

Analysis of elongation variance of tendons using stress-strain graphs

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Abstract. The South African design standards (SANS 2001-CC1 and COLTO) prescribes an elongation variation limit of $\pm 6\%$ and an average variation limit of $\pm 3\%$. Most often these limits are exceeded in practice. If the elongation variation of a tendon falls outside the prescribed elongation limits it must be assessed by the engineer. This paper analyses data of bonded tendons from post-tensioned structures. The aim of this study is to explain the elongation variance of tendons in post-tensioned structures using selected stress-strain graphs. These structures include a reservoir (Mthatha 1-10) and a viaduct (Gautrain Jean Avenue P80).

Keywords. Elongation, variation, elastic modulus, tendon, friction, wobble.

Introduction

Post-tensioning is a process of reinforcing (strengthening) concrete with high-strength steel strands or bars, typically referred to as tendons. There are two main types of post-tensioning systems; unbonded and bonded (grouted). In an unbonded tendon the mono-strand tendon consists of a seven-wire strand that is coated with a corrosion-inhibiting grease and encased in an extruded plastic protective sheathing, as shown in Figure 1(a). The plastic sheathing acts as a bond breaker between the concrete and the pre-stressing strands. It also serves as a barrier that prevents moisture and chemicals from reaching the strand and provides protection against damage by mechanical handling. In bonded systems, two or more strands are inserted into a metal or plastic duct that is embedded in the concrete. A large, multi-strand jack is used to stress the strands. After the strands have been anchored, the duct is filled with a cementitious grout, as shown in Figure 1(b). The grout provides corrosion protection to the strand and bonds the tendon to the concrete surrounding the duct.

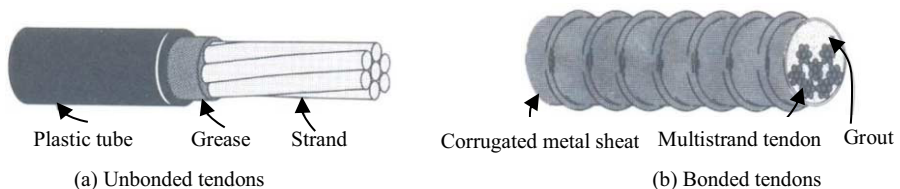


Figure 1. Bonded and unbonded tendons

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The tendons reported in this paper were all bonded. The average areas and elastic moduli of these tendons are given in Table 1. Table 1 show that the values of the elastic modulus and cross-sectional area of the strand tend to be greater than the assumed values of 195 GPa and 150 mm², respectively. This causes a slight reduction in the elongation of the average tendon. Since the value of the elastic modulus and cross-sectional area vary along the length of the strand, the elongation will vary too. The average and standard deviation in Table 1 gives a combined average elastic modulus of 195.49 GPa for the 15.7mm strand and an average elastic modulus of 191.61 GPa for the 15.24 mm. Based on these elastic modulus results it is recommended that the average elastic modulus of 195 GPa be maintained, however the elastic modulus should range from 195±5 GPa, for locally manufactured strands. This range is more stringent than the elastic modulus range of 195±10 GPa, suggested by BS 5896 [1] and EN1992-1-1 [2]. Such a reduction in the elastic modulus range will impact the elongation variation positively.

Table 1. Average areas and elastic modulus for the strand

Strand	Project	Tendons	Average material properties		Standard deviation	
			Area (mm ²)	E (GPa)	Area (mm ²)	E (GPa)
15.70mm	K71 Beams	11	154.05	196.93	0.94	6.07
	Coega to Colchester	42	153.79	192.23	0.98	6.22
	Mthatha	100	153.89	196.14	1.34	5.30
	Jean Ave. P76	24	150.70	196.61	0.98	2.94
	Jean Ave. P77	18	150.54	193.99	1.10	5.01
	Jean Ave. P80	16	150.00	196.52	0.00	3.78
	John Vorster P6	18	150.28	195.63	0.70	3.00
	John Vorster P7	16	150.04	195.74	0.10	3.29
	John Vorster P8	20	150.00	195.42	0.00	4.46
	John Vorster P10	6	150.13	195.68	0.15	1.69
	Average			151.34	195.49	0.63
15.24mm	K46	70	143.86	191.61	0.86	4.91

1. Elongation variations

To explain the elongation variance of tendons in post-tensioned structures, selected stress-strain graphs of the tendons from two post-tensioned structures are presented and discussed in this section. These structures include a reservoir (Mthatha 1-10) and a viaduct (Gautrain Jean Avenue P80). A summary of the elongation variations for these structures is given in Table 2.

Table 2. Summary of elongation variation results

Project	Tendons	Average (%)	Std. Deviation (%)	Max. Value (%)	Min. Value (%)	Var.range (%)
Mthatha 1-10	50	+0.73	5.38	+10.84	-13.21	+7.43
Jean Ave. P80	16	+6.55	3.97	+11.88	-2.08	+5.72

1.1. Mthatha 1-10 tendons

The stress-strain graphs for Mthatha 1-10 set of tendons is shown in Figure 2. The length of the tendons tensioned is 15.85 m and the elongation variation is given in the legend (and this applies to the two stress-strain graphs discussed in the paper). Over-elongation variations are positive and under-elongation variations are negative. Positive elongation means that the tendons exceeded the required elongation and the reverse is true for negative elongation. Since a small average elongation variation of 0.73% was obtained for the fifty (50) Mthatha 1-10 tendons (Table 2), the elongation can be regarded as balanced. These average elongation variation is also well below the limit of 3%, provided by SANS 2001-CC1 [3] and COLTO [4]. The corresponding standard deviation of 5.38% indicates a large dispersion of elongation results; however, they are below the limit of 6%, provided by these standards. Further evidence of the large dispersion of the elongation variation is shown by the maximum and minimum values in Table 2.

Over-elongation variations do not pose problems in post-tensioning; however, under-elongation can be problematic. Over-elongation is either caused by the plastic deformation of the strand, low strand strength or less than expected friction, wobble, elastic modulus and cross-sectional area, or any combination of these. If the strand deform plastically, then the gradient of the stress-strain graph will decrease. This is immediately apparent to an experienced jack operator since the jack would carry on extending at the same jacking pressure. Better tension distribution is achieved if there is less than expected friction and wobble or any combination of these, and this is the most desirable case in post-tensioning. A larger than expected friction or wobble causes under-elongation, and might indicate that the tension in the tendon is not distributed evenly. This is a cause for concern since some sections of the tendon might be tensioned more than the others. It should be noted that under-elongation can be caused by higher values of the elastic modulus and cross-sectional area of the strand.

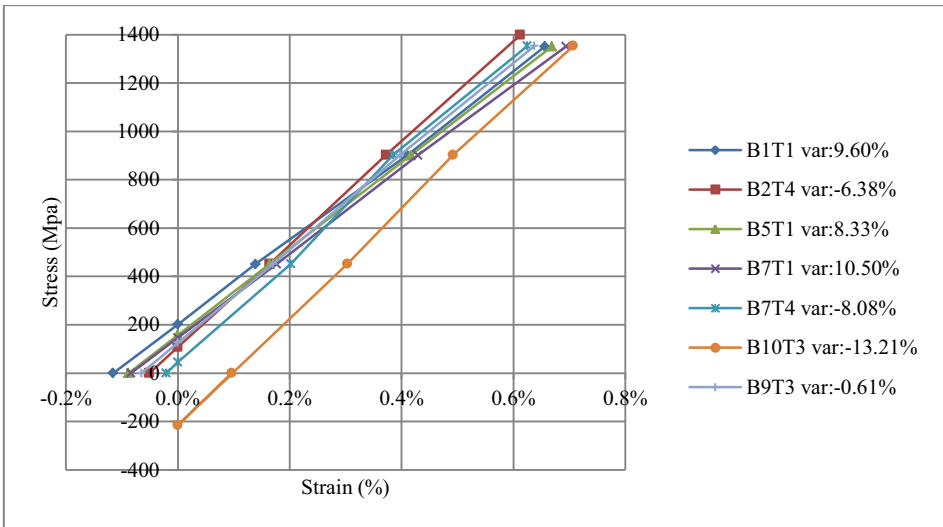


Figure 2. Selected stress-strain graph of Mthatha 1-10 Tendons

Although the elongation variation results of Mthatha 1-10 tendons vary considerably, the stress-strain gradients of most tendons are almost the same. Tendon B9T3 (Figure 2) can be regarded as a perfect elongation result, since it has a small elongation variation of -0.61%. Tendons B10T3 and B2T4, in Figure 2, have steeper stress-strain gradients than the other tendons, and this is usually evidence of higher friction or significant wobble experienced by the tendons. None of the strand certificates showed an elastic modulus or cross-sectional area that is high enough to cause such a drastic change in gradient. Steeper gradient means more force is required to attain a pre-determined elongation. Friction increases the tensile force and reduces the resultant elongation; this increases the stiffness of the tendon. A lower friction will have the reverse effect, causing greater elongation than theoretically predicted. The slight difference in the gradient of the other tendons is most likely due to the variable nature of both the elastic modulus and the area of the strand along its length.

The positive strain of tendon B10T3 at zero pressure shows that there might have been loose strands in the tendon or slippage in the anchor. Such a tendon should be checked for signs of slippage to explain the shift to the right of the stress-strain graph. All the other tendon graphs crossed the zero x-axis at a positive stress. A shift to the right of the stress-strain graph of a tendon is usually caused by the slack of the tendon in the sheath, before the tendon is tensioned. When a force is applied to the strand, the slack disappears, however this also elongate the strand slightly, hence elongation occurs beyond the zero strain point. COLTO [4] and SANS 10100-1 [5] recommends that 10% of the tensioning force be applied to the tendon before re-setting the jack to zero-elongation. In compliance with the specifications, the stresses achieved are almost 10% of the tension force.

Tendon B7T4 (Figure 2) differ from the other tendons in that they show alternate stages of over-elongation and under-elongation. This behaviour is referred to as “slip-stick” and is attributed to the squeeze effect of strands in the tendon on each other during tensioning [6]. It occurs when localized friction holds tension and then releases it at the next stressing increment. A final negative or positive elongation variation is evidence that the magnitudes of under-elongation and over-elongation were different. When higher localized friction occur the tendons usually under-elongate as is the case with Tendon B7T4.

1.2. Gautrain Jean Avenue P80 tendons

The long tendons for the Gautrain Jean Avenue segment P80 (length ranging from 83.86 m to 111.09 m), in Figure 3, were only linear at low stress levels, and non-linear at high stress levels. The non-linear or slip-stick (over and under-elongation) behaviour exhibited by these tendons was caused by friction, as discussed previously. The high friction is due to the squeezing of tendons on each other over regions of large curvature [6]. All tendons in this range were stressed from both ends, starting with the live-end, and then the dead-end. A cable is double-end stressed when the length of the cable is long and the frictional forces along the tendon are expected to be large. In this situation, the stress-strain plot only shows the stressing from the live-end since only the live end's stressing is done in increments. The other end of the tendon is stressed in one increment; this is termed “top-up” in the industry. It is important to note that although the tendons experienced alternate over and under-elongations during tensioning, the tendons still over-elongated, which indicate that the force was uniformly distributed along the length of the cable.

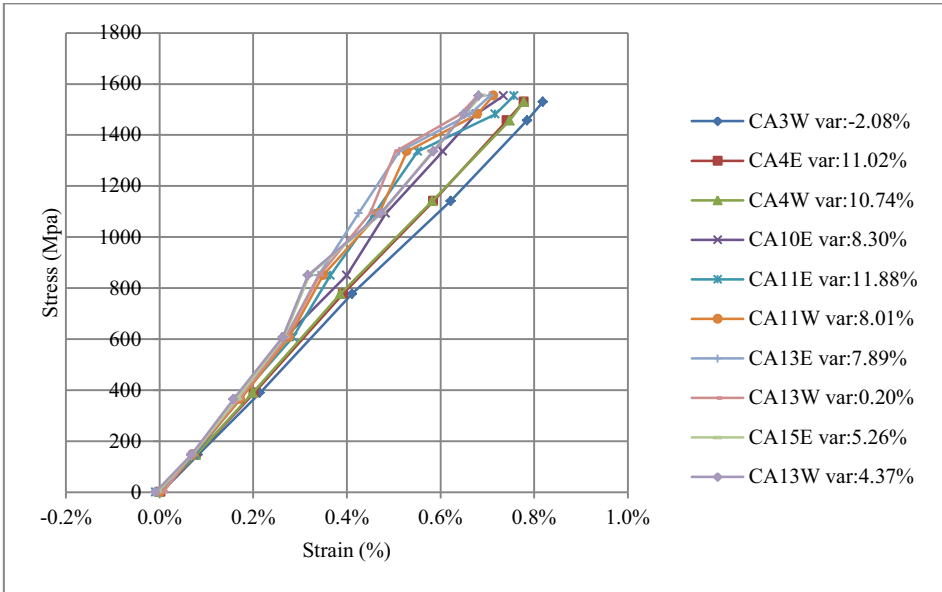


Figure 3. Selected stress-strain graph of Gautrain Jean Avenue P80 tendons

2. Conclusions

Table 1 gives a combined average elastic modulus of 195.49 GPa for the 15.7mm strand and an average elastic modulus of 191.61 GPa for the 15.24 mm. From these elastic modulus results it is recommended that the average elastic modulus of 195 GPa be maintained, however the elastic modulus should range from 195 ± 5 GPa, for locally manufactured strands. This range is more stringent than the range suggested by BS 5896 [1] and EN1992-1-1 [2]. Such a reduction in the elastic modulus range will impact the elongation variation positively.

Elongation variations are dependent on the assumed friction and wobble coefficients. Over-elongation is caused by less than expected friction, wobble, elastic modulus and cross-sectional area, or any combination of these. When these factors are large they favour negative elongation. A larger than expected friction or wobble might indicate that the tension in the tendon is not distributed evenly. This is a cause for concern since some sections of the tendon might be under-tensioned and others over-tensioned.

It has been shown that the slip-stick behaviour that occurred in numerous tendons in this study is due to high localized friction. This behaviour is caused by squeezing effect of strands in a tendon during tensioning [6], and occurs when localized friction holds tension and releases it at the next stressing increment. Longer tendons show greater non-linear behaviour than shorter tendons. This is due to numerous zones of friction. Stressing of the tendon from both ends (live and dead-end) ensures uniform tension distribution in the strand.

References

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