Frequently Asked Questions

Field Elongation Measurements

Answers from the PTI Unbonded Tendons Committee July 2007 • Issue No. 6

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QUESTION:

Why are discrepancies in field elongation measurements so ***difficult*** to resolve?

ANSWER:

Probably every technology used today in construction or elsewhere, has its Achilles Heel. In post- tensioned construction, especially unbonded applications where shorter tendon lengths are prevalent, this is the dreaded "field measured elongation review". Every contractor, installer, independent inspection company, engineer, and yes even the post-tensioning material fabricator, dreads this like a swift kick in the backside. While it is an integral part of all post-tensioning operations, its results can be misunderstood, leading to disagreements, finger-pointing, and late nights trying to get a resolution prior to tomorrow morning's 4 a.m. concrete placement – we have probably all been there once or twice … or more.

This ***Frequently Asked Question*** response is intended to provide some basic points in an attempt to convey to those involved in the application and review of field measured elongation reports an explanation of why they are necessary, what they mean to those involved in the review process, and how to interpret these results. This is not intended to be an engineering explanation with a lot of equations and code statements; it is intended to be a practical approach for those involved in the field application and review process, as well as at the engineer's level.

WHY ARE FIELD ELONGATION MEASUREMENTS NECESSARY?

We all know from the theoretical side of "how post-tensioning works" that it involves a combination of prestress ing force (P) and tendon profile (e), sometimes referred to as tendon drape. In basic principle, when the tendon is placed in the required profile and the force is applied, the tendon tries to straighten itself out between anchorage points (or between inflection points in multiple span conditions) but the density of the concrete prevents this resulting in an upward lifting force, commonly referred to as the balanced load. In addition, compression is applied on the concrete through the bearing surface of the anchorages. *The field measurement of tendon elongation is a confirmation that the required force has been transferred to the tendon.*

Since the physical properties of the prestressing steel, the curvature due to the tendon profile, the length of the tendon, and the force that is applied (this is where calibrated stressing equipment is important) are all known values, the theoretical elongation of the tendon can be calculated.

WHAT FACTORS ARE INVOLVED IN CALCULATING ELONGATIONS?

The prestressing steel in an unbonded post-tensioning system is encased in a plastic sheathing to prevent it from bonding to the concrete. As the prestressing force is applied and the tendon elongates, there is a frictional resistance force that is developed between the steel and the sheathing. The application of P/T coating (the grease that gets on everything) that is applied to protect the steel from corrosion helps reduce the friction, but nonetheless significant friction still exists and is still a very real consideration. Although the stressing jack is applying a consistent jacking force (under full tensioning load, 33 kips for 270 ksi, ½ in. diameter prestressing steel), the fixed end feels a slightly lower force than the stressing-end due to this frictional resistance. (Fig. 1)

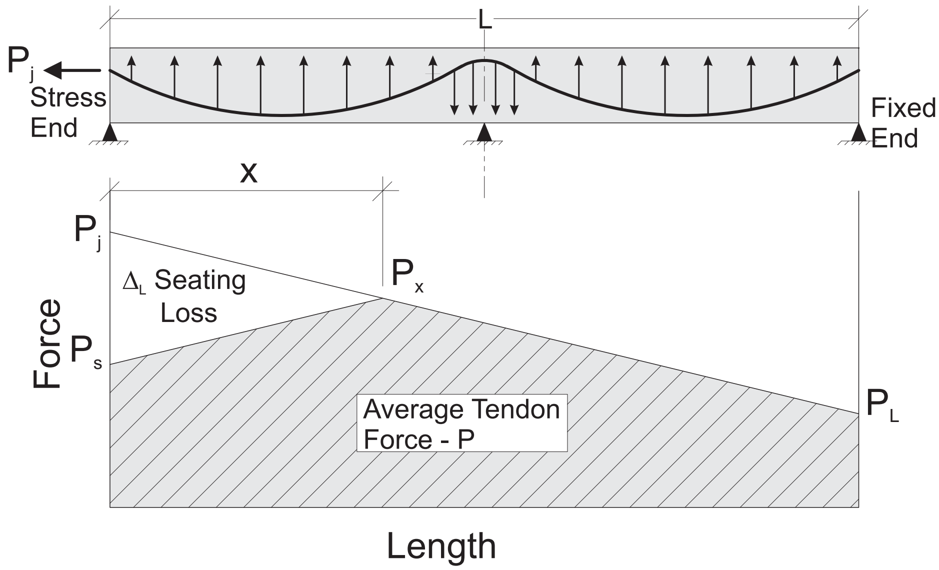

Fig. 1 – Prestress losses in post-tensioned construction

Where,

$$P_L = P_J * e^{-(\mu\alpha+kL)};$$

$$P_X = P_J * e^{-(\mu\alpha+kX)};$$

$$X = \{E(\Delta_L)L / 12(P_J - P_L)\}^{1/2};$$

$$P_S = P_J - \{E(\Delta_L)(P_J - P_L) / 3L\}^{1/2}$$

The theoretical elongation is predicted using a fundamental equation that is based on the "average force" in the tendon, the length of the tendon, and the physical properties of the steel itself or:

$$\Delta = PL/AE$$

Where

Δ = Elongation (in.)

P = Average Force in the Tendon (kips or lbs)

L = Tendon Length (in.)

A = Area of steel in the 7-wire strand (in^2)

E = Modulus of Elasticity of the steel (ksi or psi to be consistent with P units)

Typically, the post-tensioning material supplier performs this calculation and shows the theoretical elongation value for each tendon on the installation drawings.

The problem is that this value is based on several assumptions that must be made prior to the actual construction:

- The value P, which is also dependent on several additional assumptions:
  - o The friction coefficient (μ) – most often this is an accepted average value that has not changed in the past 40 years even though we know that the quality of the P/T coating and sheathing has improved. However, this can also be affected by several other variables:
    - Not enough P/T coating or a non-concentric application
    - Sheathing that has been damaged exposing a portion of the steel tendon. As the tendon is elongated, additional friction is built up between the steel and the concrete that it has come into contact with.
    - Sheathing that has been stripped too far from the back of the stressing anchor exposing the prestressing steel to contact with the concrete and increasing friction (this is only applicable in standard system installations since any exposed steel is covered in encapsulated systems).
    - Securing the tendon with tie wire too tightly to the rebar or chair supports (ties should not indent the plastic sheathing).
  - o The wobble coefficient (k) is a term that applies to the unintended horizontal curvature of a tendon to avoid blockouts, plumbing sleeves, embeds, etc and can vary between tendon groups within a specific project; however, most often this is assumed to be a

single value that is used throughout a project and is based (again) on an accepted average value that has not changed in the past 40 years and is also interdependent on the friction coefficient (μ).

  - o The amount of wedge-set that occurs as the tendon is anchored.

- The area of steel is assumed to be relatively constant but it can also vary slightly between steel shipments without affecting the ultimate tensile strength of the tendon.

- The modulus of elasticity can vary between what was assumed in the calculations and what was actually supplied to the project.

So, what do we have – a theoretical elongation value that is based on several assumptions. The only variable in the above equation that is absolutely known is "L", the length of the tendon from anchor to anchor.

HOW CAN THESE FACTORS LEAD TO LOW ELONGATION RESULTS?

- Excessive friction compared to the assumed value caused by inaccurate placement or breaches in the tendon sheathing

- Excessive wobble compared to the assumed value caused by sloppy placement or excessive tendon deviations around slab penetrations (common in residential applications)

- Excessive seating loss, caused by either:

  - Poor placement of the stressing anchorage allowing cement paste to enter the wedge cavity

  - Stressing equipment that has a seating plunger that is not being activated properly or is worn-down

- Modulus of elasticity and/or steel area value that is higher than the value assumed in the calculations

- Excessive friction caused by the strand being placed improperly entering the anchor at an angle and dragging across the anchor wedge cavity

- A mathematical error in the calculation of the theoretical elongation or an error in transferring the information to the installation drawings

HOW CAN THESE FACTORS LEAD TO HIGH ELONGATION RESULTS?

- Friction that is lower than the value assumed in the calculations

- Wobble that is lower than the value assumed in the calculations

- Modulus of elasticity and/or steel area value that is lower than the value assumed in the calculations

- Overstressing the tendon by going "a couple of hundred psi" above the calibrated gauge pressure or even high enough to go into the inelastic range

- A mathematical error in the calculation of the theoretical elongation or an error in transferring the information to the installation drawings

SO WHERE DOES THIS LEAVE US?

The ACI 318 Building Code recognizes that these variable factors can result in differences between the theoretical and measured elongations and has set a tolerance of +/- 7% to allow for these fluctuations (NOTE: Because of the shorter length tendons prevalent in residential slab-on-ground foundations, the PTI Slab-on-Ground Committee has increased the allowable tolerance to +/-10%). The question is what happens when measured values fall outside of the allowable tolerance range and what do these variations mean? Does this mean that there is a deficiency in the stressing operation and that this will adversely affect the quality of the project – <u>not necessarily</u>.

The ultimate question is "what to do when the recorded elongation measurements fall outside of the allowable tolerance"? The first thing that must be done is to verify that all of the field processes have been correctly performed so that construction can continue.

When elongations are low, this indicates that the force in the tendon is lower than required; however, several factors can affect this and the following should be done to confirm the measured values before proceeding:

- **Perform a "lift-off" test** on selected tendons to confirm that the *drop-back* pressure corresponds to the length of tendon being stressed. It is not necessary to perform this operation on all of the tendons that are out of tolerance at this time. At this point, you are looking for a cause, not a solution. Cement paste in the wedge cavity is the primary cause, but not the only one, of high seating losses. The seating loss is fixed (e.g. ¼ in.) but the elongation is a variable based on the length of the tendon; the shorter the tendon the lower the elongation and the longer the tendon the higher the elongation. For a short tendon, the seating loss will have a greater affect on the transfer force (and subsequently the final effective force) than for a longer tendon. The lift-off test will verify whether the force on the tendon, after seating the wedges, is correct. This should be done with a recently calibrated jack that is known to be reading accurately. Simply using the same jack used to originally stress the tendon without it being recalibrated may only repeat the original problem.

- **Check the jack calibration** to confirm that the correct jacking force has been applied at the stressing end.

- **Detension, re-mark and re-stress** several selected tendons to verify that the original marking and measuring procedures were correctly performed. Again this should be done with a recently calibrated jack that is known to be reading accurately. Simply using the same jack used to originally stress the tendon without it being recalibrated may only repeat the original problem. Once the tendon has been detensioned, the original mark needs to be verified to confirm that the tendon has been completely detensioned. It is possible that some of the force was not completely released when the tendon was detensioned (due to the friction between the sheathing and the prestressing steel) leaving a small amount of elongation remaining. This small amount must be added to the new elongation to get the revised total measured elongation. It is not necessary to perform this operation on all of the tendons that are out of tolerance at this time. Remember that you are looking for a cause and not necessarily a solution.

Conversely, when elongations are high, it does not necessarily indicate that the force on the tendon is higher than specified, or if it is, that the higher force is detrimental. In the case of high elongations, the most important factor that needs to be determined is if the force on the tendon has exceeded the yield stress of the prestressing steel. If the steel has not yielded, the high elongations will virtually always be of little or no detrimental structural consequence, regardless of their cause. Two of the initial actions described above are recommended:

- Check the jack calibration

- Detension, remark and restress

If the jacking force, seating loss and measured elongations have been verified and are accurate, the field construction should continue. Nothing more can be done in the field with the post-tensioning stressing operation on the tendons that are in place. Repeated stressing is not advised as the re-gripping of the tendon by the wedges at the approximate same location on the tendon can lead to notching from the wedge teeth which could in-turn lead to premature failure of the tendon. Overstressing past $0.80f_{pu}$ based on a minimum ultimate strength of 270 ksi and 0.153 in^2 for ½ in. diameter tendons (0.217 in^2 for 0.6 in. diameter tendons) should not be done to achieve elongation.

THE HEAT IS OFF ---

Now that it has been concluded that there is nothing wrong with the field procedures and construction is not being held-up, reasons for the discrepancies can be investigated and a determination made if they have any affect on the integrity of the design and what corrective measures, if any, are required.

Tendons with measured elongations that exceed the allowable do not indicate a deficiency in the stressing operation. Variations in modulus of elasticity, steel area, seating loss, and angular friction and wobble coefficients can combine to result in higher elongation values.

For example, consider an 80-ft tendon with an average tendon profile and normal factor variables of A_s=0.153 in^2, E_s=29,000 ksi, μ=0.07, k=0.0010 and P_j=33.04 kips (½ in. strand), the theoretical elongation would be 6.48 in. or 6-½ in. If the modulus changed to 27,500 ksi, the theoretical elongation would become 6.84 in. or 5.6% higher and if the steel area was reduced to 0.150 in^2, this value would become 6.99 in. or 7.9% above the original theoretical value. Now assume that these are beam tendons or tendons that were well placed in a slab with limited or no wobble (likely to occur in a one-way slab in a parking garage application) and the coefficient "k" was reduced by half to 0.0005, this could become 7.13 in. or +10.0%. This now exceeds the allowable tolerance <u>before</u> any field considerations are included.

These are all very realistic fluctuations and while each acting alone would not necessarily result in measured elongations that would be out of the 7% tolerance, two or more of these occurring at the same time could produce results that are outside of the tolerance. Does this reflect a deficient stressing operation – certainly not. Does it reflect inaccurate calculated values supplied by the p-t material supplier – certainly not. The <u>theoretical</u> calculations are based on average values because the actual physical properties of every tendon used in the construction is not known at the time the calculations are originally prepared.

<u>Provided</u> that the jacking force has not been exceeded during the original stressing operation, elongations that are above the allowable tolerance should not be considered a problem and no remedial action should be required other than to verify that measured elongations are correct. Restressing will only increase the elongation further and detensioning runs the risk of breaking the tendon and having to deal with the real problem of a broken tendon and the lower final force. Higher than anticipated elongations may indicate that the final tendon force is also higher than anticipated. However, this small increase in force can generally be accommodated within the original design, and in most cases is beneficial rather

than detrimental to the as-built structure.

Use logic – elongation measurements are not a perfect method of verifying field stressing procedures. Remember that humans are still involved and that they are oftentimes trying to measure the distance from an uneven surface to a paint mark on the end of a greasy tendon that has rotated slightly during stressing. This process alone may be subject to +/-7% tolerance without any consideration for fluctuations in the material properties or other variables.

Look at the entire report – how consistent are the variations? If the elongations are consistently high or consistently low, this could be indicative of a particular problem, such as a higher or lower modulus of elasticity. When random highs and lows are recorded, this might be indicative of poor marking or measuring practices and could be discounted in the review process after verifying by random lift-offs or detensioning and restressing procedures whether the correct force was on the tendons to begin with.

The majority of reported measured elongation irregularities stem from jobsite management of the stressing operation. This includes preparation for stressing, stressing, and recording. In some cases, the inspector recording the elongations has never seen the jobsite until the morning the stressing operation begins and in many other cases the inspector is not prepared. The elongation reporting form has not been filled out with the tendon numbers and required elongations; therefore, he (or she) has no clue if the tendon is being stressed correctly until they complete the report *after* the stressing operation is finished. There have been cases where an entire pour has been overstressed by the use of an out-of-calibration jack that was not discovered until the entire stressing operation was finished. Had the inspector been prepared, the problem would have been identified after the first few tendons were stressed and the jack changed or recalibrated. Instead a small problem became a big one.

The same goes for the installer that is performing the stressing operation. In many cases, the tendons are not prepared for stressing until just prior to commencing the actual stressing operation. It generally takes more man-hours to prepare for a stressing operation than it does to complete one. If the prep work does not start until just before the stress, the inspector does not have a chance to verify that the initial marks are accurate, legible and that stressing is ready to begin. The installer should begin to prepare for stressing the morning after the pour, as soon as the edge forms have been removed. This also makes the prep work easier because the concrete is still green allowing the easy removal of the pocket formers and any cement paste that might have entered the wedge cavity.

The post-tensioning material supplier has responsibilities that provide the basis for the stressing operation. Accurate and easy to read installation drawings and precise elongation calculations are essential as well as providing stressing equipment that is in good working order and accurately calibrated. However, it is the installer's responsibility to maintain the equipment in good working order and report any problems <u>immediately</u> to the equipment provider.

What can be done to ensure that the records accurately reflect the field operation that was performed?

There are several "key" field practices that must be followed to ensure that the stressing operation results in accurate elongation measurements:

- Is the stressing equipment calibrated correctly? Is the calibration chart dated within the last 6-month period?
- Is the stressing equipment operating correctly?
  - o Check the wedge setting mechanism:
    - ▪ Is it operating correctly by moving in and out as the valve is switched to the retract position? (Fig. 2)

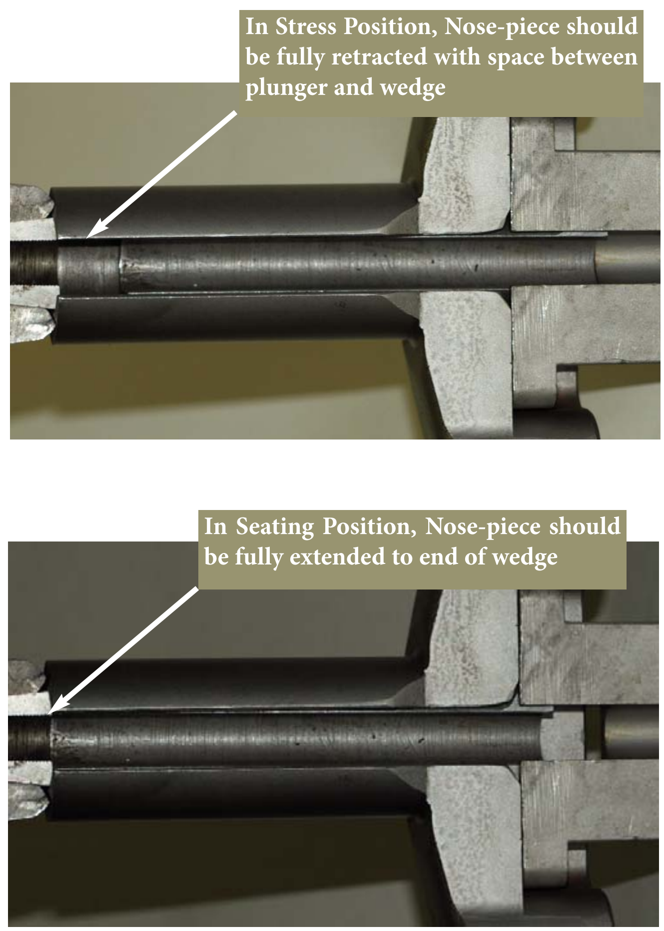

Fig. 2 - Check stressing jack to ensure that the wedge seating mechanism properly moves in and out.

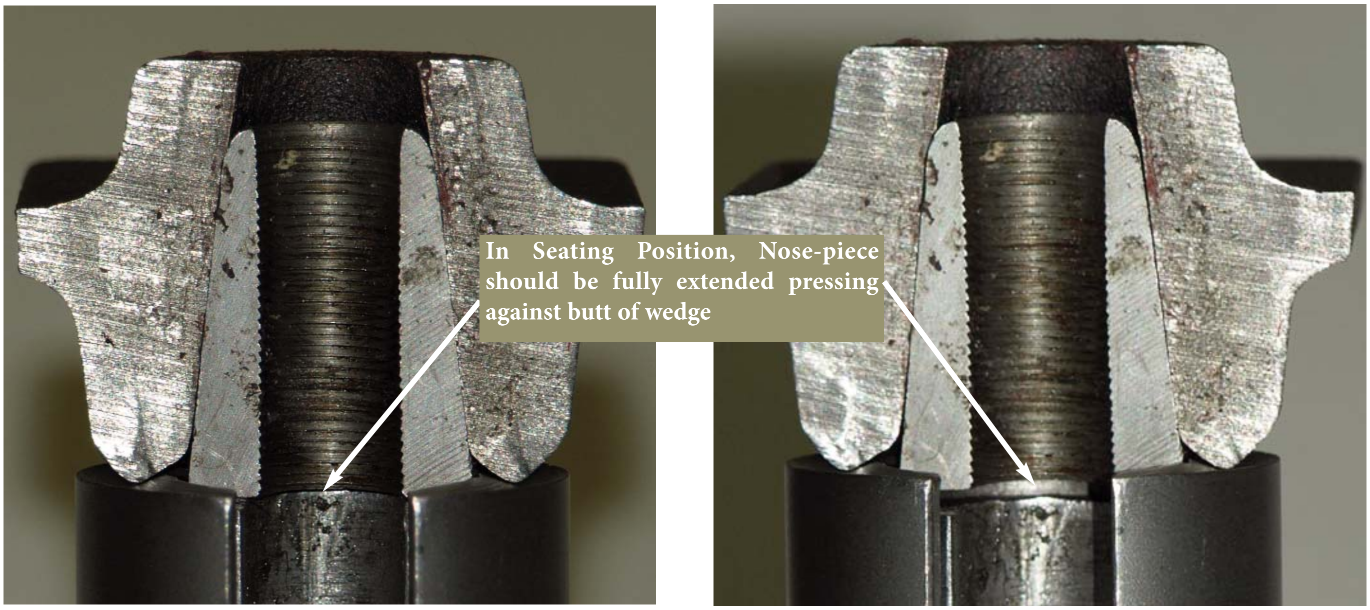

Fig. 3 - Check that the nose-piece is extending the proper distance.

Is it extending the proper distance to control seating loss? (Fig. 3)

- o Is the centering lip on the nose-piece worn down? This prevents the jack from centering on the anchor and can affect wedge seating. (Fig. 4)

- o Does the gauge read zero (not above or below) when the valve is in the neutral position? **NEVER, NEVER use a gauge that does not zero.** (Fig. 5)

- Are the initial marks on the tendon tails legible and accurate?

- Is the agency that is recording elongations present and ready for the stressing operation to commence? Are the forms pre-prepared and have they verified the operation of the stressing equipment

- Is the agent certified by the PTI Inspectors program or have they produced other documentation showing that they are qualified to perform the scope of work?

ADVICE TO THE ENGINEER

ACI 423.6 states in section 3.4.3 "Discrepancies exceeding +/-7% shall be resolved by the post-tensioning installer to the satisfaction of the engineer." This does not mean that every single tendon elongation "must" fall within the allowable tolerance for the project to be in compliance with the code. It only means that the engineer should be satisfied that the stressing operation was properly conducted,

Fig. 4 - Ensure that the centering lip on the nose piece of the jack is not excessively worn.

a. Good gauge

b. Bad gauge

Fig. 5 - Gauge should read zero when valve is in neutral position.

whatever the results may be, and be convinced that the required force has been transferred to the structure. The engineer needs to look at the consistency of the report and the overall elongation values, and not whether each tendon is within the prescribed tolerance.

Making the assumption (which we obviously do) that "elongation and force" are directly related, consider the following example:

Given a beam (or band) with a required force of 424 kips. Assuming that the final effective force after all losses for a ½ in. diameter 270 ksi low-relaxation tendon is 27 kips, 15.7 tendons would need to be used. Obviously 16 tendons would be provided. If after stressing, 2 of the tendons are 10% low, 12 of the tendons are perfect, and 2 of them are 8% high. What should be done with the 4 tendons that are out of tolerance? The force that the beam "*feels*" is 99.75% of that made available from the 16 tendons, which already exceeds the design force since, as is typically the case, it is unlikely that the required design force divided by 16 exactly equals the final effective force per tendon (there is most always some reserve capacity). If the 2 that are low are restressed to try to get them inside of the 7% or lift-offs were performed on the 2 that were high, there is a chance that one of them could break resulting in a force far less than the 99.75% where it was originally. Therefore, this condition should be considered acceptable and no further action is required. However, this is not to say that if you had a similar condition where 2 tendons were 15% low and 2 were 22% high that this would be acceptable because the same calculation procedure was followed and the total force on the beam was okay. Tendons that are this far out of tolerance would require further investigation.

SUMMARY AND CONCLUSIONS

Everyone would agree that the comparison between theoretical and field measured elongations is essential in providing information that confirms to all parties that are involved in the project that the stressing has been properly completed. The accuracy and importance of this should not be underestimated. However, the results should be carefully understood and any corrective action that is undertaken be absolutely necessary and not just done to make the "records right".

Before the first stressing operation is performed on every job, a meeting should be held to make sure that all relevant parties are on the same page; to make sure that everyone is properly trained, knowledgeable of his or her responsibilities, and prepared before the stressing operation begins. Too often, no one cares about the elongation report during the actual stressing operation; the emphasis is to get the stressing operation completed so that construction can move on. Then, before the next pour can be made or the forms dropped, the elongation report becomes an issue. Now everyone is scurrying around trying to piece the report together; the report winds up being inaccurate and/or incomplete, the marks have been damaged or are faded and cannot be accurately read and measurements cannot be verified, and/or the equipment calibration cannot be located or is wrong. Then it becomes a problem. If a simple meeting is held where stressing and recording is the subject and everyone is made to understand the importance of providing accurate results, most of these inconsistencies can be avoided.

Properly calibrated and maintained equipment is essential to have any chance of the elongations coming out right. The equipment has to get to the jobsite in good condition to begin with. This means that the supplier has to check the equipment to make sure that all seals, fittings, and wedge seating mechanisms are working correctly and that the jack is calibrated properly to the gauge. Equipment that gets banged around on the job may get out of calibration and cause the gauge to not read accurately. The equipment should arrive in a box specifically designed to protect the equipment, be stored in the box and be moved in the box; not swung around loose hanging from the crane. The calibration of all equipment should be checked at least every 6 months.

Provided that the stressing jacks are properly calibrated and functioning, provided that the required stressing gauge pressure was not exceeded, measured elongations that exceed the allowable tolerance need not be considered a deficiency and no corrective action is required.

For tendons where the measured elongation is less than the required tolerance, a lift-off or restressing procedure should be "properly" conducted one time. After that there is no need to go back and perform additional work on the tendon. This only runs the risk of damaging the tendon causing premature failure and a bigger problem than just a low elongation. At this point, an estimate of the prestressing force can be made based on the "recorded results" and the engineer would then determine if the lower force was acceptable using the actual in-place concrete strength derived from the on-site testing.

For tendons that are shorter than 25 ft (calculated elongation of about 2 in.), the tolerance should be +/- ¼ in. instead of in percent, as even a small discrepancy will exceed the allowable 7% tolerance.

The bottom line is that field recorded elongations are a very important part of the post-tensioning process. To the engineer, the report should not be the end-all, it should be understood and analyzed in light of the total process and not based on the results of individual tendons. To the installer, contractor, and inspector, it is not a hard process provided that the proper processes and procedures are followed. It can be as difficult or as easy as you want, depending upon the amount of effort that you put into it.

Remember that there are a lot of individual variables, both human and mechanical, that go into stressing and recording elongations and that any single or combination of inaccurate components can produce erroneous results that only make life more complicated. Attention to detail, following proper procedures, being prepared, and being familiar with the specific project and processes can lead to a successful stressing operation and subsequently an accurate field elongation report.

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