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EVALUATING PRESTRESS LOSSES DURING PRE-TENSIONING

S. Robitaille[1], F. M. Bartlett[2] and M. A. Youssef[2]
[1] Incon Industrial Consultant Ltd., London ON Canada
2 Dept. of Civil and Environmental Engg., Univ. of Western Ontario, London ON Canada N6A 5B9

Abstract: Prestressing losses due to friction between strands and ducts are typically accounted for in post-tensioned concrete members. Similar losses that occur in pre-tensioned prestressed concrete members due to friction at hold-up and hold-down points are typically ignored. A clause in the recent AASHTO Bridge Specification, however, requires consideration of losses that may occur at hold-down devices without providing any guidance about how this should be done. This paper derives equations to predict losses at hold-up and -down points, describes the design and calibration of a unique load cell to measure prestressing strand forces, and presents typical friction losses measured for pre-tensioned members produced at the PSI plant in Windsor Ontario with predicted values. The observed losses can be accurately predicted using a simple pulley-belt friction model with a coefficient of friction of 0.29. Using this model, strand inclinations of more than 2.5 degrees would cause losses at the dead end of a single member of more than 5%.

1. INTRODUCTION

Pre-tensioned prestressed concrete members often have draped strand profiles so that the primary prestressing moment variation along the length of the member approximately matches the shape of the bending moment diagram due to external loads. The draped profile is achieved using hold-up devices at points where the strand is deflected downward and hold-down devices at points where the strand is deflected upward. It is usually uneconomical to form a profile that requires more than two hold-down devices (Gerwick 1971).

Figure 1 (a) shows a typical hold-down device used to deflect up to four pairs of strands. Hold-down devices vary in shape, size and capacity depending on the number of strands and deflection angles they must accommodate. Specifications for readily available hold-down devices can be obtained from the design manuals provided by their manufacturers (e.g., Dayton 2005). Many precasters design and fabricate simple hold-down devices in-house when the production schedule can not accommodate the manufacturer's delivery time.

Although standard hold-up devices can also be found in a manufacturer's product catalogue, they are often improvised using various steel elements. One of the hold-up devices used by Prestressed Systems Inc. (PSI) in Windsor consists of two large vertical steel angles interconnected by bolts: the strands are deflected over the bolts to achieve the desired eccentricity of the prestressing force. Figure 1 (b) shows a different hold-up device consisting of a vertical steel angle with drilled holes through one leg that is welded to the side of the stressing bed. The strands pass through holes drilled through the outstanding leg of the angle section.

The strands are typically tensioned at one abutment only, the "live" end, and anchored at the other abutment, the "dead" end. The strand tension at the dead end, T_D, is expected to be less than that at the live end, T_L, due to friction between the strand and the hold-up and hold-down devices According to the specifications in the hold-down manufacturer's product catalogue, the strands are tensioned in descending order from the top strands down to the lower strands (Dayton 2005). This sequence of tensioning avoids entanglement of the strands and minimizes unbalanced loads on the bed (CPCI 1996). The forces in the strands may therefore vary from top to bottom but the percentage of force lost between the live and dead ends should remain approximately constant.

Figure 1(a): Hold-down device

Figure 1(b): Hold-up device

Clause 5.9.5.2.2a in the AASHTO LRFD Bridge Design Specifications (AASHTO 2002) requires that losses that may occur at hold-down devices be considered in the design of pre-tensioned members. It provides no guidance to designers, however, about how to satisfy this requirement. The research presented in this paper therefore examines quantitative methods to predict losses due to friction during the pre-tensioning operation and so predict the dead end tensile force accurately. The specific research objectives are:

1. Derive an analytical solution for predicting friction losses at hold-up and hold-down points.
2. Design and implement a load cell to measure dead and live end prestress forces in the field.
3. Gather field data using the load cells to validate the analytical model.

The paper will address these objectives in the order given above.

2. ANALYTICAL SOLUTION

The standard equation for belt friction, involving the integration of friction forces that occur as a flexible object slides around a curved surface is (e.g., Hibbeler 2004):

[1] $$T_1 = T_2 \exp\{-\mu\theta\}$$

where: T_2 is the tension force acting in the direction of the belt motion and is reduced by friction to a tension force T_1; μ is the coefficient of friction between the belt and the surface; and, θ is the angle in radians that defines the extent of the contact between the belt and the surface. The friction coefficient is likely the kinematic value given that some slippage must take place. Equation [1] can be applied at the four locations, shown in Fig. 2, where the strand tension force changes to compute the uniform tensions T_1, T_2 and T_3 between the hold-up and hold-down points.

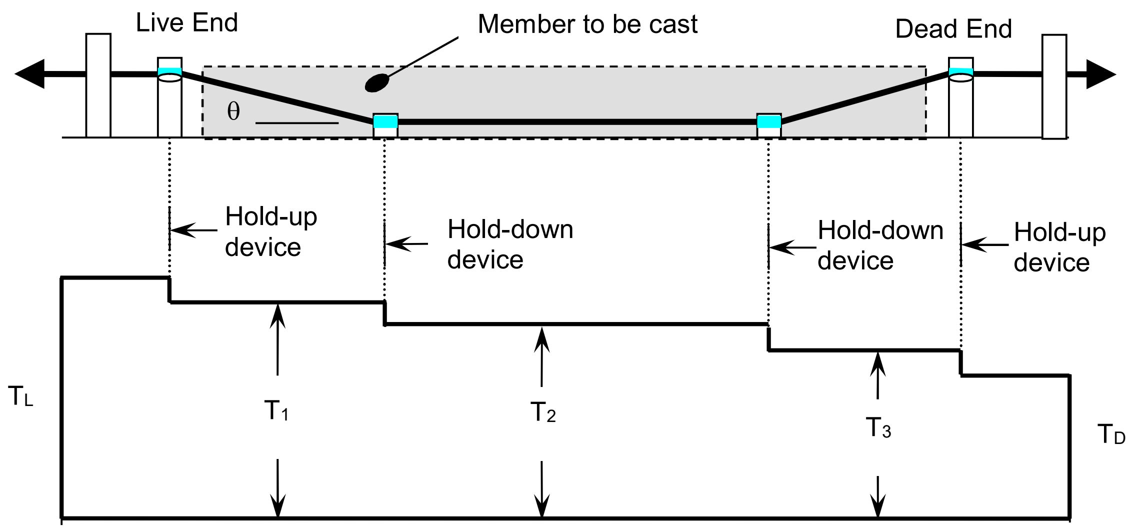

Figure 2: Strand Tension Force Distribution from Live End to Dead End.

Thus:

[2a] $T_1 = T_L \exp\{-\mu_{HU}\theta\}$

where μ_{HU} = the coefficient of friction at the hold-up point,

[2b] $T_2 = T_1 \exp\{-\mu_{HD}\theta\}$

where μ_{HD} = the coefficient of friction at the hold-down point,

[2c] $T_3 = T_2 \exp\{-\mu_{HD}\theta\}$

and

[2d] $T_D = T_3 \exp\{-\mu_{HU}\theta\}$

Combining Eqs. [2a] through [2d] to eliminate T_1, T_2 and T_3:

[3] $T_D = T_L \exp\{-2(\mu_{HU} + \mu_{HD})\theta\}$

and rearranging:

[3a] $\ln(T_D / T_L) = -2(\mu_{HU} + \mu_{HD})\theta$

Thus a graph of $\ln(T_D/T_L)$ versus θ should be linear with a slope of $-2(\mu_{HU} + \mu_{HD})$. Because the deviation angles at the hold-up and hold-down devices are identical, it is impossible to isolate μ_{HU} and μ_{HD} in tests if only T_D and T_L are measured.

3. LOAD CELL DESIGN AND CALIBRATION

Many factors influenced the load cell design criteria. The load cell must be less than 38 mm wide because the minimum strand spacing on some girders is 38 mm and the chuck used to grip the strand during stressing has a diameter of 38 mm. The load cell will be located between the strand chuck and the abutment, so the force in the strand will be transferred by bearing through the load cell. A central hole of at least 13 mm (½″) diameter is therefore necessary to allow the strand to pass through the load cell. The minimum cross section of the load cell must be able to withstand a load corresponding to 80% of the ultimate strength of the strand, 160 kN, without yielding. However the cross section where the strain gauges are mounted must not be excessively large as this would reduce the sensitivity of the load cell.

The final load cell dimensions, based on a steel yield strength of 380 MPa (55 000 psi) are shown in Fig. 3. The load cell is a waisted hollow cylinder with an overall length of 125 mm, a maximum diameter of 37 mm and a hole diameter of 19 mm. The cross-section area of the waisted region, where the strain gauges are attached, is 571 mm^2. Detailed calculations of the dimensions of the load cell are presented elsewhere (Robitaille 2007).

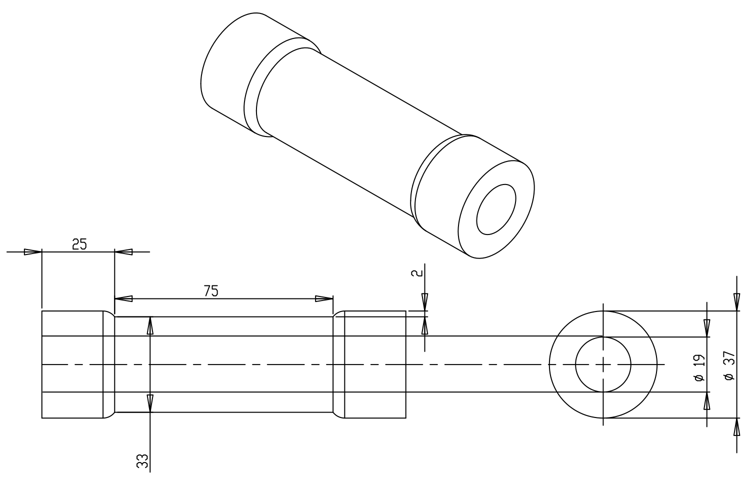

Figure 3: Shop Drawing of Load Cell

Western's University Machine Shop produced two prototype load cells for preliminary testing. Four foil strain gauges were glued to each cell. After the pilot testing confirmed that the design was fully functional, 8 additional load cells were produced to the same design.

The load cells were calibrated using a 245 kN (55 kip) hydraulic actuator. Each load cell was compressed to approximately 140 kN to simulate the load it would be subjected to during prestressing. Simultaneous readings of the load cell strains and the actuator load were recorded electronically. Analysis of these readings allowed accurate evaluation of the accuracy of each load cell.

A preliminary estimate of the load cell error can be made assuming it is entirely due to the strain gauge error. If four strain gauges on one load cell have independent, identically distributed errors, the error of the average strain reading, $\delta_{\bar{\varepsilon}}$ is:

[4] $$\delta_{\bar{\varepsilon}} = \frac{\delta_{\varepsilon}}{\sqrt{4}}$$

where δ_{ε}, the error in an individual strain gauge reading, is typically less than 10 $\mu\varepsilon$ (Nocent 2005). From Eq. [4], the error of the average strain reading must be less than 5 $\mu\varepsilon$. For a load cell cross-section area, A, of 571 mm^2 and Young's Modulus, E, of 210000 MPa, the predicted load cell error, δ_{LC}, is $\delta_{LC} = \delta_{\bar{\varepsilon}} AE = 600 N$, which is only 0.4% of the typical live end tension, 150.7 kN. The calibration factor, i.e., the reciprocal of the load cell rigidity, 1/AE, is 8.34×10^{-9} 1/kN.

Unique calibration factors for each load cell were determined experimentally, and calibration errors were quantified using regression analysis. The regression model considered was:

[5] $$\bar{\varepsilon} = \left(\frac{1}{AE}\right) P_A + \text{Error}$$

where P_A is the hydraulic actuator load corresponding to mean load cell strain $\bar{\varepsilon}$, and the error term is assumed to be an independent identically distributed normal variable. Calibration factors 1/AE and associated standard errors determined by the regression analysis are shown in Table 1. The calibration factors for all load cells except Load Cell 6 range from 8.22×10^{-9} to 8.53×10^{-9} 1/kN, which is close to the value of 8.34×10^{-9} 1/kN predicted using the nominal values. The standard errors in all load cells except Load Cell 6 are less than 5 $\mu\varepsilon$, as was predicted by Eq. [4]. The calibration of Load Cell 6 was repeated and similar results were obtained. There is no explanation for the Load Cell 6 anomalies, but it was not used in the subsequent experimental investigation.

Table 1: Load Cell Calibration Factors and Standard Errors from Regression Analysis

Load cell	Calibration Factor ($\times 10^{-09}$/kN)	Standard Error ($\mu\varepsilon$)	Load cell	Calibration Factor ($\times 10^{-09}$/kN)	Standard Error ($\mu\varepsilon$)
LC1	8.38	1.9	LC6	7.98	8.3
LC2	8.36	1.5	LC7	8.53	1.9
LC3	8.22	5.0	LC8	8.43	4.1
LC4	8.24	3.1	LC9	8.45	3.0
LC5	8.23	1.2	LC10	8.27	3.0

After all field work was completed, each load cell was recalibrated using the hydraulic actuator. The calibration factors for Load Cells 3 were inconsistent with the values initially determined, so data from Load Cell 3 were not analysed further.

4. EXPERIMENTAL DATA

Two pilot tests were conducted to determine the quantity of data to be collected and the frequency of the archived readings. The pilot tests helped the PSI field personnel, the lead hand and the researcher to become familiar with the test procedure to ensure that the tests could be completed with minimum disruption to the daily production cycle. A trust relationship was also established between the researcher, the lead hand and the workers that was essential to the accuracy of the results obtained during the main field testing program because it ensured full cooperation between all participants.

Each load cell was connected to the data acquisition system and installed on the strand between the chuck and the stressing abutment as shown in Figure 4. Readings were taken throughout the precasting process, initiating just before the strands were stressed, continuing while the concrete was placed (approximately 2 hours after stressing) and terminating just after the strands were cut to transfer the prestress (approximately 16 hours after stressing). Due to data acquisition limitations, only four strands could be instrumented during a typical day of testing.

Once the load cells were mounted on the strands the strain indicators were balanced to give a zero reading when zero load was present. To reduce the quantity of data collected while capturing the necessary behavioural features, readings were taken at intervals of:

- 20 seconds from the beginning of stressing until the concrete was placed in the form;
- 5 minutes from the concrete placement until just before the first strand was cut the next morning, and
- 20 seconds while the strands were cut

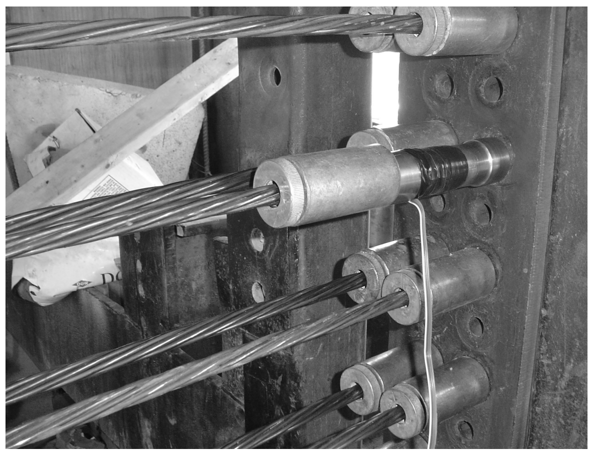

Figure 4: Load Cell in Operation

The main field testing program occurred between July 31st and August 14th 2006. As some load cells were shaded after the strands were stressed while others were exposed to direct sunlight, and typical daytime temperatures approached 30°C, it was necessary to determine the sensitivity of the load cell reading to the temperature. On July 31st, two load cells used to investigate the effect of temperature indicated that the maximum force change caused by temperature variation averaged only 0.19 kN. It was therefore concluded that the measured prestress differences between the live and dead ends were not sensitive to temperature.

Figure 5 shows the force variation with time for Strand 8, tested on August 8th, 2006. The maximum force at the live end, approximately 152 kN, was reached immediately after stressing of the strand at 11:30 am (11:30 on the figure). The force in the strand remained constant until 11:38 when all remaining strands were stressed. The strand tension at the dead end was consistently less than that at the live end and the difference between the strand tensions at each end with time is reasonably constant. There was a slight reduction of the tension force after the concrete placement at approximately 15:00. The most significant reduction of the tension force at both ends occurred around 21:30. Prior to the cutting of Strand 8 just before 7:00 am the following morning, the tension forces at both ends rose sharply due to the cutting of other strands. After Strand 8 was cut, the load cells registered zero, as they should. The average observed loss between the live and dead ends of Strand 8 was 3.98 %.

Robitaille (2007) presents time histories of the strand forces observed on the other instrumented strands that consistently show the strand force at the live end to be larger than that at the dead end. All strands demonstrated a significant reduction of strand force at both ends of the strand at approximately 21:30: it is believed that this phenomenon is temperature-related but to date no rationale has been found to explain it.

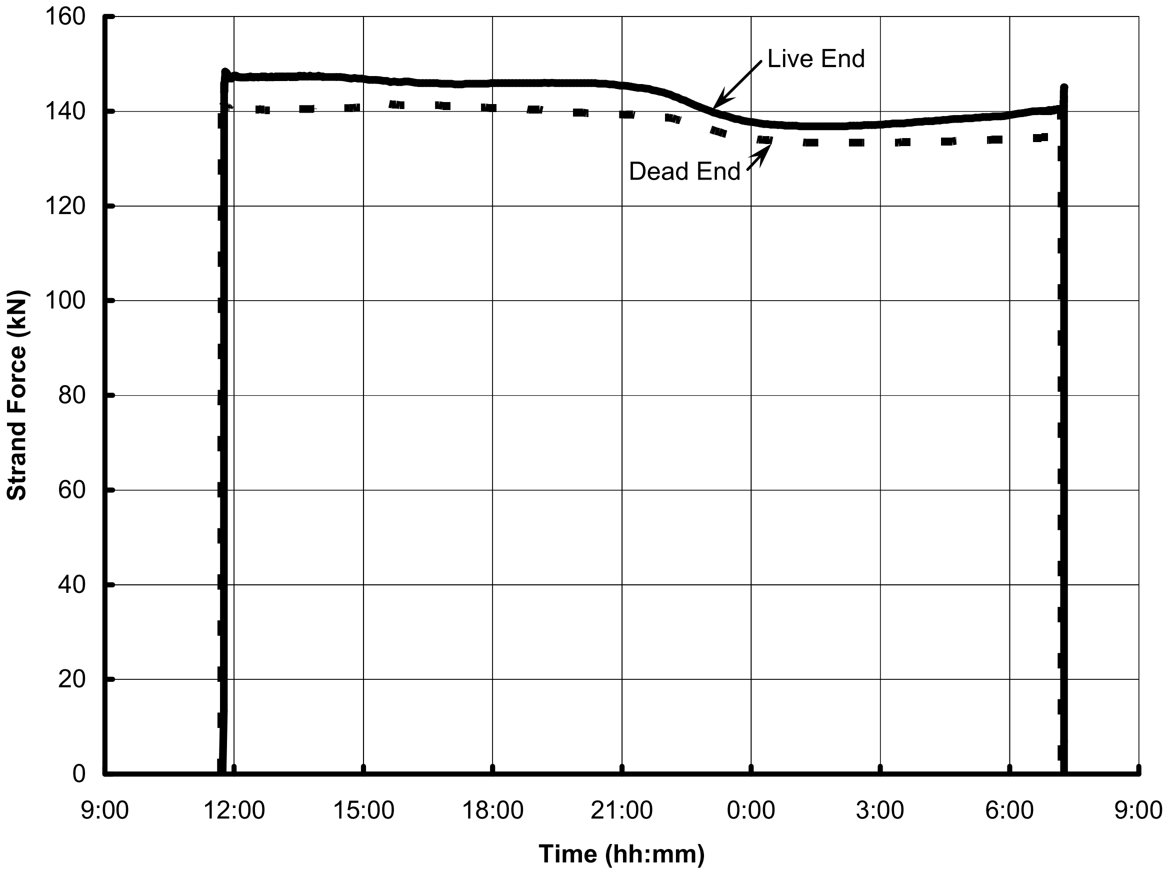

Figure 5: Time History of Strand Force Variation (Strand 8 – 08 August)

Although the strain indicators were balanced (i.e., zeroed) before stressing initiated, some load cells indicated significant non-zero values after all strands had been cut. This is clearly impossible and is attributed to drift of the zero reading during the period of testing. This “zero-drift” phenomenon has been observed in situations where a measurement system has been balanced and measurements have been taken with a particular load condition that cannot be repeated to re-check the original zero (Pople 1978). In those cases where a zero-drift phenomenon occurred, the data were rectified by assuming that the drift occurred instantaneously upon stressing, and the non-zero force value recorded after all strands were cut was subtracted from all force readings obtained during the test from that load cell (Robitaille 2007).

The results for 13 strands successfully instrumented in the investigation are summarized in Table 2. The data for three strands indicate that the measured load at the live end is slightly smaller than that at the dead end. In each case, the loss is less than within 0.4% or 600 N and can be attributed to load cell errors, as shown in Table 1. A possible explanation for the high losses observed consistently for of Strand 6 is that the strand elevation changes between the abutment and where it enters the form due to placement constraints.

Table 2: Summary of Measured Friction Losses during Pre-tensioning

Strand	Date	θ (°)	T_L (kN)	Loss (%)	Strand	Date	θ (°)	T_L (kN)	Loss (%)
3	Aug. 11	1.83	147.52	0.31	7	Aug. 8h	2.15	143.41	1.65
4	Aug. 9	1.91	145.13	-0.25	7	Aug. 9	2.15	144.23	-0.16
4	Aug. 10	1.91	154.82	4.29	7	Aug. 10	2.15	154.94	4.94
5	July 31	1.99	165.72	3.73	8	Aug. 8	2.20	148.34	3.98
5	Aug. 11	1.99	150.52	6.25	10	Aug. 9	0	147.49	-0.19
6	July 31	2.07	161.32	6.01	10	Aug. 11	0	159.26	3.16
6	Aug. 11	2.07	167.64	6.11					

5. DISCUSSION

The test summary results shown in Table 2 are presented in Figure 6. The observed data correspond to a narrow range of deflection angles between 1.8 and 2.2 degrees. The "predicted" value shown in the figure is computed using Eq. [3] with an assumed coefficient of friction, μ, of 0.25.

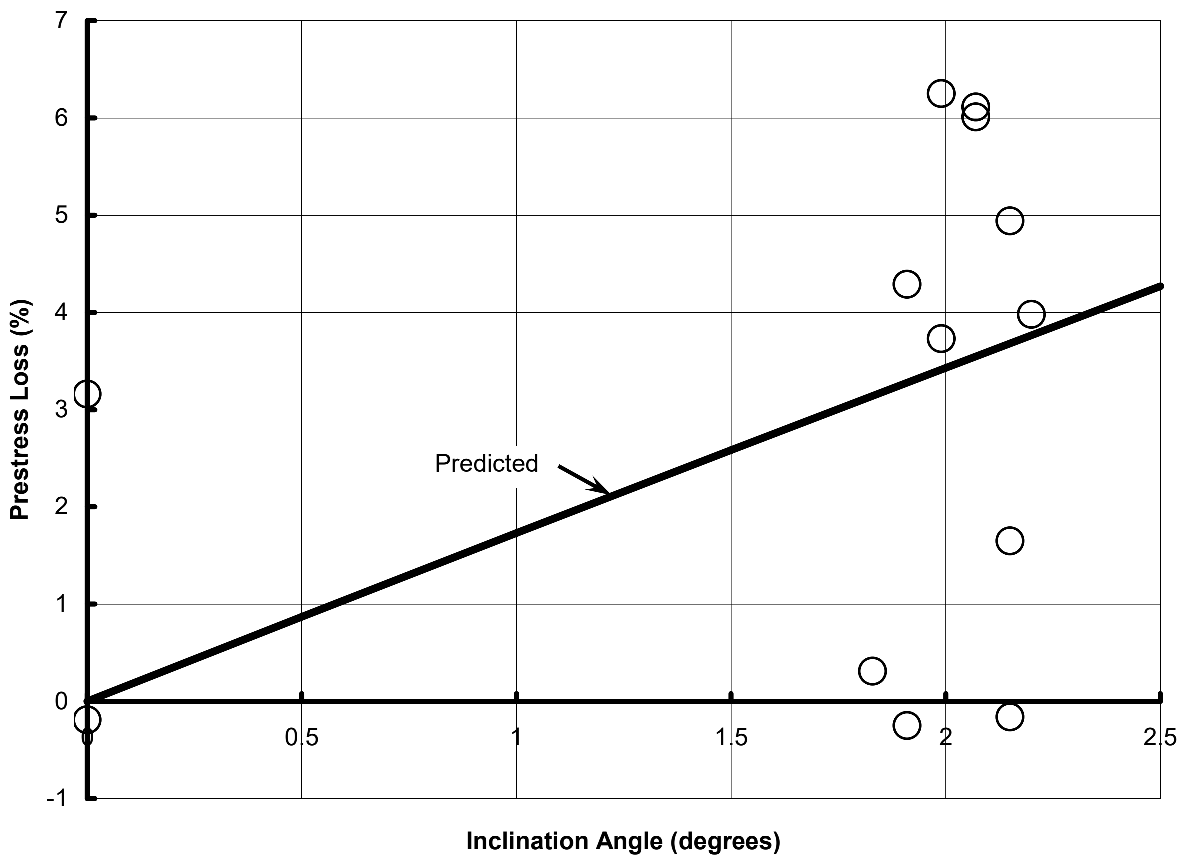

Figure 6: Prestress Loss versus Inclination Angle

Considering the losses measured for Strands 5 through 8 only, which have the highest deflection angles, a more organized comparison can be drawn. The average observed losses of Strands 5 through 8 are

4.99%, 6.11%, 3.30% and 3.98% respectively. Ignoring the data for Strand 6 due to the local strand elevation changes between the abutment and the hold-up point, described previously, the average observed loss of Strands 5, 7 and 8 is 4.11%, which corresponds to the value computed using Eq. [3] with a coefficient of friction of 0.29.

Equation [3] can be used to predict the loss, $(T_L – T_D)/ T_L$, for different deviation angles θ. For a 12.7-mm (0.5-inch) diameter Grade 270 strand, A=108mm^2 so T_L is (108×0.75×1860×10^{-3} =) 150.7 kN. If the coefficient of friction for the hold-ups and the hold-downs is assumed to be 0.29, the loss at the dead end will exceed 5% if the deviation angle exceeds 2.5 degrees. It is not uncommon to find strand profiles with deflection angles this large especially if the girders are short. For example, shop drawings of 27 m long I girders produced in Windsor in 2006 have strand deflection angles between 3.4 and 5.6 degrees. The situation would be worse for strands in a long prestressing bed where several girders with draped strands were being precast end-to-end.

6 SUMMARY AND CONCLUSIONS

Friction losses can occur during tensioning of deflected strands in pre-tensioned precast girders at the hold-up and hold-down locations. The magnitude of these losses was measured in the field and compared to values computed using an analytical model based on pulley-belt friction. Strain gauge readings were taken from the live and dead ends of thirteen strands at a precasting plant in Windsor over a period of two weeks in August 2006. To capture these data, ten project-specific load cells were designed and fabricated. Each load cell was calibrated using regression analysis to obtain a factor to convert the measured strains into strand forces. Also, on a day when the air temperature reached 37°C, two load cells were placed beside the form at each end of the member to investigate the effect of temperature on the load cell reading. Preliminary analysis of the data identified several significant anomalies that were attributed to significant drift of the strain gauge zero reading that occurred instantaneously when the strand was stressed. These problematic data were rectified by subtracting the zero-drift value from all data for that strand.

From the experimental and analytical investigations carried out in this study, the following conclusions appear warranted:

1. Significant prestress losses can occur in pre-tensioned members at the time that the strands are stressed due to friction at the hold-up and hold-down devices. A loss that averaged approximately 4% was observed for strands with inclinations in the order of 2%.

2. The observed losses can be accurately predicted using the simple pulley-belt friction model, Eq. [1], with a coefficient of friction of 0.29.

3 Using the analytical model, strand inclinations of more than 2.5° would cause losses of more than 5%. This could not be validated experimentally since the testing schedule and the production schedule didn't allow for girders of such inclinations to be tested.

4. The load cell design and fabrication were completed with precision. Initial calibration showed 9 out of 10 load cells to be accurate with standard errors less than approximately 0.6 kN. Recalibration after testing indicated that Load Cell 3 and 6 proved to be problematic while the remaining results were consistent with the initial calibration.

5. The effect of having some load cells exposed to the sun while others were shaded was investigated to see if the results could have been influenced by temperature variations. The measured strand forces varied up to approximately 1 kN (0.7% of the typical live-end prestress force) when exposed to temperature changes up to 37°C and therefore have limited impact on the phenomena observed.

It is recommended, however, that the evaluation of prestress losses during pre-tensioning be further investigated. New data obtained by testing strands with greater inclination angles would allow further confirmation of the accuracy of the analytical model presented in this paper. A test procedure should also be developed, and testing conducted, to obtain the exact coefficients of friction for the various types of hold-up and hold-down devices to enhance the accuracy of the analytical model further.

7. ACKNOWLEDGEMENTS

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