Short-term Elongation Variation of Post-Tensioned Tendons

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Abstract

When tension is applied to steel tendons they elongate in proportion to the tensile force, as predicted by Hooke's law. This elongation is used by the South African standard on concrete structural works (SANS 2001-CC1) and South African standard specification for road and bridgeworks (COLTO) to determine the adequacy of the force applied in a tendon. The standards prescribe an elongation variation limit of ±6% and an average elongation variation limit of ±3%. According to these standards, if the elongation variation of the tendon falls outside these prescribed limits it must be brought to the attention of the engineer. The scatter of tendon elongation results is often greater than the range prescribed by these standards. This usually requires the contractor to re-tension the tendons at huge financial costs. In most cases the results obtained after re-tensioning are the same. This paper analyses tensioning data obtained from a variety of projects that have been completed in South Africa in recent years. The aim of this investigation is to determine the causes of variation in elongation and suggest adjustments, if any, to the current elongation variation.

Keywords: elongation variation, post-tensioning, tendon, tension, friction, wobble, elongation limits.

1.0 Introduction

Post-tensioning is a method of reinforcing concrete elements with high-strength steel strands, commonly referred to as tendons, to reduce the tension experienced by the concrete member. The tendon is stressed after the concrete has cured and attained the minimum specified strength. To fully appreciate the benefits of post-tensioning, it is important to understand the behaviour of concrete. Concrete is very strong in compression but weak in tension, that is, it will crack when forces act to pull it apart or elongate. This is what happens at the bottom of the beam or slab in conventional concrete construction when subjected to downward loading. Unlike steel reinforcing bars (rebar), which resist forces only when beam/slab deflect (passive reinforcement) post-tensioning tendons are considered "active reinforcing", because the steel is effective as reinforcement before the concrete has not deflected. The compression that results from the post-tensioning counteracts the tensile forces created by subsequent applied loading, thereby increasing the load-carrying capacity of the concrete. This paper analyses test data from bonded tendons only. A bonded tendon consists of several 7-wire strands or a multi-strand tendon (Figure 1(a)). The strands are placed in a duct that is embedded in the concrete, and then tensioned with a hydraulic jack. The voids between the strands and the metal duct are grouted to form a continuous bond with the surrounding concrete.

Figure 1 Bonded tendons

In South Africa, guidelines for post-tensioning are provided by South African standard on concrete structural works (SANS 2001-CC1 [1]) and South African standard specification for road and bridgeworks (COLTO [2]). In these standards the specification for high tensile steel wire and strand for the pre-stressing of concrete comply with the requirements of British standard, BS 5896 [3], and the mechanical tests for post-tensioning systems (including anchorages and couplers) comply with the requirements of European standard, EN 13391 [4]. According to these specifications [1, 2, 3, 4] the final stage of tensioning will be deemed to have been satisfactorily accomplished when the tendons comply with the following requirements:

- Each tendon has been tensioned to the required force;
- The measured extension on individual tendons is within 6% of the theoretical extension;
- The average of the measured extensions of all the tendons in a unit does not deviate from the theoretical extension by more than 3%; and
- The release or pull-in (or both), in the case of each tendon, be within 2 mm of the designated value. Release is the specified elastic shortening of the tendon at the anchorage achieved before or during transfer and pull-in is the elastic shortening of the tendon caused by relative movement between the anchorage or coupler components on account of seating and gripping action during or immediately after transfer.

The individual and average tendon tolerances of 6% and 3%, respectively, acknowledges the fact that the elongation of a tendon cannot be determined accurately because of friction and wobble losses, and less than expected workmanship in the manufacture of tendons and placement of concrete. However, the accomplishment of these tolerances is causing problems in the South African post-tensioning industry because some tolerances do not fall within these specifications. Such tendons are normally re-stressed at a huge cost to the post-tensioning contractor; however, it has been found that after re-stressing the elongations do not change. In some cases re-stressing has resulted in the breakage of a tendon, thereby creating an additional problem. One of the reasons why this is happening is that tendon tolerances are used irrationally as absolute values, without considering other aspects of post-tensioning. When tolerances fall outside the prescribed limits, they are brought to the attention of the engineer so that the engineer can evaluate these deviations against the stressing operation and critical design limit states of the element or structure under consideration. Based on the consistency of the report and the overall elongation values, the engineer should be satisfied that the stressing operation was properly conducted, and that the required force has been transferred to the structure, and not whether every single tendon is within the prescribed tolerance or not.

The Concrete Society of Southern Africa [5] recommends less stringent elongation variation for individual tendons of 10%, and an average elongation variation for a group of tendons of 6%. This standard complies with the Cement and Concrete Association standard [6] and the International Federation for Prestressing (IFP [7]). The Post-Tensioning Institute Manual (PTI [8]) and the American Concrete Institute standard (ACI 318 [9]) stipulates that if the theoretical and real elongation values do not correlate by more than ±7%, then the post-tension supplier should review the conditions and correct the variation. According to the American Association of State Highway and Transportation Officials (AASHTO LRFD) construction standard [10], the net measured elongation shall be within ±5% of the calculated elongation. The fact that these tolerances vary from standard to standard, is clear evidence that they cannot be an absolute value. This paper seeks to study post-tensioning data on several projects constructed in South Africa in order to solve this puzzle. The data was provided by Freyssinet, South Africa.

2.0 Code treatment of post-tensioning.

The design for post-tensioning and the calculation of elongation is a complicated process that requires many assumptions to attain the desired elongation. The elongation is only accurate if good assumptions are made, but even so there are factors that are beyond the control of the post tension contractor, such as shifting of the duct during pouring of concrete, incorrect tendon profile design and variable friction in the duct.

2.1 Post-tensioning force

When the tendon is placed in the required profile and a force is applied, the tendon tries to straighten itself out between anchorage points or between inflection points in multiple span conditions. The concrete prevents this from happening, 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. As the force is applied and the tendon elongates, a frictional resistance force develops between the steel and the duct. The force in a curved post-tensioned tendon is generally predicted by the Eytelwein-Euler equation (IFP [7]), given in Equation 1.

$$F_x = F_0 e^{-\mu \alpha_x} \quad (1)$$

This force is a function of the initial force in the tendon before the region of curvature F_0, friction coefficient between the tendon and duct μ, and the angle of curvature of the tendon α_x. If the length of a post-tension tendon was very short and straight there would be negligible friction in the duct. Hence friction losses would not need to be accounted for. Since most post-tension profiles are curved, friction forces will occur over these curvatures. Figure 2 shows the change in force produced by the jack, along the length of the tendon due to the friction between the tendon and the duct.

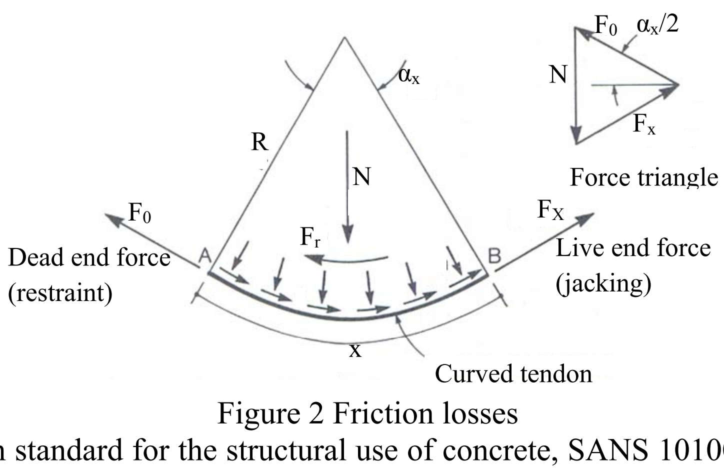


Figure 2 Friction losses

The South African standard for the structural use of concrete, SANS 10100-1 [11], calculates the post-tensioning force, based on Equation 2.

$$F_x = F_0 e^{-\mu x / r_{ps}} \tag{2}$$

where, r_{ps} is the radius of curvature. Although written differently, simple mathematics shows that the two equations are actually the same, since $x = \alpha_x r_{ps}$. Where the radius of curvature is not constant, the profile must be subdivided into sections, and each section must be treated separately. The friction coefficient (μ) depends on the surface characteristics of the tendon and of the duct. Table 1 provide a list of the recommended friction coefficients between the tendon and duct, from different standards. When tendons have more than one plane of friction, which is the case in multi-strand tendons, an additional friction force is generated, caused by the squeezing effect of the tendons. A correction factor κ is used to modify the friction coefficient of a single tendon on a duct (μ_0) to that of multi-tendons, as given in Equation 3.

$$\mu = \mu_0 \kappa \tag{3}$$

The correction factor (κ) is dependent on the duct diameter and the pre-stressed steel type. According to IFP [7], the value of κ varies between 1.1 and 1.4. For a tendon filling 50-60% of the duct a value of between 1.3 and 1.35 can be expected.

Table 1: Friction coefficient and wobble factors for bonded tendons

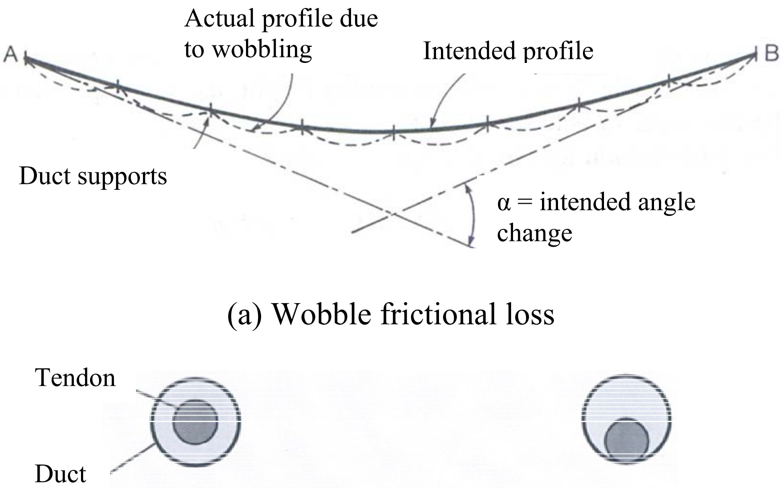
Standard	Type of duct	μ/rad	K/m
SANS10100-1 [11]	Steel duct	0.25	0.0017
EN 1992-1-1 [12]	Steel duct	0.19	0.005-0.01
PTI [8]	Flexible, non-galvanized	0.22	0.0025
	Flexible, galvanized	0.18	0.0016
	Rigid, non-galvanized	0.25	0.0001
	Rigid, galvanized	0.20	0.0001
ACI 318-11 [9]	Flexible	0.15-0.25	0.0016-0.0066
	Rigid	0.15-0.25	0.00066
CEB-FIP [13]		0.20	0.0020
AASHTO [14]	Semi and rigid galvanized metal	0.15-0.25	0.0002
	Polyethylene	0.23	0.0002
	Rigid steel deviators	0.25	0.0002

The friction coefficients for bonded tendons range from 0.15-0.25, depending on whether the duct is flexible or rigid and galvanized and non-galvanized. Flexible and galvanized ducts tend to produce lower coefficients of friction. In cases where a range of coefficients is given, the range is significantly wide (0.15-0.25). It is important to note that some of the standards provided in Table 1 are not explicit on the type of duct that should be provided (flexible, rigid, galvanized or non-galvanized). For example, The European standard for the design of concrete structures, EN 1992-1-1 [12], recommends a single friction coefficient (μ) for internal tendons of 0.19, and does not specify the type of duct. Despite the fact that strands are lubricated to reduce corrosion during storage, SANS 2001-CC1 [1] requires no lubricate or corrosion inhibiting substance on tendons. The variation in the coefficients of friction shows that there is no real consensus about what the exact value should be. It is therefore clear that in order to calculate friction losses accurately, the information on the specific system being used is needed. A value of $\mu = 0.18$ was used in the design of Gautrain viaducts in Table 4 (Jean Avenue P76, P77, P78, P80 and John Vorster P6, P7, P8, P10), based on the tests, performed by the European Organization for Technical Approvals (EOTA [15]). This tests yielded a lubricated friction coefficient μ = 0.17 and un-lubricated value of μ = 0.19.

In practice, tendons experience additional unforeseen or unexpected deviations (Figure 3). These deviations change the angular displacement of the tendons and the resultant friction force. This problem is accounted for by the introduction of the wobble factor. Wobble of the tendons is caused by variable rebar heights during placement of the rebars and any displacement of the tendons caused by the placement of concrete or poke vibrators. Standards use different expressions to account for the wobbling. SANS 10100-1 [11], and ACI 318-11 [9] uses Equation 4 to calculate the post-tensioning force with unintentional deviation from the specified profile.

$$F_x = F_0 e^{-Kx} \tag{4}$$

where, K is the wobble factor. The wobble factor depends on the type of duct employed, number of tendons in the duct, the nature of its inside surface, the method of forming it, site conditions and the workmanship of those installing the duct and pouring concrete [16].



(a) Wobble frictional loss

(b) Idealized situation (c) Real situation

Figure 3 Wobble and curvature effects

Equations 1 and 4 can be combined to give an effective post-tensioning force (which covers the friction effects caused by both curvature and wobble), defined by Equation 5.

$$F_x = F_0 e^{-(\mu\alpha_x + \kappa x)} \tag{5}$$

EN 1992-1-1 [12] uses Equation 6 to calculate the effective post-tensioning force.

$$F_x = F_0 e^{-\mu(\alpha_x + \kappa x)} \tag{6}$$

The difference between Equation 5 and 6 lies in the exponent. Recommended wobble factors for 7-wire tendons from SANS10100-1 [11], EN 1992-1-1 [12], PTI [8], and ACI 318-11 [9], and the Euro-International Committee for concrete and International Federation for Prestressing (CEB-FIP [13]) are given in Table 1. These factors must only be used when no wobble factors are available from manufacturers.

The variation of the wobble factors, in Table 1, shows how uncertain and difficult it is to predict these factors. In this table, the smaller wobble factors provided by PTI [8] shows that the standard considers out-of-alignment of ducts to be an infrequent occurrence and that the duct installed follows the design profile very closely. The larger wobble factors, presented by EN 1992-1-1 [12] shows that greater variation in profile is expected from their theoretical layout. The wobble factor assumed for the Gautrain viaducts, in Table 4, is κ = 0.00135/m. The use of this wobble factor and the large amount of over-elongation results presented by Kruger [17], suggest that wobble factors should be lower, probably closer to the PTI [8] stated values. One other potential source of unaccepted elongation variation is that most often the friction and wobble coefficients in Table 1 are values that have not changed in the past 50 years even though the quality of manufacture of the tendons and duct has improved substantially during this time.

Once the force is known, the elongation of the tendon can be calculated, as given in Equations 7 and 8.

$$\Delta_x = \frac{F_0 . x}{EA} e^{-(\mu\alpha_x + \kappa x)} \tag{7}$$

$$\Delta_x = \frac{F_0 . x}{EA} e^{-\mu(\alpha_x + \kappa x)} \tag{8}$$

where, E is the elastic modulus of the strand, A is the area of the strand and x is length of tendon. Equation 7 was used by Freyssinet to calculate all the tendon elongations considered in this paper.

2.2 Strand Strength Parameters

At the time the elongation calculations are originally prepared, the actual physical and mechanical properties of the tendons used in the construction, are not known. The only parameter that is absolutely known in the calculation of elongation is the length of the tendon. This means that the theoretical calculations are only based on average values, provided by standards, yet the area of steel can vary slightly between steel shipments and the modulus of elasticity can vary between the assumed value and the value that was actually supplied to the project. The South African post-tensioning standard, SANS 2001-CC1 [1], stipulates that the material properties of a 7-wire strand should be in accordance with BS 5896 [3]. BS 5896 [3] and EN 1992-1-1 [12] specify an elastic modulus of 195±10GPa in post-tensioning design, unless otherwise stipulated by the manufacturer of the strand. A large margin of variation in elongation arises from the variation of ±10GPa. This variation alone, can potential result in an elongation variation of about 5% from the mean value (1% lower than the limit of 6%, specified by SANS 2001-CC1 [1] and COLTO [2]), before any other effects are considered [17]. The variation in the elastic modulus is predominately as a result of the variation in the cross-sectional area of individual wires. Variation in cross-sectional area of a strand as a result of as little as ± 0.02mm tolerance in wire diameter could result in a ±2.5% change in elastic modulus. This tolerance in diameter is within the -2% to +4% range specified by the European Communities Prestressing Specification, EURONORM 138-79 [18], and BS 5896 [3]. The variation in diameter is due to the wear of the die that produces the individual wire that makes up the strand [16]. A wire produced from a new die will have a smaller cross sectional area than that produced by an old die. When the strand is of the same type and diameter, but different coil, then it is possible for the elastic modulus to vary by as much as ±5%.

The elastic modulus and the elongation of the strands are also dependent on the state of equipment and testing procedure of the manufacturer. Extremely good laboratory equipment and manufacturing procedures are needed if the elastic modulus established in laboratory is to be within 2.5% of the actual elastic modulus of a strand tensioned on site [19, 20]. Elastic modulus test results of strands for the Gautrain viaducts are given in Table 2. The tests were performed by a South African company, SCAW, and an independent company from the UK. For all the coils, the elastic modulus is almost the same, except coil number, PID-JA-NGGF-0B. The table also shows that for the same company (for example SCAW) and different coil numbers, the elastic modulus can vary from -5.25% to 0.96%. Since the test is destructive the strands cannot have been the same in both tests and the tests results merely prove that the strand properties vary along the length of the strand (since segments from the same coil were used in both tests), albeit within the given tolerance. It is important to note that most of the time, friction and wobble impact elongation far much more than the modulus of elasticity. This implies that in situations where there are large elongation tolerances, the cause of this variation is primarily due to friction and wobble loss.

Table 2: Strand test results for the Gautrain viaducts

Coil Number	SCAW Elastic Modulus (GPa)	Independent Elastic Modulus (GPa)	Difference	% Variation of SCAW Modulus
PID-EA-KYDJ-1C	198.5	196.6	1.9	0.96
PID-JA-NGGJ-4B	189.8	190.6	-0.8	-0.42
PID-JA-NGGF-0B	188.7	198.6	-9.9	-5.25
PID-JA-NGGG-1A	196.1	197.3	-1.2	-0.61

There is a further complication that can arise during the manufacturing process. A seven wire strand is made up of a central king wire around which the six remaining wires are wrapped. During manufacture, a constant tensile force is applied on the king wire while the outer wires are wound tightly around the king wire. If this process is not done properly the strand will have one or more loose wires. Loose strand(s) will result in a greater than anticipated elongation during tensioning. In addition, a loose strand will attempt to unravel while being tensioned [17]. This phenomenon is not picked up during strand testing because the test specimens are too short, usually 1000mm long. The effect of loose strand shows greatest effect on long tendons [17].

The average areas and elastic moduli of the 15.7mm and 15.24mm strands that were considered in this paper are given in Table 3. Table 3 shows that the values of the elastic modulus and cross-sectional area of the strand tend to be greater than the assumed values of 195GPa and 150mm². 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 3 gives a combined average elastic modulus of 195.49GPa for the 15.7mm strand and an average elastic modulus of 191.61GPa for the 15.24mm. Based on these elastic modulus results it is recommended that the average elastic modulus of 195GPa be maintained, however the elastic modulus should range from 195±5GPa, for locally manufactured strands. This range is more stringent than the range suggested by BS 5896 [3] and EN1992-1-1 [12]. Such a reduction in the elastic modulus range will impact the elongation variation positively. A summary of the elongation variation is given in Table 4.

Table 3: Average areas and elastic modulus for the strand

Strand	Project	Tendons	Average material properties	Standard deviation

			Area (mm²)	E (GPa)	Area (mm²)	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	4.18
15.24mm	K46	70	143.86	191.61	0.86	4.91

3.0 Tendon elongation results

The elongation of post-tensioned strands is a result of three elongations; the elongation of the tendon, shortening of the structure and draw-in at the anchorage (IFP [7]). Only the elongation associated with the tendon is considered in this paper since the shortening of the structure (time dependant elongation) has a negligible effect on elongation specification measurement, and the draw-in of the anchorage is dependent on the system used and is well-defined. Tendon elongation variation can further be divided into two parts; namely 1) over-elongation and 2) under-elongation. 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. 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. Plastic deformation can easily be recognized by a decrease in the gradient of the stress-strain graph. 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. Over-elongation variation does not cause as much anxiety as under-elongation as long as it can be proved that the tension in the tendon is adequate. Under-elongation is caused by excessive friction and wobble compared to the expected/assumed value, and modulus of elasticity and/or steel area value that is higher than the value assumed in the calculations. Under-elongation could indicate blockage of the tendon, and this is problematic since it can lead to over-stress in some regions of strand and insufficient tension in other regions [6]. It could also occur due to ingress of grout into the duct since this would increase friction in the duct [18].

As indicated in the introduction of this paper, several standards [1, 2, 3, 4] recognises that there can be differences between the theoretical and measured elongations. The question is what happens when measured values fall outside the allowable tolerance range (±6%), what do these variations mean, and ultimately can adjustments be applied to this tolerance? Obviously, the first thing that must be done is to verify that all the field processes have been correctly performed. To deal with the second and third question, 402 tendons from various projects were studied. Table 4 summarizes the average, standard deviation, maximum, minimum and range of the elongation results for the 402 tendons that were considered. The data was divided into groups and these groups were split according to type of project, date of stressing and type of jack. This ensured that tendons in the same group were stressed under similar conditions. Tendons of the same project, but stressed at different dates are numbered differently. For instance, Mthatha 1-10 tendons are from the same project as those of Mthatha 11-20, however these tendons were stressed on a different dates. As can be seen from the Table 4, the average value of +4.06% for all tendons is high, considering that the expected average elongation variation is ±3% (SANS 2001-CC1 [1] and COLTO [2]. Since only five of the sixteen tendon groups met this requirement, this requirement can be considered to be too stringent. The positive average elongation variation also shows that post-tensioning tendons tend to over-elongate during stressing.

Table 4: Summary of elongation variation results

Project	Tendons	Average (%)	Std. Deviation (%)	Max. Value (%)	Min. Value (%)	Var. range (%)
Coega-Colchester (1-14)	28	+6.07	2.27	+10.18	+1.04	+8.30
Coega-Colchester (15-21)	14	+5.03	2.09	+7.41	+1.39	+8.22
Kwa-Mashu	14	+0.78	5.02	+9.83	-5.94	-3.03
K46 15.24mm (1-9)	18	-8.38	4.10	+0.49	-15.29	+6.85
K46 15.24mm (17-32)	52	-3.87	6.00	+3.70	-22.85	-2.43
Malendela	54	-0.14	3.60	+8.12	-7.69	-2.90
Mthatha 1-10	50	+0.73	5.38	+10.84	-13.21	+7.43
Mthatha 11-20	50	+0.11	5.16	+9.99	-13.21	+7.38
Jean Ave. P76	24	+2.53	8.82	+14.46	-22.81	+4.46
Jean Ave. P77	18	+5.70	5.04	+16.00	-1.10	+4.28
Jean Ave. P78	4	+8.76	4.19	+14.09	+4.12	-
Jean Ave. P80	16	+6.55	3.97	+11.88	-2.08	+5.72
John Vorster P6	18	+10.17	5.40	+19.17	+3.00	+4.43
John Vorster P7	16	+6.50	5.13	+16.75	-1.00	+3.74
John Vorster P8	20	11.00	3.75	+16.70	+4.81	+5.58
John Vorster P10	6	+13.43	2.92	+16.39	+9.33	-
Mean		+4.06%	4.55%	11.63	-5.09	+5.56

The standard deviation from Table 5 of 4.55% indicates a high degree of scatter of elongation variation results. It means that the majority of elongation variation results will occur in the region of 4.55% on either side of the average value. Since this standard deviation is the average value of the standard deviations of a group of tendons, the tolerance range can be taken as two standard deviations combined, from the average value. Hence, a standard deviation of 4.55% would give an elongation variation of ±9.1% (rounded to 9%), which is about 50% greater than the current limit of ±6%. A range of ±9% correlates to the ±10%, recommended by the Concrete Society of Southern Africa [5], Cement and Concrete Association [6] and IFP [7]. Since none of the tendons considered in this paper failed when subjected to the prescribed tension, an elongation variations of ±9% can be considered to be safe. Hence the limit of elongation variation of ±6% is too stringent, and do not reflect site conditions. All the tendons in Table 4 were stressed to their target tension forces.

To illustrate how the elongation variations of tendons compare with standards, selected elongation variation graphs of tendons are presented and discussed in this section. These graphs help to show the actual scatter of variation data from 0% and how these results relates to the limits provided by SANS 2001-CC1 [1] and COLTO [2]. The results considered in this section includes tendons that predominantly experienced balanced elongation (Mthatha 1-10 and Mthatha 11-20), over-elongation (Coega to Colchester 1-14 and John Vorster P8) and under-elongation (K46 (1-9)). The variation in elongation was calculated as the difference between the theoretical and the real elongation.

3.1 Mthatha 1-10 and Mthatha 11-20 tendons

Mthatha 1-10 and Mthatha 11-20 tendons, in Figures 4 and 5, are examples of projects that experienced balanced elongation variations. This is due to the fact that the corresponding average elongation variations of +0.73% and +0.11% are small (close to 0%) and well below the average elongation variation of ±3% (Table 4). In addition standard deviations of 5.38% and 5.160% are below the limit elongation variation of ±6%, provided by the standards. In both groups of tendons the scatter of elongation results is almost the same about the datum (Figure 4 and 5), which clearly shows that there was a balance between under and over-elongation results. Despite the fact that the length of these two groups of tendons were the same (15.85m) Mthatha 1-10 tendon elongation results vary from a minimum of -13.21% to a maximum of 10.84%, and Mthatha 11-20 from a minimum of -13.21% to a maximum of 9.99%. According to the SANS 2001-CC1 [1] and COLTO [2] specifications, 13 out of 50 of Mthatha 1-10 tendons (26%), and 14 out of 50 tendons of Mthatha 11-20 (28%) fall outside of the limit of ±6% (Figures 4 and 5). If the recommended elongation variation range of ±9% is applied then only six Mthatha 1-10 and 3 Mthatha 11-20 would fall out of the specification limits. Tendons with significantly higher negative elongations show evidence of higher friction or 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. Negative elongation variations imply that 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.

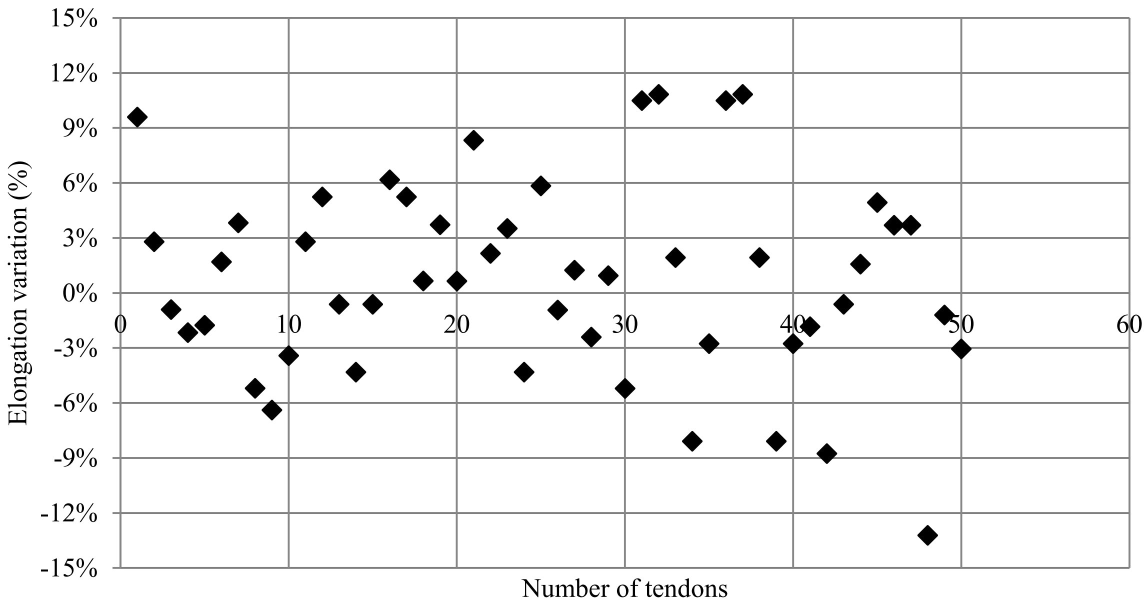


Figure 4: Elongation variations of Mthatha 1-10 tendons

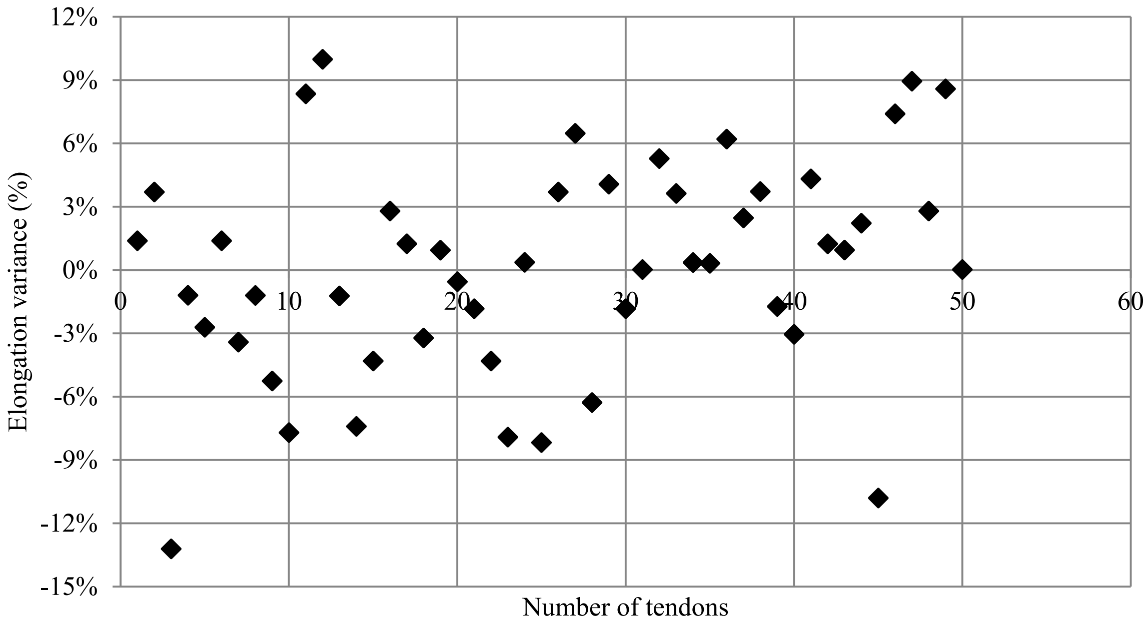


Figure 5: Elongation variations of Mthatha 11-20 tendons

3.2 Coega to Colchester 1-14 and John Vorster P8 tendons

The Coega to Colchester 1-14 (Figure 6) and John Vorster P8 (Figure 7) tendon set of tendons produced average elongation variations of 6.07% and 11.00%, respectively, which are completely outside of the limit of 3%. However, their corresponding standard deviation of 2.27% and 3.75% are low, which indicates that there is little deviation from the average values of 6.07% and 11.00%, respectively. The large average elongation variations occurred despite the fact that the prescribed tensile force was achieved in the tendons. The positive maximum and minimum elongation values for the two groups of tendons (+10.18% and +1.04% for Coega to Colchester 1-14, and +16.70% and +4.81% for John Vorster P8) shows that the tendons experienced significant over-elongation. When excessive elongation occurs, the jack calibration should be checked, and stressing records should be reviewed for any evidence of wire or strand breakage. Wire or strand breakage is shown by a nonlinear force-elongation diagram. When accessible, dead end anchors should also be checked for strand movement. According to Russell and Price [21], the majority of the irregularities in elongation tolerance results from the management of the stressing operation on site. This process includes all the necessary preparation for stressing, stressing operation itself, and the recording of results. Provided that all of the preceding factors can be dismissed, the only sources for excessive tendon elongations would be lower strand modulus of elasticity, wobble and friction coefficients than the values assumed in calculations. It is interesting to note that if the average value in these graph was taken as the datum, then all the elongation variations for Coega to Colchester 1-14 tendons will fall within the ±6%, specified by SANS 2001-CC1 [1] and COLTO [2]. If such a shift in noticed earlier, re-stressing of the tendons can be avoided. It is also important to note that if the proposed limit of ±9% was applied, then both Coega to Colchester 1-14 and John Vorster P8 tendons will be within the specified limits.

As indicated before, a shift in elongation results could also be caused by the loose “lay” of the strands in the tendons. Loose, outer wires tend to have a greater length than a normal tight strand. When a force is applied to the strand, the outer wires are tightened, causing the strand to lengthen, under a small tensile force from the jack. This elongation shifts the stress-strain plots to the right of the graph. Loose wires can also result in a lower initial elastic modulus in the strand. This situation is caused by the uneven distribution of tension in the 7-wire strand. When the strand is tightened the centre wire immediately resists the tension whilst the outer wires lag behind. Such a tendon would experience over-elongation during the initial tensioning increments.

Loose wires in a strand increase the variability of the elongation results, however, they do not seem to have affected Coega-Colchester (1-14) and John Vorster tendons much, because the elongation standard deviations of 2.27% and 3.75 are small. It should be noted that over-elongation was not caused by the material properties since the actual average elastic moduli and areas of these two groups of tendons did not differ much from the assumed values of 195GPa and 150mm².

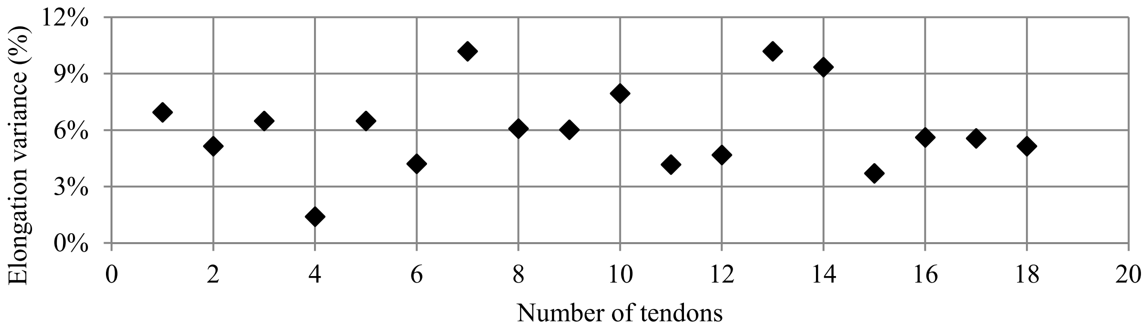


Figure 6: Coega to Colchester 1-14 tendons

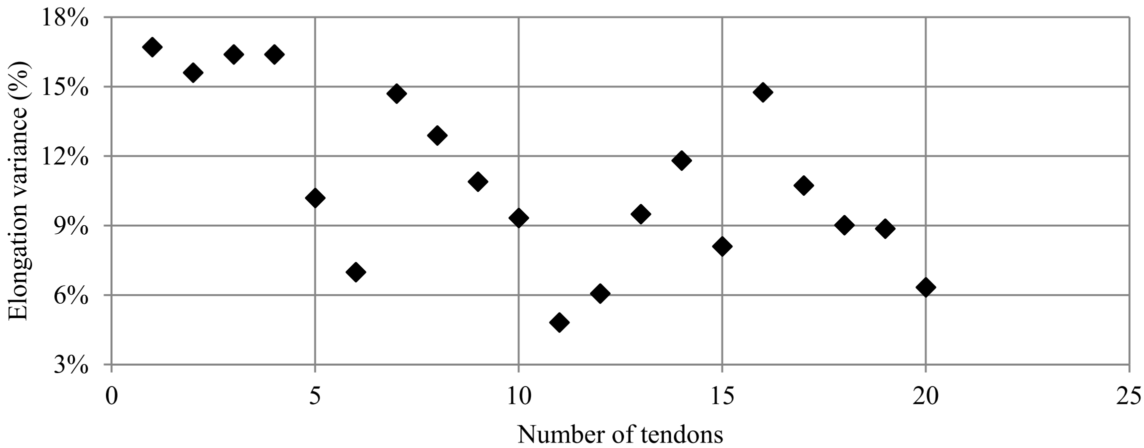


Figure 7 John Vorster P8 tendons

3.3 K46 (1-9) tendons

Except one, all K46 (1-9) tendons (Figure 8) experienced under-elongation. As with over-elongation, when elongations are lower than the accepted tolerance, the calibration should be checked to confirm that the correct jacking force has been applied and selected tendons should be de-tensioned, re-marked and re-stressed to verify that the original marking and measuring procedures were correctly performed. Re-stressing should be careful done since there is a risk of dealing with two problems, the problem of a broken tendon and that of a low final force. The tendons are 16.22m long, and can be accommodated by the proposed elongation variation limit of ±9% if the datum is shifted downwards. Since the material properties of each group of tendons are almost the same, it can be assumed that under-elongation was either caused by higher than expected friction, wobble, elastic modulus and cross-sectional area, or any combination of these. 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 tensioned more than the others.

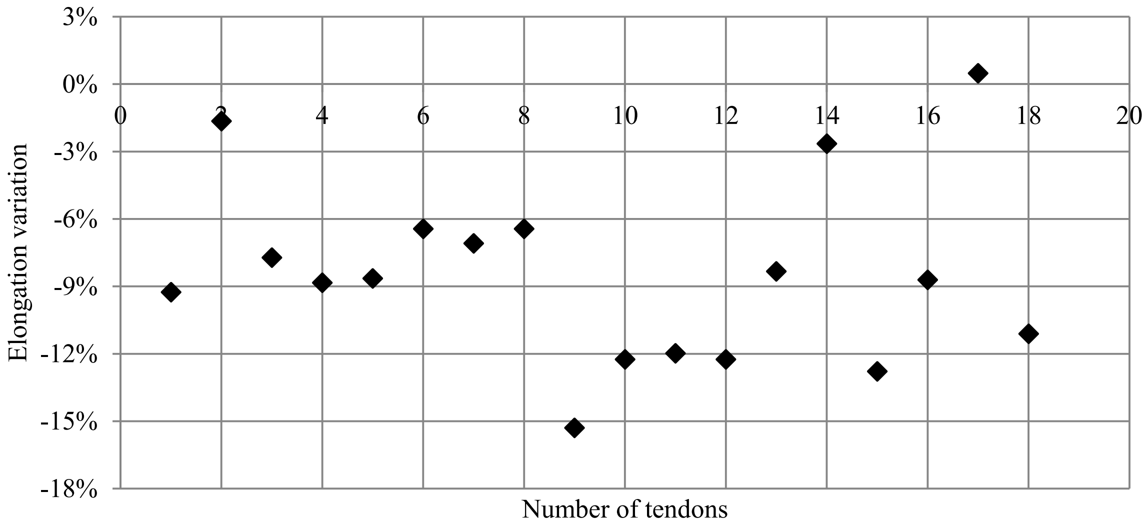


Figure 8 K46 (1-9) tendons

4.0 Summary and conclusions

The aim of this paper was to determine if the SANS 2001-CC1 [1] and COLTO [2] limits for elongation variation of ±6% are too stringent or not. To achieve this selected elongation variation graphs of tendons are presented and discussed. The following conclusions are deduced from this study:

1) Locally manufactured strands possess slightly greater elastic modulus and cross-sectional area than the recommended average elastic modulus of 195GPa and cross-sectional area of 150mm^2 (Table 3). This causes a slight reduction in the elongation of the average tendon.

2) 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 then under-elongation occurs. 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. As long as the stressing jacks are properly calibrated and functioning, required jacking force has not been exceeded during the original stressing operation, over-elongation should not be considered a deficiency and no corrective action is required.

3) It is also noted that when larger values of friction and wobble are assumed during the calculation of the tendon elongation then there is a positive shift of results. This means

that the results would shift in the negative side if the friction and wobble values are small. In interpreting the results, the engineer must consider the shift and judge the elongation results of the tendons accordingly.

4) The average elongation variations of the tendons range from a minimum of -8.38% to a maximum of +13.43%. An average elongation variation of 4.06% shows that tendons tend to over-elongate during stressing. Over-elongation reflects a better distribution of tension in the strand due to lower friction encountered by the strand [6]. The average elongation variation also exceeds the average elongation variation limit of ±3%, provided by SANS 2001-CC1 [1] and COLTO [2]. It can be seen from Table 4 that only five out of sixteen tendon groups met this requirement.

5) It is obvious from this study that an elongation tolerance of ±6% is easier to achieve in short elements. However when the tendons are of larger lengths, size and complicated geometry and more demanding workmanship, then this tolerance becomes difficult to fulfil consistently. The standard deviation from Table 4 of +4.55% indicates a high degree of scatter of elongation variation results. This scatter occurred despite the fact that the correct tension was applied to all of the tendons considered in this paper. Since this standard deviation is the mean of the average standard deviation for all groups of tendons, the elongation variation of tendons can be expected to extend two standard deviations from the average value. Hence, it is recommended that the limit ±6 be adjusted to ±9%. This gives an average elongation variation of ±4.5%. Fluctuations of elongations that exceed these tolerances will not indicate a deficiency in the stressing operation.

6) The importance of elongation variations should not be trivialized, however, the results from the stressing operation should be carefully understood and any corrective action that is undertaken should be absolutely necessary and not just done to make the "records right". Properly calibrated and maintained equipment is essential to achieve the correct elongations.

5.0 Acknowledgements

The author wishes to thank Mr Sebastian Rupiper, who collected the data reported in this paper, during his vacation work with Freyssinet, South Africa.

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