Technical Notes

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Short Tendon Elongations

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Elongations are difficult to accurately and consistently predict when post-tensioning tendons are short. One reason for this is, in short tendons, normal seating losses are a significant percentage of the calculated elongation. Normal *variations* in seating losses in short tendons can often result in differences between measured and calculated elongation, which fall outside the range of ±7% tolerance permitted in ACI 318-11, Section 18.20.1, which requires that differences between measured and calculated elongations exceeding ±7% "…shall be ascertained and corrected." For normal-length tendons, seating loss, and particularly *variations* in actual measured seating losses, are a much smaller percentage of the total tendon elongation and do not present the same problem as they do in short tendons. Another reason is that any inaccuracies in placing the initial reference mark on the tendon tail or measuring the elongations have a larger effect on small elongations than on large elongations. Just the width of the line made on the strand to mark the unstressed position can be a significant percentage of the calculated elongation. Variations between assumed and actual seating losses in short tendons can also result in significant differences in effective tendon force.

There is no precise borderline defining the difference between a "short tendon" and a tendon of "normal length." Herein, the PTI Special Topics Committee (PTI DC-70) defines a short tendon as one whose length is less than the tendon length affected by wedge travel after jack release (anchor set) L_{set} with an assumed anchor set distance of 0.25 in. Typically, this will result in "short tendon" lengths up to 35 ft. The purpose of this paper is to examine the ramifications in seating loss variation in short tendons and recommend measures to ensure that short tendons satisfy their full design intent. It should be noted that "short tendons" can result not only from building geometry but also by the placement of a stressing construction joint across a longer tendon.

Two remedies for the problems inherent in short tendon elongations have been discussed within the Committee. One remedy involves modifying the ACI 318 tolerance for short tendons from a percentage (±7%) to a finite length, such as ±1/4 in. The other involves retaining the same ±7% tolerance, but conservatively reducing the effective tendon force in short tendons to reflect the largest possible seating loss likely to occur. A combination of these two remedies has also been discussed.

To study the ramifications of each remedy, an analysis was performed examining various parameters for three tendon lengths: 15, 20, and 30 ft. The three short tendons were assumed to be parabolic in profile, each in one-way concrete slabs with thicknesses of 5 in. for the 15 ft length, 6 in. for the 20 ft length, and 9 in. for the 30 ft length. Tendon stresses were calculated before and after jack release using standard procedures* assuming four sample seating losses of 0.125, 0.25, 0.375, and 0.50 in. for each of the three tendons.

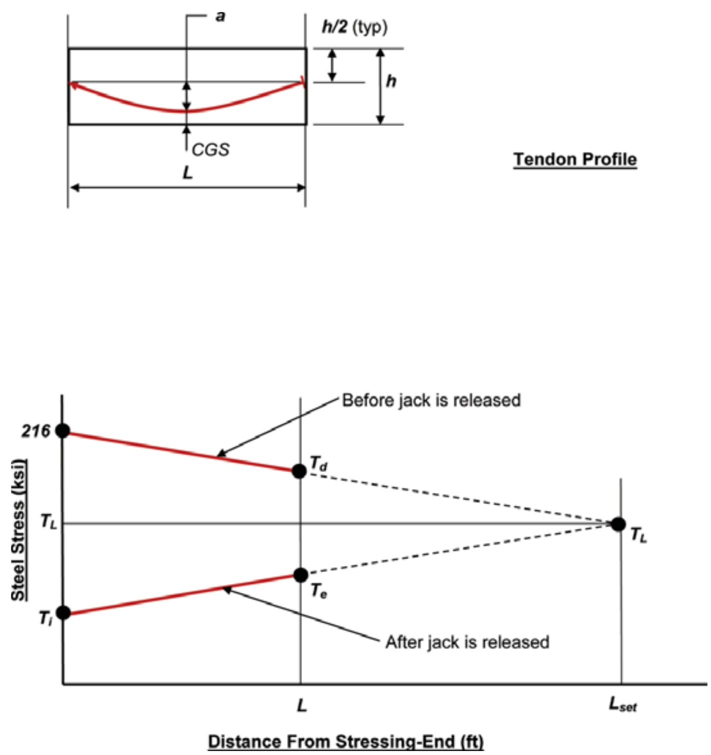

Fig. 1—Tendon profile and tendon stress diagram.

The Committee feels that the conditions studied realistically represent the range of conditions found in practice for short tendons. Tendons shorter than 15 ft in length are rarely used; designers are encouraged to use non-prestressed reinforcement in such conditions. The elongation discrepancy problems greatly diminish with tendon lengths longer than 35 ft. Thus, it is felt that meaningful conclusions and recommendations can be drawn from the study executed herein.

**Post-Tensioning Manual*, fifth edition, Post-Tensioning Institute, Farmington Hills, MI, 1990, 406 pp.

ANALYSIS

For purposes of this analysis, Fig. 1 and the following notation will be used—all specific to this discussion. In all cases, steel stress at the jacking end of the tendon, before release, is $0.8f_{pu}$ = 0.8 × 270 = 216 ksi; low-point *CGS* = 1 in.; and long-term losses are assumed to be 15 ksi.

NOTATION AND DEFINITIONS

L = tendon length (ft)
h = slab thickness (in.)
a = tendon drape (in.)

$$a = \frac{h}{2} - CGS$$

where *CGS* represents the distance between the bottom of the concrete member and the center of the steel strand.

T_{grad} = friction loss gradient, average stress loss per unit of tendon length due to friction between stressing end and fixed end (ksi/ft)

$$T_{grad} = \frac{216 - T_d}{L}$$

L_{set} = tendon length affected by anchor set (ft)

$$L_{set} = \sqrt{\frac{28,500(SL)}{12T_{grad}}}$$

SL = seating loss; wedge travel distance in anchorage after jack is released (in.)

T_d = steel stress at fixed end before jack is released (ksi)

$$T_d = 216e^{-(KL+\mu\alpha)}$$

T_L = steel stress at a distance L_{set} from stressing end (ksi)

$$T_L = T_d - T_{grad}(L_{set} - L)$$

T_e = steel stress at fixed end after jack is released (ksi)

$$T_e = 2T_L - T_d$$

T_i = steel stress at stressing end after jack is released (ksi)

$$T_i = 2T_L - 216$$

e = base of Naperian logarithms
K = assumed friction wobble coefficient = 0.0014
μ = assumed friction curvature coefficient = 0.07
α = total tendon curvature in distance L (radians)

$$\alpha = \frac{16a}{L}$$

Δ = calculated tendon elongation (in.)

$$\Delta = \frac{\frac{(216 + T_d)}{2}L}{28,500} - SL$$

F_e = effective force per 0.5 in. diameter, 270 ksi low-relaxation strand (kips)

$$F_e = 0.153(T_i - 15)$$

where 15 represents the long-term losses in ksi.

F_{jack} = jacking force per 0.5 in. diameter, 270 ksi low-relaxation strand (kips)

$$F_{jack} = 0.153 \times 0.8 \times 270 = 33.04 \text{ kips}$$

F_i = steel force at stressing end after jack is released (ksi)
$F_i = 0.153T_i$

The results of the analysis are presented in Table 1.

EXPERIMENTAL STUDY

A study† was conducted in 2011 to measure actual seating losses in short tendons. In the study, wedge travel after jack release SL and initial anchor force F_i were measured in four randomly selected industry-standard anchorages using a tendon with a length of 20 ft, 11 in. between the stressing-end and fixed-end anchorages and stressed with a jack having hydraulic

†Report 2011-1, available from PTI.

Table 1

L, ft	15				20				30			
h, in.	5				6				9			
SL, in.	0.125	0.25	0.375	0.50	0.125	0.25	0.375	0.50	0.125	0.25	0.375	0.50
L_{set}, ft	26.3	37.1	45.5	52.5	27.4	38.7	47.4	54.8	28.3	40.0	49.0	56.6
T_d, ksi	209.6	209.6	209.6	209.6	208.1	208.1	208.1	208.1	204.9	204.9	204.9	204.9
T_L, ksi	204.7	200.0	196.4	193.4	205.2	200.7	197.2	194.3	205.5	201.2	197.8	195.0
T_i, ksi	193.4	184.0	176.9	170.8	194.3	185.3	178.5	172.6	195.0	186.3	179.7	174.0
T_e, ksi	199.9	190.5	183.3	177.3	202.2	193.3	186.4	180.6	206.1	197.5	190.8	185.2
Δ, in.	1.22	1.09	0.97	0.84	1.67	1.54	1.41	1.29	2.53	2.41	2.28	2.16
F_e, k	27.3	25.9	24.8	23.8	27.4	26.1	25.0	24.1	27.5	26.2	25.2	24.3

Notes: 1 in. = 25.4 mm; 1 ft = 305 mm; 1 ksi = 6.89 MPa.

wedge power-seating capability. Each tendon was installed in a steel tube with a load cell at the fixed end. Because there was no friction acting on the strand between anchorages, the force in the tendon was constant at each point in the strand and the load cell at the fixed end also measured the force in the strand F_i immediately behind the stressing-end anchorage. Each tendon was stressed to a jacking force F_{jack} of 33.04 kips; the wedges were seated, and wedge position was measured before and after jack release. As in the analytical study mentioned previously, long-term losses were assumed to be 15 ksi for the determination of the effective tendon force F_e. Results of the study are shown in Table 2.

Note: Stressing jacks that do not have hydraulic wedge power-seating capabilities and that use mechanical wedge seating will have higher seating losses. This type of stressing jack is not recommended to be used when stressing short tendons, unless the effects of the higher seating losses are considered in the final effective force calculation.

DISCUSSION OF RESULTS

The results of the experimental study presented in Table 2 show that effective tendon forces can be determined accurately with the analytical methods used to develop Table 1. For example, in Table 2, the effective tendon force F_e with the maximum measured seating loss of 0.35 in. was 24.57 kips. This is within 2% of the calculated effective force for the 20 ft long tendon with SL = 0.375 in. in Table 1 (25.0 kips). Similar correlation between experimental and analytical results can be found with all of the tendons studied. The experimental study also suggests that a realistic value for the maximum seating loss is 3/8 in. when using a stressing jack with hydraulic wedge power-seating capability.

Knowing that effective tendon forces can be reliably calculated for the full anticipated range of seating losses, the ramifications of variations in seating losses can be evaluated. To accomplish the evaluation it will be assumed, as is normally done, that the calculated elongation for each tendon length was based on a seating loss of 0.25 in. Those values are highlighted in yellow in Table 1. Then, the ramifications of different actual measured elongations assuming seating losses of 0.125, 0.375, and 0.50 in. were evaluated. Seating losses between 0.125 and 0.50 in. represent the maximum range reasonably anticipated in normal construction; in addition, the Committee feels that a seating loss of 0.50 in. represents the maximum seating loss physically possible with commercially available single-strand unbonded wedge anchorage systems. This was supported by the results of the experimental study.

For all three tendon lengths, any of the studied seating losses different from the 0.25 in. value assumed in the elongation calculation would result in measured elongations exceeding the ±7% tolerance permitted by ACI between measured and calculated elongations. For example, with a tendon length of 15 ft, an actual seating loss of 0.125 in. would result in a difference in measured and calculated elongation of 12% (1.22/1.09-1) × 100, which exceeds the ACI tolerance. The percentage differences are even greater for actual seating losses greater than 0.25 in. Similar conclusions can be drawn for the 20 ft long tendon. As expected, it is seen that even small differences between actual and assumed seating losses will result in differences between actual and measured elongations that exceed the ACI ±7% tolerance. On the other hand, a tolerance of ±1/4 in. between measured and calculated elongations would be satisfied for each tendon length within the reasonable range of expected seating losses (0.25 to 0.50 in.) for all three tendon lengths.

Table 2

Test	F_{jack}, kips	SL, in.	F_i, kips	F_e, kips
1	33.04	0.225	29.20	26.90
2	33.04	0.245	28.82	26.52
3	33.04	0.350	26.87	24.57
4	33.04	0.225	28.48	26.18

SUMMARY AND RECOMMENDATIONS

Whenever variations between measured and calculated tendon elongations are observed, it should be standard practice to confirm that there are no shortcomings in the original elongation calculations or the standard stressing procedures. However, the following factors can have a particularly significant effect on the measured elongation and the final effective force in short tendons:

- Variation in seating loss;
- Inaccuracies or inconsistencies in placing the initial reference mark on the tendon tail; and
- Inaccuracies in measuring the elongation.

Refer to Chapter 6 and 7 in the third edition of PTI's "Field Procedures Manual" for additional potential causes of elongation variation. The PTI Special Topics Committee recommends the following to mitigate these factors and ensure that short tendons satisfy their original design intent.

At the design and detailing stage (addressed to the licensed design professional and the tendon supplier, as appropriate):

- Perform friction and long-term loss calculations using a conservative assumption for seating loss for short tendons, similar to the analysis presented in Table 1. These calculations should be system-specific and should consider stressing equipment to be used (power seating, spring-loaded seating devices, and so on). For example, for the specific geometry studied in Table 1, with the largest seating loss of 0.5 in., the minimum effective tendon force for all tendon lengths is 23.8 kips/tendon. Thus, for this geometry, limiting the effective tendon force for short tendons to 23.8 kips would account for all reasonable variations in actual seating loss. If this approach is used, the effects on the structure of larger actual effective tendon force (resulting from smaller actual seating loss) must be evaluated.
- Indicate the assumed effective tendon force for short tendons, and the length that defines a short tendon, on the contract documents.

When tendon elongations are evaluated (addressed to the licensed design professional responsible for approving elongations):

- Rather than a percentage tolerance, consider an arbitrary length tolerance, such as ±1/4 in., for variations between measured and calculated elongations for short tendons.

- Consider a percentage tolerance larger than ±7% for variations between measured and calculated elongations for short tendons, as done by the AASHTO LRFD Standard (1998).

If all of the aforementioned recommendations and conservative assumptions are executed by the design professionals and the tendon supplier at the design and detailing stage, variations between measured and calculated elongations in short tendons larger than 7% can be evaluated and deemed acceptable.

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