Fracture Mechanics of Concrete and Concrete Structures -
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Prediction of time dependent effects in prestressed concrete

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ABSTRACT: The effect of temperature in the prediction of long-term loss of prestress, particularly on the relaxation loss of prestressing strands, in prestressed concrete has been studied. The factors affecting the relaxation loss in prestressing strands have been varied experimentally in Structural Engineering Laboratory at the Indian Institute of Technology Madras. The measured relaxation loss is compared with different experimental results and various codes.

1 INTRODUCTION

1.1 *Time dependent loss of prestress*

The decrease in initial applied prestress i.e., the loss of prestress, with time is a concern for the design of prestressed concrete members. Even though the accurate estimation of the final prestress is important for the design, determination of the same is complex because of the time dependent and interdependent material and environmental characteristics.

The major contributors for the loss of prestress at the service stage are creep and shrinkage of concrete and relaxation of steel. Many models have been developed to accurately predict the creep and shrinkage of concrete, including various parameters and reducing uncertainties. To predict the long-term relaxation of prestressing steel, very few reliable models are available considering various factors. Hence in this study an attempt has been made to consider the effect of various factors on relaxation of steel.

1.2 *Relaxation of steel*

Relaxation (Intrinsic relaxation) is the time dependent decrease in the initially applied stress at a constant strain. Even though in prestressed concrete the strain in the strands will alter due to creep and shrinkage of concrete, intrinsic relaxation tests are done to understand the behaviour of the prestressing steel and also to estimate the loss of prestress approximately. Relaxation depends on time, exposed temperature, initial stress and type of steel. Many studies had been done to understand the dependence of relaxation of steel on these factors (Magura et al. 1997). The relaxation has been expressed as a function of time and initial applied stress, assuming that relaxation varies with logarithm of time linearly. Schwier (1958) found that relaxation loss at 100^0C is eight folds the loss at 20^0C. Since the temperature variation during the normal operation is nominal, relaxation was not expressed in terms of temperature. Later a general equation had been introduced to determine the relaxation loss for stress relieved steel and low relaxation steel (PCI Committee 1975, Ghali & Trevino 1985).

1.3 *Relaxation test specifications*

Several Codes *e.g.*, IS 14268 (1995) specify that the stress relaxation test should be performed at an initial load of 70% of the guaranteed ultimate tensile strength (GUTS) of the strand under constant temperature of 20 ± 2^0C for a testing period of 1000h. The load should be applied within 5 minutes and the loss of stress should be measured from the sixth minute. In stress relieved strand the 1000h relaxation should not exceed 5% (IS 6006, 1983). In low relaxation strands, it should not exceed 2.5% for 1000h and 1.8% for 100h.

1.4 *Effect of temperature*

In nuclear power plant (NPP) containment structures the average temperature around the prestressed wires was found to vary between 30^0C and 35^0C (Ashar et al. 1997). The loss due to relaxation of steel extrapolated at such temperatures over a design service life of 40 years was found to be 17.5% which is relatively very high compared to the loss specified by many codes i.e. about 10-12%. The Fritz Engineering Laboratory of Lehigh University investigated the relaxation loss on 14 prestressing tendons at temperatures of 20^0C (68^0F), 25^0C (78^0F), and 40^0C (104^0F) and at an initial prestress of 0.70 and 0.75 GUTS of wires. It was found that appreciably higher relaxation of wires observed at 25^{0}C and 40^{0}C than those at 20^{0}C.

Petersson and Sundquist reported that a temperature rise from 20^{0}C to 40^{0}C may lead to two fold increase in the relaxation loss (Roth 2004). A test program was conducted in CBI laboratory, Sweden on thirty-year old (seven) wires from Forsmark and seven new wires. The central wires of 7-ply prestressing strands were tested at two temperatures 20^{0}C and 55^{0}C at the load of 70% of the ultimate load. The 5-day relaxation loss was found to increase from 2 to 4% as the temperature increased from 20^{0}C to 55^{0}C in fresh wires while the increase in relaxation loss in the old wires was negligible.

The prestressing losses were measured for a period of 30 years, in six Swedish reactors located at two different power plants (Anderson 2005). The results indicate that the loss of prestress ranges between 5 and 10% of the initial prestress, which is much lower than the predicted loss for design i.e. about 20–25%. Similar observations have been reported on a few British containments. The main reasons for such relatively low losses could be due to slow drying process of concrete and high concrete age at the initial stage of tensioning of wires. Further, it was confirmed that the temperature has a major influence on the loss of prestress.

2 RESEARCH SIGNIFICANCE

In several civil engineering structures such as bridge structures, since variation in the exposed temperature during operation is negligible, it does not influence the relaxation loss significantly. In special structures like power plant containments, where the temperatures vary from ambient temperature to about 130^{0}C or 150^{0}C during operation the effect of temperature on relaxation loss plays vital role on the longevity of the structures and hence need to be studied in detail. This study attempts to address the effect of temperature on loss of prestress due to relaxation of steel strands.

3 MATHEMATICAL EXPRESSIONS

3.1 *Relaxation of steel*

Magura et al. (1964) expressed the remaining stress as a function of time and initial stress ratio.

$$\frac{f_s}{f_i} = 1 - \frac{\log t}{10}\left[\frac{f_i}{f_y} - 0.55\right] \; for \; \frac{f_i}{f_y} \geq 0.55 \qquad (1)$$

where f_s is the remaining stress, f_i is the initial stress, f_y is the yielding stress and t is the time in h at which the remaining stress is required.

PCI Committee on prestress losses (1975) recommended an expression based on the above study to estimate the intrinsic relaxation as follows:

$$\Delta\sigma_{pt} = -\frac{1}{M}\sigma_{pi}\left[\frac{\sigma_{pi}}{\sigma_{py}} - 0.55\right]\log\left(\frac{t}{t_i}\right) \; for \; \frac{\sigma_{pi}}{\sigma_{py}} \geq 0.6 \qquad (2)$$

where $\Delta\sigma_{pt}$ is the intrinsic relaxation at time t in steel tendon, t_i is the initial time in hours at which load is applied, σ_{py} is the yield strength and M is a factor related to the type of steel, the values 10 and 45 are valid for stress relieved and low relaxation wires and strands respectively.

Ghali & Trevino (1985) introduced relaxation reduction coefficient to estimate the relaxation loss considering the effect of creep and shrinkage of concrete. The relaxation loss can be expressed as:

$$\overline{L}_r = \chi_r L_r \qquad (3)$$

where $\overline{L}_r$ is reduced relaxation value, L_r is intrinsic relaxation which occurs in a constant length tendon and χ_r is relaxation reduction coefficient.

Intrinsic relaxation is further expressed as:

$$L_r(t) = L_{r\infty}\left[\frac{1}{16} ln\left(\frac{t-t_1}{10}+1\right)\right] when \; 0 \leq (t-t_1) \leq 1000 \qquad (4)$$

$$L_r(t) = L_{r\infty}\left[\frac{t-t_1}{10}+1\right]^{0.2} when \; 1000 < (t-t_1) \leq 0.5\times10^6 \qquad (5)$$

$$L_r(t) = L_{r\infty} when \; (t-t_1) > 0.5\times10^6 \qquad (6)$$

$L_{r\infty}$ is the intrinsic relaxation at infinite time, t is the time at which intrinsic relaxation is required and t_1 is the time at which the initial load is applied. The ultimate relaxation is a function of type of steel and intial stress ratio as follows.

$$\frac{L_{r\infty}}{f_i} = -J(\lambda - 0.4)^2 \; when \, \lambda \geq 0.4 \qquad (7)$$

$$L_{r\infty} = 0 \quad when \;\; \lambda < 0.4 \qquad (8)$$

λ is the initial stress ratio defined as the initial stress applied to the ultimate stress and J is the material factor, 1.5 and 2/3 for stress relieved and low relaxation steel respectively.

Rostasy et al. (1991) studied the effect of temperature on the relaxation of low relaxation wires and developed an expression from their experimental results as follows.

$$R(t,T) = a(t)\, e^{b(t)T} \qquad (9)$$

R is the relaxation at any time, t and temperature, T. $a(t)$ and $b(t)$ are functions of time:

$a(t) = 0.320\ (1+0.23\ ln\ \mathrm{t})$ & $b(t) = 0.014\ (1+0.03 ln\ \mathrm{t})$

3.2 *Creep and shrinkage of concrete*

Creep and shrinkage are the time dependent strains in the concrete, which are influenced by several factors such as strength of concrete, age of concrete at loading, type of curing conditions, relative humidity, temperature, water-cement ratio, size and shape of the member etc. Many popular analytical models *e.g.* ACI 209 (1996), CEB-FIP model code (1990), B3 Model, BP-KX Model and GL2000 Model are in existence to describe the behaviour of the creep and shrinkage of concrete.

Jayakumar et al. (2007) studied the creep and shrinkage experimentally on high performance concrete specimens for a period of 500 days. The specimens were 150mm x 150mm x 600mm, with a compressive strength of 50MPa. The test temperature and relative humidity were 20^{0}C and 56% respectively. The measured strains were compared with different code predictions. They observed that CEB-FIP model code, slightly over predicts at an early age but matches well at a later age.

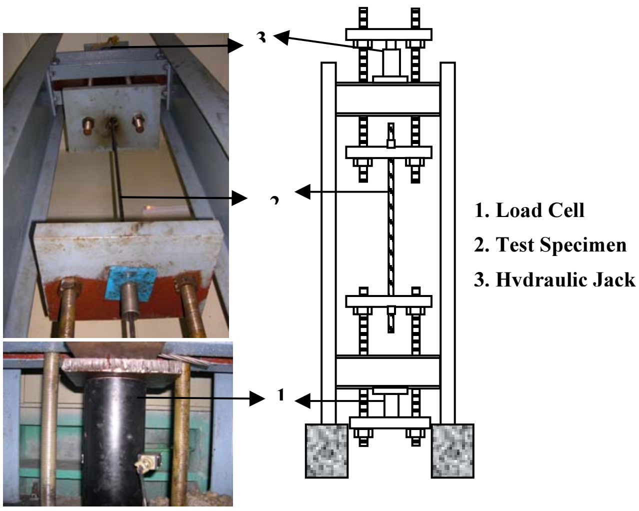

Figure 1. Experimental Set up.

4 EXPERIMETAL PROGRAM

The test specimens were low relaxation seven-ply prestressing strands, with a diameter of 12.7mm and an ultimate tensile strength of 1860 MPa. The test parameters were; temperature, initial prestress and time. Two different initial prestress ratios 0.7 and 0.8 were considered at different temperatures in the range of 20^{0}C to 45^{0}C. The duration of the testing was 1000h or until the loss stabilizes, whichever is less. The test set up is shown in Figure 1.

4.1 *Temperature studies*

The relaxation test was conducted according to IS 14268 (1995). The temperature was varied from the test specifications i.e., 20±2^{0}C. At every initial prestress the test was conducted at temperatures of 20^{0}C, 25^{0}C, 30^{0}C, 35^{0}C, 40^{0}C and 45^{0}C. Constant temperature was maintained throughout the experiment using temperature control chamber. At 0.7 initial stress, the relaxation loss at temperatures 50^{0}C and 150^{0}C were also studied. In this context the strand was heated using direct heating element.

5 EXPERIMENTAL RESULTS

The variation of relaxation loss vs. time is shown in Figure 2 at various temperatures and at an initial prestress of 0.8. The relaxation loss at a temperature of 20^{0}C and at 1000h is 3.24% which is less than the code value, 3.5%. The relaxation loss at 45^{0}C is 7.92% which is about 2.5 times the loss at 20^{0}C. The test was terminated at 1000h as per the code provisions.

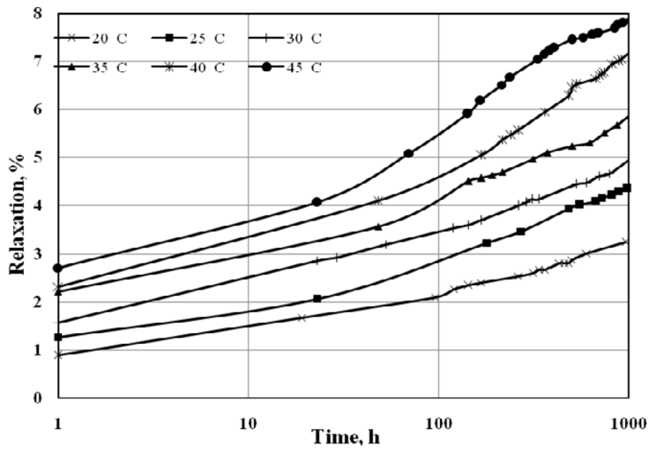

Figure 2. Relaxation vs. time at an initial prestress of 0.8.

At an initial prestress of 0.7 the variation of relaxation loss vs. time is shown in Figure 3 at different temperatures. The 1000h relaxation loss at a temperature of 20^{0}C is 2.03% which is less than 2.5%, as specified by the codes. Similarly, the 100h relaxation loss is 1.0% which is much less than the loss specified by the codes i.e. 1.8%. The relaxation loss at 45^{0}C is 5.33% which is 2.6 times the loss at 20^{0}C.

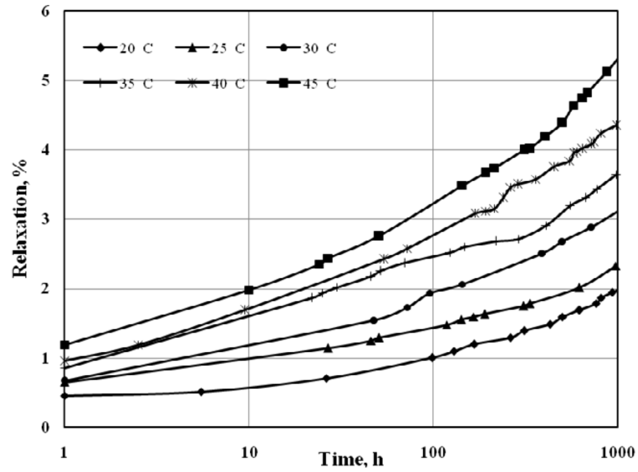

Figure 3. Relaxation vs. time at an initial prestress of 0.7.

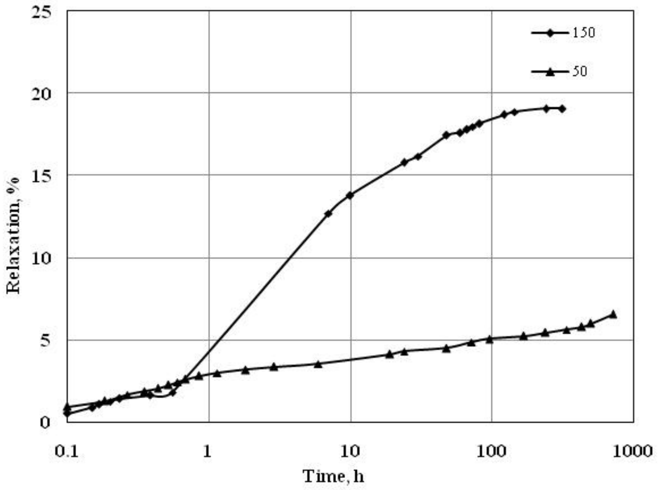

Figure 4. Relaxation loss at 50^{0}C &150^{0}C at 0.7 initial prestress.

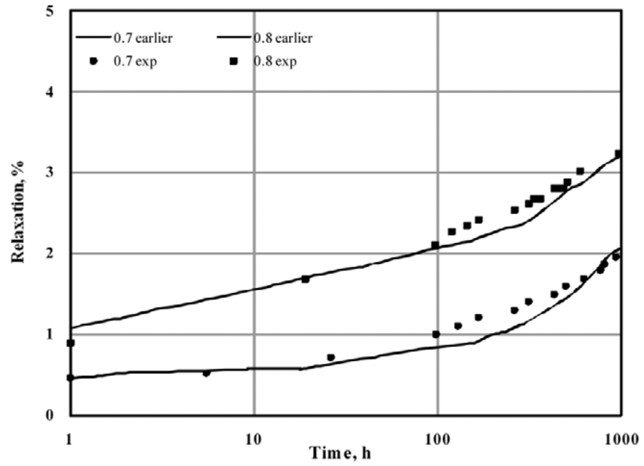

Figure 5. Comparison of experimental results with Erdelyi (1989) research.

Figure 4 compares the relaxation loss at 50^{0}C and 150^{0}C. At 50^{0}C the relaxation loss stabilized with a loss of 6.6% at 800h. The 100h relaxation is 5.0%, which is about 5 times the relaxation loss at 20^{0}C. When the loss was stabilized, the 50^{0}C relaxation loss was 6.6%, which is about 3.25 times the relaxation loss at 20^{0}C i.e. 2.03%. At the elevated temperature of 150^{0}C, the rate of relaxation is very less after 100h. At about 240h the relaxation loss was found to be stabilized. The loss at that stage was 19.0%.

Figure 5 compares the experimental observations with the earlier reported research results on 7-ply strands at a constant temperature of 20^{0}C with two different initial stress ratios 0.7 and 0.8. Even though the results deviate during 100h, at 1000h the experimental values coincide with the earlier research results.

Figures 6 & 7 show the comparison of experimental results with the predicted relaxation loss from PCI committee on prestress losses (1975) and CEB-FIP Model Code (1978). The PCI expression estimates the relaxation as a linear function of logarithmic time and underestimates in both cases. The results predicted by CEB-FIP Model initially deviate from the present results but converges at around 100 h at an initial prestress ratio of 0.7 and at around 1000h when the initial applied prestress is 0.8.

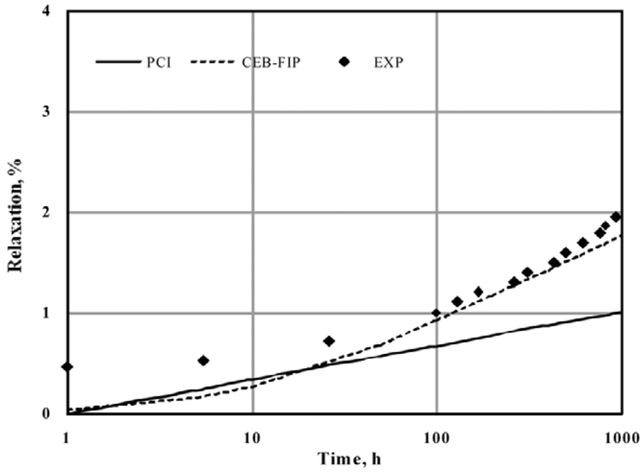

Figure 6. Comparison of observation with PCI and CEB-FIP at 0.7.

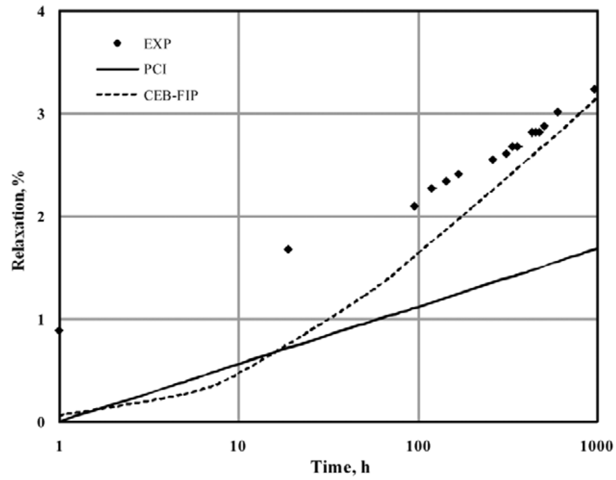

Figure 7. Comparison of experimental with PCI and CEB-FIP at 0.8.

6 CONCLUSION

The PCI and CEB-FIP codes underestimate the relaxation at 20^{0}C. The relaxation loss increases with temperature at a high rate during the initial period and slows down later irrespective of the initial stress. Increasing the temperature accelerates the stress relaxation process and helps to reduce the duration of the testing of the strands. CEB-90 Model code and BP-KX model are in good agreement with the creep and shrinkage of high performance concrete and with the experimental observations.

REFERENCES

American Concrete Institute (ACI) 1996. Prediction of creep, shrinkage and temperature effects in concrete structures ACI 209 R-92, *ACI manual of concrete practice, Part I*.

Anderson, P. 2005. Thirty years of measured prestress at Swedish nuclear reactor containments. *Nuclear Engineering and Design* 235(10): 2323-2336.

Ashar, H., Costello, J., and Graves, H. 1997. Prestress force losses in containments of U.S. nuclear power plants. *Joint WANO/OECD-NEA Workshop Prestress Loss in NPP Containments Poitiers* (France): 337–351.

Comite Euro-Internationale du Beton (CEB)-Federation Internationale de la Precontrainte (FIP) 1978. *Model code for concrete structures.*

Erdelyi A. 1989. Estimating the relaxation of prestressing tendons. *Periodica Polytechnica*, Civil Engg 33(1): 19-32.

Ghali, A. & Trevino, J. 1985. Relaxation of steel in prestressed concrete. *PCI Journal* 30(5): 82-94.

Indian Standard 14268 1995. *Uncoated Stress Relieved Low Relaxation seven-Ply Strand for Prestressed Concrete Specification*.

Indian Standard 6006 1983. *Specification for Uncoated Stress Relieved Strand for Prestressed Concrete*.

Jayakumar, K., Upadhyay, A., & Bhandari, N. M. 2008. Artificial Neural Network for predicting creep and shrinkage of concrete. *Journal of Advanced Concrete Technology* 6(1): 135-142.

Magura, D. D., Sozen, M. A., & Siess, C. P. 1964. A study of stress relaxation in prestressing reinforcement. *Journal Prestressed concrete institute* 9(2): 13-57

PCI Committee on Prestress Losses, 1975. Recommendations for estimating prestress losses. *PCI Journal* 20(4): 44-75

Rostasy, F. S., Thienel K.-ch., & Schutt K. 1991. On prediction of relaxation of cold drawn prestressing wire under constant and variable elevated temperatures. *Nuclear Engineering and Division* 130: 221-227

Roth.T. 2004. Lifetime Issues Concerning Prestressing Steel in Concrete Structures *Licentiate Thesis Division of Structural Design and Bridges*, Department of Civil and Architectural Engineering: KTH, Stockholm