: 1 ft = 0.305 m; 1 psi = 6.9 kPa.

Effect of debonded length

The effect of debonded length was studied using models for the R2 beam series. Fig. 6(b) shows traces of the maximum principal tensile stresses for beams R2-1, R2-2, R2-5 and R2-6, which were debonded using soft material for 0 ft (0 m, i.e., fully bonded), 1.5 ft (0.46 m), 3 ft (0.91 m), and 5 ft (1.52 m), respectively. It can be seen that for the beams with debonded strands the tensile stresses along the debonded length are higher than the maximum stress value of the fully bonded beam (R2-1). In addition, it can be observed that a longer debonded length lead to a longer region of high stresses, i.e., strand debonding delays the decrease of the tensile stress level.



(a) C1 Beam Models (b) R2 Beam Models

Fig. 6 Comparison of maximum principal stress (psi) along the top surfaces for the C1 and R2 beam models. Note: 1 in. = 25.4 mm; 1 psi = 6.9 kPa.

Effect of adjacent strands

Results of maximum principal strains (or maximum tensile strain) for the beam models with four strands (R4 cross-section) are presented in **Fig. 7** for sections at the beam end. The strands in beam R4-1 were fully bonded from the beam end were debonded with soft material for 3 ft (0.91 m) and 5 ft (1.52 m) in beams R4-3 and R4-4, respectively. The strands in beam R4-5 were debonded with a rigid oversized debonding material (ideally debonded) for 3 ft (0.91 m). Since the R4 beams featured multiple strands, particular attention was paid to the effect of adjacent strands when evaluating the simulation results.

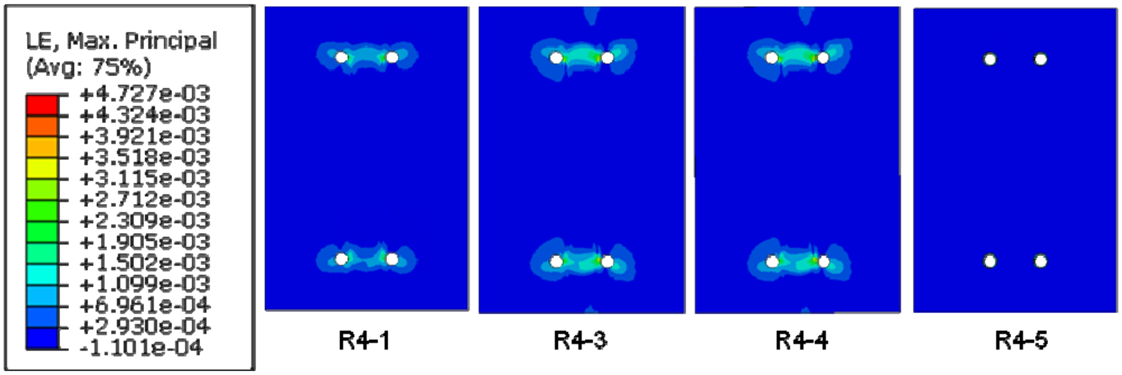


Fig. 7 Maximum principal strains at the end cross sections of the R4 beam models.

It can be observed from Fig. 7 that the maximum principal strains are high around the strands for all beams except for beam R4-5 (beam with rigid and oversized debonding material.) It can also be seen that the high strain region around adjacent strands tends to merge, which represents the growth of a potential cracking region. Further, a small high strain region on the top and bottom of the beam surface is apparent for beams R4-3 and R4-4, which indicates that cracking may propagate to these surfaces. It needs to be noted that the concrete strength for beam R4-3 and R4-4 was lower than for the other beams.

DISCUSSION

RELATION BETWEEN STRAND BOND-SLIP RESPONSE AND DILATION

It has been shown in the previous section that the concrete around a debonded strand was highly stressed within the debonded region if the strand and concrete have a tight contact. The reason follows from the fact that the absence of bond strength maximizes expansion of the strand after release. This phenomenon is explained in the following paragraphs with reference to the equivalent system shown in Fig. 8.

Consider a strand segment in which the expansion of the strand after pre-tension release is represented by an equivalent axial compressive force ΔF. Force ΔF can be considered to be the force drop in a strand segment along the transfer region after release. The bond strength between strand and concrete is represented by two springs in the horizontal direction with stiffness K_Z and the radial interaction (or normal interaction between strand and concrete surfaces) is represented by two springs in the vertical direction with stiffness K_r.

By considering equilibrium for the system and loading in Fig. 8, if the stiffness K_Z is significantly high (bond strength is high) the axial force ΔF will be balanced by the force in the two horizontal springs with very small longitudinal deformation (Δ_z). Thus, the lateral deformation (Δ_r), which depends on Δ_z due to the strand's Poisson's ratio, is very small. As a consequence the force in the vertical springs, $F_r = \Delta_r$ Kr, will be very small. Thus it can be expected that if the longitudinal springs have lower stiffness (poor bond strength) the force in the vertical springs will be larger and will be maximized if stiffness K_Z is zero (i.e., no bond strength at all. This is the reason why the numerical models have shown that concrete within the debonded region will be highly stressed if there is no room for the strand to expand freely. It follows that such phenomenon also implies that the radial expansion of strand after release will also be greater if the strand has substandard bond quality.

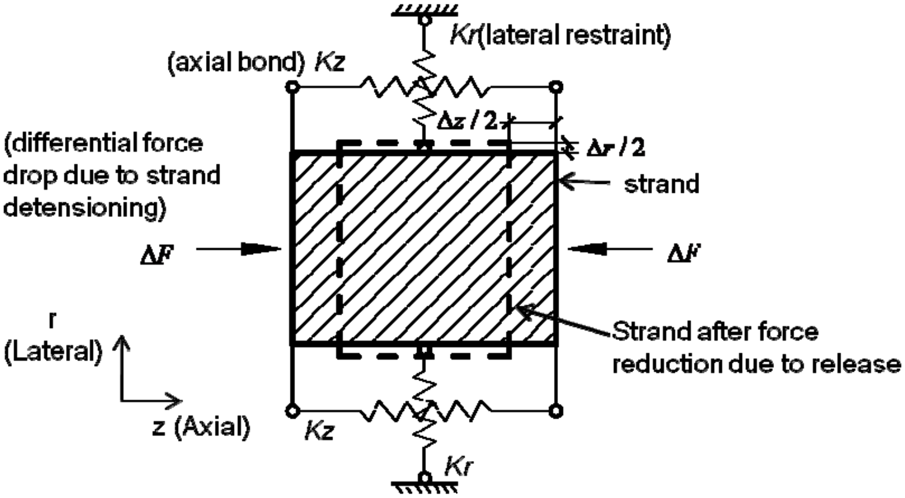


Fig. 8 Free body diagram of a strand segment under the effect of a differential force change during the stress transfer process.

TRANSFER LENGTH

The findings from the presented study provide valuable information for future research on the estimation of design parameters such as transfer and development length but, as previously noted, determining new expressions for these factors was not the focus of the study. Moreover, the development of a general transfer length expression is not statistically appropriate since the number of tests is relatively small for the large number of variables considered. The aim was rather to conduct a systematic investigation and provide scientific evidence to mechanisms and behavior that, while empirically known to different degrees, may benefit the precast/prestressed concrete industry by providing sound technical evidence.

CONCLUSIONS

The study summarized in this paper led to the following findings and conclusions:

1. Sudden release (flame cutting) of strand will lead to longer transfer lengths compared to strand released gradually (annealed). This is due to the larger kinetic energy transferred to the concrete upon sudden release. The degree of this effect depends on the beam mass, damping along the stress transfer zone and the friction with the casting bed.
2. Strand debonded with flexible slit sheathing can transfer longitudinal and radial stresses to the concrete due to the shear resistance provided from the Poisson effect (i.e., dilation) of the strand at the beam end, and to a lesser degree from the strand dilation along the debonded length (which increases friction resistance). This effect is not related to the shear resistance that can result from paste infiltration inside the split sheathing.
3. Strand sheathing with oversized rigid (or closed) tubing fully eliminates any stress transfer from the strand to the concrete in both longitudinal and radial directions.
4. As a consequence of the findings noted in (2) and (3), the transfer length for strand blanketed with flexible sheathing can be shorter due to the force transferred over the debonded length. However, the effect diminishes when the release is sudden and it depends on the concrete stiffness and the damping characteristics of the flexible sheathing material. Thus, the reduction in transfer length cannot be relied upon.
5. Similar to the point above, the transfer length of strand blanketed with oversized rigid sheathing is longer than for strands blanketed with soft tight fitting sheathing.
6. Strand shielded with oversized rigid material can have longer transfer lengths than fully-bonded strands since more of the pre-tension strain energy in the debonded region is released and transferred to the concrete. The additional released strain energy is not as large for strand shielded with a soft tight sheathing since part of the energy is lost through friction resistance and damping.
7. Debonded strands with tight-fitting flexible sheathing can lead to concrete cracking along the debonded length due to the radial expansion resulting from the reduced bond strength. Conversely, the use of oversized rigid sheathing avoids damage from strand dilation.
8. Concrete damage from the dilation of debonded strand with tight-fitting flexible sheathing can be more severe for adjacent debonded strands as the induced tensile stress states interact.

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