pti Technical Notes

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Specifying Post-Tensioning Requirements for Buildings: Force or Number of Tendons?

By DC-70, The Special Topics Committee of the Post-Tensioning Institute

At some point in the design of every post-tensioned concrete member, the licensed design professional (LDP) must determine the prestressing forces required in the member to satisfy code requirements. This prestressing force is calculated after all initial and long-term losses have been accounted for and is commonly referred to as the Final Effective Force (FEF). The FEF and the tendon profile are the two most important design parameters in post-tensioned members. The FEF and the tendon profile determine the flexural stresses under service loads. Using appropriate code equations and unbonded tendons, the prestressing force at nominal strength is a function of the FEF. There are several ways to assure that the FEF in the structure is achieved, depending on the size and strength of the prestressing steel installed.

Over the years, various prestressing steels have been used, including seven-wire strand with several different diameters, stress-relieved and low-relaxation, with strengths of 250 and 270 ksi (1723 and 1862 MPa); 1/4 in. (6 mm) diameter wires with a strength of 240 ksi (1655 MPa); and high-strength bars with varying strengths and diameters. Each type of steel can have unique friction and long-term loss properties. Today, the prestressing steel used in most buildings in the United States is 1/2 in. (13 mm) diameter, 270 ksi (1862 MPa), low-relaxation, seven-wire strand conforming to ASTM A416/A416M.

When stressed from one end only, friction along the tendon reduces the force applied by the jack to a smaller force at the fixed end. For normal-length tendons, once the jack is released and the wedges are seated, the force in the tendon reduces at the stressing end, increases to the stress acting at the wedge seating influence distance, and then decreases further to the fixed end. This assumes a bilinear force distribution from the stressing to the fixed end. For short tendons, where the wedge seating influence distance is greater than the distance between anchorages, the force at the stressing end is reduced when the jack is released and the wedges are seated and then increases to the force at the fixed end. In a tendon stressed from both ends, the lowest tendon force normally occurs near the middle of the tendon length. It has been commonly assumed that, with time, this force eventually redistributes over the length of the tendon, resulting in a constant "average" force along the entire tendon length. Most post-tensioned buildings in the United States have been designed with this "constant force" assumption. Whether the redistribution actually occurs has been debated and the possible resulting ramifications have been studied.[1]

This document will highlight the three most common methods used by LDPs to specify the FEF requirements in contract documents. These methods are:

1. Specifying the minimum required FEF after all friction and long term losses have occurred (usually expressed in terms of kips or kips per foot).
2. Specifying the number of tendons of a particular size ***and*** strength and the FEF per tendon assumed in the design.
3. Specifying ***only*** the number of tendons of a particular size and strength with no mention of effective force per tendon.

While all three methods are used, they involve significant differences in responsibility assumed by LDPs and post-tensioning (PT) suppliers. LDPs and PT suppliers should be aware of and clearly understand these different options. The benefits and limitations of each method are discussed below.

METHOD 1: SPECIFY FEF

In this method, the LDP specified in the contract documents only the minimum required FEF, the tendon profile assumed in the design, the location of any closure strips assumed in the design, and whether the design was based on a constant-force method or a variable-force method.* The selection of number and size of tendons required to furnish the required FEF with the specified profile is assigned to the PT supplier. The PT supplier, using the unique known material properties of their selected post-tensioning system, along with the contractor's preferred sequence of construction and construction joint locations, determines the number of tendons required to satisfy the design—that is, to furnish the required FEF shown on the contract documents. This involves the calculation, ***by the PT supplier,*** of all friction losses, initial losses, long-term losses, the FEF in each tendon, and the total number of tendons required to satisfy the design.

All of this is shown by the PT supplier on the PT instal-

*If no information about constant or variable force design methods appears in the contract documents, it is standard practice to assume that the design was based on the more commonly used constant force method.

lation drawings and calculations, which are usually submitted to the LDP for review. Generally, the total required FEF specified in contract documents in a particular member or length of slab is not an exact multiple of the calculated FEF per tendon. Rounding, either up or down, is then required on the part of the PT supplier. The LDP should establish rules for such rounding, and include them in the contract documents. A general discussion on rounding, including some general guidance, is included at the end of this document.

In this method, the ***PT supplier***, not the LDP, has the responsibility for accurately calculating losses in accordance with the standard of care for post-tensioning loss calculations.

Advantages of the FEF method (Method 1) are:

- It does not exclude any size or type of tendon;
- It places the responsibility for calculating losses in the hands of the PT supplier, who is most familiar with loss calculations in general, and for its own system in particular;
- It allows the Contractor and PT supplier to work out construction joint locations and sequence of construction without changing the design. Providing the number of tendons to meet the minimum FEF is required regardless of construction joint locations; and
- It offers the best assurance that the design is satisfied—that is, that the required FEF is actually provided.

A disadvantage of the FEF method (Method 1) is:

- If clear rules for rounding (including if it is permissible) are not established, either on the contract documents or by local standard practice, disputes can arise between the LDP and the PT supplier. A rational rounding protocol is presented later in this paper.

METHOD 2: SPECIFY NUMBER OF TENDONS AND MINIMUM FEF PER TENDON

In this method, the LDP specifies the number, material properties, and size of tendons required, and also specifies the minimum FEF per tendon on which the number and size was based. The LDP also requires that the PT supplier verify, by calculation, that the minimum FEF can be achieved with the construction joint locations and pour sequence selected by the Contractor and PT supplier. If the PT supplier cannot satisfy the LDP's specified minimum FEF per tendon, the PT supplier must then provide more than the minimum number of tendons specified in the contract documents.

This method is closely related to the FEF method (Method 1), since the LDP is indirectly specifying the minimum total FEF required as the product of the number of tendons and the minimum FEF assumed per tendon. In spite of the fact that the LDP specifies the number of tendons, the PT supplier is still responsible for loss calculations to verify the specified minimum FEF per tendon.

Advantages of Method 2 include:

- The LDP has more control over the post-tensioning materials than in Method 1 because both number of tendons and a minimum FEF per tendon are specified; and
- Easier correlation between structural and installation drawings than in Method 1.

Disadvantages of Method 2 could include:

- Responsibility for losses is unclear, as they are implicitly specified by the LDP (by the number of tendons) but calculated by the PT supplier to verify the minimum FEF per tendon; and
- Changes in construction joint location and/or pour strips may require the LDP and PT supplier to change the number of tendons and issue revised contract documents and installation drawings.

METHOD 3: SPECIFY NUMBER OF TENDONS ONLY

In this method, the LDP specifies only the number and size of tendons required in each member, as well as specifying the location of all construction joint(s) and closure strip(s) assumed in the design. No mention is made, on the contract documents, of any type of force or stress in the prestressing steel. To specify the number of tendons on the drawings, the LDP must first assume prestressing steel properties and calculate, estimate, assume, or otherwise determine all losses, and therefore the LDP assumes responsibility for the accuracy of those losses. The PT supplier satisfies the contract documents merely by furnishing the number and size of tendons specified. In this method, the PT supplier has no responsibility for prestressing losses.

The advantages of Method 3 include:

- It is easier for the PT supplier to interpret the drawings.
- It is easier to correlate between structural and installation drawings.
- "Rounding" disputes are avoided.

The disadvantages of Method 3 include:

- A single set of loss properties must be assumed, and it could exclude, or at least discourage, the use of otherwise acceptable tendon types and sizes; and
- Changes in location of construction joint(s) and/or closure strip(s) may require the LDP to change the number of tendons and issue revisions to the contract documents.

ROUNDING WHEN CONVERTING FEF TO NUMBER OF TENDONS

Some engineers feel that rounding down is **never** permissible when determining the required number of tendons. They argue that a minimum specified force (FEF) means just that: nothing less than the minimum force is acceptable. Others feel that there should be some tolerance on the minimum specified force. Rules for rounding should be stated in contract documents to avoid disputes when minimum forces are specified (as in Methods 1 and 2 discussed previously). One rational rounding protocol is presented in the following as an example. It involves the following terms:

$\boldsymbol{FEF_{spec}}$ = total FEF specified in a structural unit, which is taken to be a beam, a slab-band, or a width equal to half the span for pan-joists, one-way slabs, and two-way slabs with distributed tendons.

FEF_{tendon} = specified or calculated minimum FEF per tendon

N_{reqd} = number of tendons required

$$N_{reqd} = \frac{FEF_{spec}}{FEF_{tendon}}$$

If the decimal portion of N_{reqd} is less than a certain percentage of N_{reqd} (2% is often used for the limiting percentage), the number of tendons is rounded down. If the calculated percentage is equal to or greater than the limiting percentage, the number of tendons is rounded up. The larger the group of tendons evaluated (say, a band of 25 tendons or 14 tendons in a beam), the less effect rounding will have on the FEF specification.

For example, using 2% as the limiting criterion, assume the specified FEF for a beam is 440 kips and the calculated minimum FEF per tendon is 27.0 kips. N_{reqd} = 440/27 = 16.3 tendons, (Decimal portion/N_{reqd} = 0.3/16.3) × 100 = 1.8% < 2%), therefore round down and use 16 tendons.

SUMMARY AND CONCLUSION

The Post-Tensioning Institute (PTI) does not endorse the use of any one of these three methods, or the practice of rounding when converting from FEF to number of tendons. In PTI's view, these selections should be made by the LDP, who should be knowledgeable in these matters. To avoid conflict and confusion, PTI strongly recommends that both the LDP and the PT supplier understand the ramifications of these decisions and the divisions of responsibilities associated with each method.

REFERENCES

1. Bondy, K. B., "Variable Prestress Force in Unbonded Post-Tensioned Members," *Concrete International,* V. 14, No. 1, Jan. 1992, pp. 27-33.

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