FIELD EVALUATION OF THE PRESTRESSING FORCE IN UNBONDED TENDONS

By

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By Pawan R. Gupta[1]

ABSTRACT: *A common problem that engineers encounter in the evaluation/rehabilitation of existing prestressed concrete structures is determination of effectiveness of the prestressing system. Often the prestressing tendons are corroded and original stressing records are difficult to find. Engineers are faced with the challenge of determining the adequacy of these structures without knowing the effective prestress in the system. In the current state of the art it is very difficult to determine the effective prestress in the tendon accurately without de-stressing and re-stressing the cables. In absence of quantitative results engineers often rely on qualitative data about the condition of the strands to design the rehabilitation scheme. This paper describes a simple non-destructive field technique to measure in-situ prestressing force in unbonded tendons. The technique is simple and safe and requires a small length of strand to be exposed along its length. It is hoped that this would help designers in evaluating existing structures and design effective rehabilitation/upgrading schemes. The technique can also be used in quality control of new construction.*

KEYWORDS: Tension, slabs, tendon, measurement, force, prestressing, unbonded, evaluation.

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1.0 INTRODUCTION

More than one billion square feet (100 million square metres) of concrete structures in North America have been built using unbonded post-tensioned reinforcement[1]. This reinforcement consists of high-strength steel strands that are coated with a layer of grease, inserted into plastic sheathing and attached to the concrete member. The strands are tensioned at one or both ends using a hydraulic jack and anchored to concrete with anchors. Unbonded post-tensioning provides an elegant and cost-effective solution for long-span structures. Unbonded post-tensioned structures perform well provided the tendons are maintained free from moisture. Unfortunately poor construction practices used in the past and lack of understanding of protection techniques have resulted in corrosion damage of strands and eventual breakage of tendons[2]. This can eventually result in unsafe conditions[3] in the structures.

In the evaluation/rehabilitation of existing prestressed concrete structures, engineers are often required to determine the existing capacity of the partially damaged structure. In absence of a reliable way to measure the effectiveness of the post-tensioning system, they rely on the data collected from condition surveys. It is noted that due to the pre-compression applied during stressing, prestressed concrete structures often have significantly smaller crack widths and deflections when-compared to similar conventionally reinforced members. This can sometimes lead to overconfidence on the ability of the structure to carry the required loads. Condition surveys generally concentrate on the durability aspects of the structure but do little to assess the current structural capacity. In some cases it may be important to determine the actual structural capacity before an effective repair/rehabilitation scheme is developed.

2.0 SIGNIFICANCE OF THE WORK

This paper describes a simple non-destructive field technique that can be used to accurately determine the existing level of prestress. Measurements do not require de-stressing of the strands and can be made at any location along the length of the tendon. Only a small portion of the prestressing tendon needs to be exposed along its length. Generally the concrete cover at the low/high point along the length of the tendon is chipped to obtain access to the tendon. The testing frame is attached to the tendon. A known lateral force is applied and the resulting deflection of the strand is measured. The force in the strand is calculated by comparing the deflection of the strand with a theoretically derived field table. The technique has been used on a number of structures in the last four years to design effective repair/rehabilitation schemes.

3.0 ASSESSMENT METHODS FOR POST-TENSIONED STRUCTURES

In the current state-of-the-art, the condition assessment of existing post-tensioned slabs typically consists of a visual survey followed by a review of sample strands exposed over a short length[4,5]. During the visual survey, engineers inspect the slabs for anomalies, which may reflect over-stressing, and/or a likelihood of corroded strands. Frequently encountered anomalies include:

- Wide and/or numerous cracks;
- Large deflections;
- Rust stains;
- Ruptures/spalls;
- Grease stains; and
- Leakage stains below components of the post-tensioning system.

Following the visual survey, engineers select locations where exploratory openings are made by chipping the concrete cover and exposing the strands. Strands are often exposed in areas where corrosion is likely to have occurred. Typically, sufficient concrete and sheathing is removed to expose a tendon length of approximately 8 in. (200 mm), see Fig. 1. The exposed strand is then visually examined for the following:

- Presence of rust and pitting
- Loss of cross-sectional area
- Presence of moisture and condition of the protective grease
- Type and condition of sheathing

Fig. 1 - Corroded strands exposed for visual inspection

Finally, a penetration test (i.e. screwdriver test) is performed to detect wire breaks in the strands. The test also gives an idea if the strand is stressed[3]. Although the test has many limitations, it is widely used in the industry for post-tensioning evaluations. The technique is simple, non destructive and is suited for field applications. The screwdriver test is described in Section 4.4.

When deficiencies are encountered in the preliminary tests, follow-up tests that include one or a combination of the following are performed at sufficient locations:

- Extracting strands for visual and metallurgical analysis and
- Exposing and visually inspecting anchors.

In some cases a load test may also be performed to determine if the structure is capable of supporting the design loads. Based on the data collected from the inspection and physical testing, the engineer makes a decision on the extent of repairs that need to be performed on the structure. The process is very subjective and relies heavily on the engineer's expertise. Since the repairs are often disruptive and very expensive, it is important that a consistent, cost effective way of evaluating, monitoring and managing the repairs of post-tensioned structures be developed.

4.0 EVALUATION OF THE PRESTRESSING FORCE

Up until now, measuring the existing prestressing force has usually not been included in most post-tensioning assessments. Most of the current techniques to evaluate the prestressing force in the strands tend to be either unreliable or very expensive and disruptive. Structural engineers typically rely on the original stressing records to determine the effective prestress in the tendons. In cases where the stressing records are not available the engineer may make a conservative assumption on the level of prestress in the tendon or specify one or more of the tests briefly described below on a small sample of tendons.

4.1 Lift-Off Test

The lift-off test was originally developed to verify the design force of the tendon[6]. The test has also been used to approximate the in-situ tension in strands of existing structures. A lift-off is conducted by using a standard post-tensioning stressing jack on the ends of a strand. Force is applied to the tail of the strand to release the wedges from the anchors. Once the wedges are released the force in the tendon is equated to the force in the jack. In cases where the length of the tail at the end of the anchor is insufficient for the jack to grip, a short piece of strand is usually spliced to the end. If the tail has been cut very close to the anchor, an intermediate anchor is sometimes cast a short distance away from the end to allow the strand to be de-stressed at the ends without losing force in the whole tendon. The method requires access to the end anchors, which may be quite difficult to obtain in existing structures where the cladding or other obstruction prevents access to the anchors. The method is also dangerous especially for partially corroded strands where the wedges tend to stick to the anchors. A larger force is required to pry the wedges out of the anchor. This can sometimes cause the strands to be overloaded and fail. Highly trained and experienced personnel are required to conduct this test.

4.2 Strand Cutting

This test consists of cutting the strand at a location along its length. The total elastic shortening of the strand is measured. Knowing the total length and the elastic shortening, the force in the strand can be calculated. The method tends to be quite expensive and labor-intensive due to the costs of splicing and re-stressing the cut strand. In some cases temporary shoring may also be required before the strand is cut. Also re-stressing old strands is always risky.

4.3 Vibration Measurement

The test is adapted from that used to check tension in cable-stayed bridges[1]. It consists of exposing a portion of the strand, typically 2 ft. (600 mm) in length. The ends of the exposed length are choked to provide node points. An accelerometer is attached to the exposed strand and the strand is excited by tapping. The vibration is transmitted from the accelerometer to computing equipment to determine the tension in the strand as a function of the frequency of vibration. The method is well suited for laboratory applications where the conditions are easily controlled. In field applications the results tend to vary significantly because of problems involved with isolating the strand from surrounding prestressing strands and concrete and supporting it rigidly at the ends.

4.4 Screwdriver Test

The screwdriver test is widely used to detect wire breaks in a strand. A short section of the strand, usually 8 in. (200 mm), is exposed by chipping out the concrete cover from the underside of the slab. A flat head of a screwdriver is driven by a hammer to wedge between the individual wires that make up a tendon (see Fig. 2). If penetration is achieved the strand likely has broken wires or the strand is not fully stressed. The test is non-destructive and relatively easy to conduct.

Fig. 2 - Wire penetration (screwdriver) test

However, it only gives limited information about the force in the strand that can be used in the structural evaluation of capacity. The test results are very sensitive to the skill of the operator and the condition of the screwdriver tip. The test is suitable as a preliminary tool in post-tensioning assessments.

4.5 Modified rebound hammer

Rogowsky et.al.[8] have recently developed a modified rebound hammer test to determine the tension in stressed cables. It works on a similar principle as a screwdriver test but applies a calibrated amount of energy to the head of an accurately machined screwdriver bit. In addition to recording if the tip penetrates the wires of a tendon, the rebound number from the hammer is also recorded and related to the tension in the

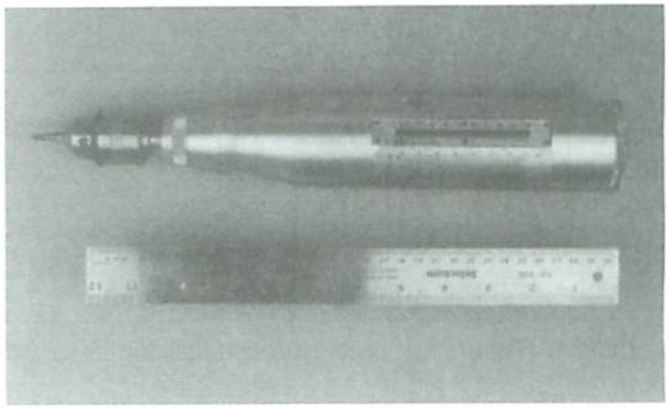

Fig. 3 - Modified Rebound Hammer[8]

cable. They tested various shapes and sizes of the screwdriver tips and noted that results could vary significantly by varying the shape of the tip. They have reported an accuracy of about 25% in the prediction of tension with this technique. Fig. 3 shows the modified rebound hammer used in the study.

5 DESIGN OF IN-SITU CABLE TENSION TEST

The technique consists of exposing a short length of the prestressing tendon (about 2 ft. or 600 mm) and applying a known force "*F*" transverse to the tendon, causing the tendon to deflect. Fig. 4 schematically shows the free body diagram of the tendon under the transverse load. The deflection has been exaggerated to make it visible. The equilibrium conditions at the point of transverse load F are defined as follows:

$$T = \frac{F}{2\sin\theta} \; where \;\; \theta = \tan^{-1}\frac{\Delta}{L/2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Knowing the magnitude of the transverse force *F* and the resulting deflection of the tendon Δ the tensile force in the tendon can be accurately calculated using Eq. (1). Table 1 shows the expected deflections Δ1 and Δ2, for a range of ten-

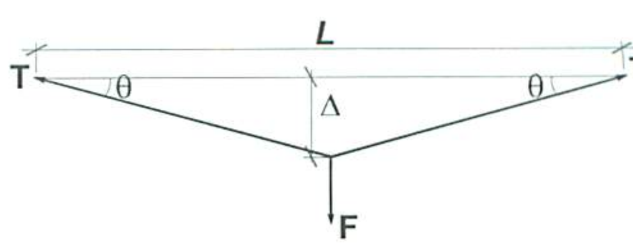

Fig. 4 - Free body diagram of tendon under transverse load

don forces when transverse forces of 0.965 kips (4.3 kN) and 2.29 kips (10.2kN) are applied.

To eliminate errors due to the initial curvature in the strands and variability in the readings due to initial slack in the system, the deflection readings are taken when the jack force is 0.965 kips (4.3kN), D1, and 2.29 kips (10.2kN), D2.The

Gauge Length (L)= 17.72 in

Gauge Pressure (F)	500 (psi) 0.965 k	1000 (psi) 2.290 k

T (k)	θ_1 (deg)	θ_2 (deg)	Δ_1 (in)	Δ_2 (in)	$\Delta_2-\Delta_1$ (in)	$\Delta_2-\Delta_1$ (mm)
5	5.54	13.24	0.859	2.084	1.225	31.12
10	2.77	6.57	0.428	1.021	0.593	15.07
15	1.84	4.38	0.285	0.678	0.393	9.99
20	1.38	3.28	0.214	0.508	0.294	7.47
25	1.11	2.63	0.171	0.406	0.235	5.97
30	1.00	2.19	0.155	0.338	0.184	4.67
35	0.79	1.87	0.122	0.290	0.168	4.26
40	0.69	1.64	0.107	0.254	0.147	3.73

Table 1 - Theoretical prediction of deflection

incremental deflection D2-D1 is used to calculate the tension in the tendon. Table 1 gives the expected deflections D2-D1 for a range of axial force in the strand.

6.0 DEVELOPMENT OF THE TEST FRAME

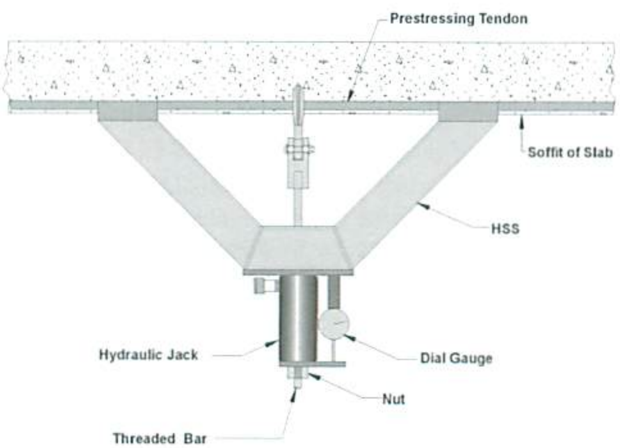

Fig. 5 - In-situ tension test frame

A test frame was developed to apply a known transverse force on the tendon and accurately measure the resulting deformation. Fig. 5 shows the schematics of the test frame. The frame is attached to the tendon by a hook either above or below the slab. A hydraulic jack that is attached to the frame and connected to a hand pump applies the lateral load. A digital dial gauge attached to the test frame measures the deflection. In field the lateral load is measured by reading the pressure in the gauge attached to the hydraulic pump. Since the frame is self supporting it does not apply significant force on the structure.

The deflection readings are taken when the hydraulic pressure

Fig. 6 - In-situ tension test set-up in field

in the jack is 500 psi and 1000 psi. Based on the calibration of the jack this translates into a lateral force of 0.965 kips and 2.29 kips respectively. Table 1 gives the expected deflections for the tendons when these forces are applied to the strand. Fig. 6 shows the test set-up in the field. A special attachment is used to hook single strands when the cables are closely spaced. It is noted that for a normally stressed 0.5 in. (12 mm)ϕ strand the expected deflection is usually less than 3/8 in. (10 mm). Since the tendon is unbonded and relatively long this represents a negligible increase in axial force during testing.

Fig. 7 - Test setup for laboratory calibration of test frame

7.0 CALIBRATION OF TEST FRAME

The test frame was calibrated in the structural engineering testing laboratory at the University of Toronto, Fig. 7 shows the test set-up for calibration. A known axial force was applied to the 0.5 in. (12 mm)ϕ and 0.6 in. (15 mm)ϕ strands. Initial deflection was measured when the pressure in the hydraulic jack was 500 psi (Jack force = 0.965 kips). A second deflection reading was taken when the pressure in the hydraulic jack was 1000 psi (2.29 kips). The increase in transverse deflection between the two loads was used to determine the tension in the tendon.

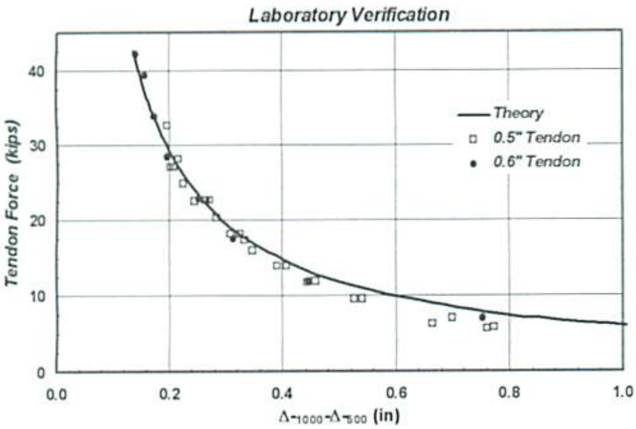

Fig. 8 - Calibration of test frame

Fig. 8 compares the results obtained from the calibration test and theoretical prediction using Eq. (1). It is noted that in the second order effects are neglected in the derivation of Eq. (1). This causes the predicted load to be higher when the axial tension in the tendons is less than 15 kips. Considering that practical range of forces for 0.5 in. ϕ and 0.6 in. ϕ strands is usually more than 25 kips, it was felt that the accuracy of the system was adequate for field applications. If needed accuracy can be improved in the lower range by considering the second order effects.

Fig. 9 - Field calibration of the test frame

The results of the test were also verified under field conditions. Two strands were exposed in the slab of a parking garage in Toronto. The test frame was attached to each tendon and the load/deflection readings were taken. Fig. 9 shows the frame during field-testing. The strands were then cut to release the prestress. The total elastic shortening of the tendon was measured. Based on the total length of the tendon, the tension in the tendon was calculated. The total elongation was also measured during re-stressing.

The results were compared to the effective force in the cable calculated using the in-situ tension tester. Table 2 shows a summary of the observations during field-testing. As expected the accuracy is somewhat lower when the force in the strand is 15 kips. However, in the normal working range of 25-35 kips the accuracy of the test is about 3%. The test frame has also been calibrated against lift-off test in the field with good results.

8.0 CONCLUSIONS

The technique presented in this paper is based on simple concepts of engineering statics. It uses basic measurement of force and deformation to determine the existing force in unbonded strands. The results from the laboratory and field calibrations have confirmed the validity of the technique. The technique has been used in the evaluation/rehabilitation of a number of post-tensioned structures in North America in the last four years, (see Table 3). Based on the results of this work the following conclusions can be drawn:

The existing prestressing force in unbonded strands can be determined reliably without damaging or de-stressing the strands because:

- Since the increase in stress in the strand caused by the measurement is negligible, it is relatively safe to use on corroded tendons.
- Under normal conditions the existing tension in prestressing strand can be estimated within 4%.
- Substantial savings in costs can be achieved in post-tensioned evaluation/rehabilitation, by using this technique.
- The technique can also be used in the quality control of new prestressed concrete construction.

Location	Length (m)	Elongation of Cable (mm)	Applied Tension (kN)	Pressure Gauge (psi)	Dial Gauge Reading (in)	Tension Predicted (kN)	Applied /Predicted (%)	Remarks
North-South*	17.35	115	131.2	500 1000	0.465 0.658	136	96.9%	Existing Cable in Slab
East-West*	44.35	240	107.1	500 1000	0.450 0.696	107	100.6%	Existing Cable in Slab
East-West*	44.35	127	56.7	500 1000	0.716 1.153	60	94.5%	During Re-stressing of Cable at 30% fpu
East-West*	44.35	222.25	99.2	500 1000	0.558 0.821	100	99.2%	After anchoring of Cable

* Toronto Condominium Parking Garage

Table 2 - Field calibration

Project	Type of Structure	Client Type	Purpose	# of Tests
Toronto, Ontario	Parking Garage	Condominium	Condition Evaluation	3
Fairfax, Virginia	Parking Garage	Owner	Quality Assurance	11
Montgomery County, Maryland	Parking Garage	Contractor	Condition Evaluation	6
Tysons Corner, Virginia	NADA Garage	Consultant	Condition Evaluation	20
Toronto, Ontario	Parking Garage	Consultant	Condition Evaluation	10
Washington, D.C.	Office Building	Owner	Condition Evaluation	85
Toronto, Ontario	Office Building	Owner	Condition Evaluation	20
New Orleans, Louisiana	Slab-on-Grade	Consultant	Condition Evaluation	16
Tysons Corner, Virginia	Office Building	Testing Agency	Quality Assurance	4
			Total	*175*

Table 3 - Field testing with in-situ tension tester

It is hoped that this technique will add to the tools available to the structural engineers involved with the evaluation and rehabilitation of post-tensioned structures. Knowing the level of prestress in the structure will help to determine the capacity of existing structure. The engineer can also use the results to design effective rehabilitation/upgrading schemes.

9.0 ACKNOWLEDGMENTS

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