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Quantifying prestressing force loss due to corrosion from dynamic structural response

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ABSTRACT

In prestressed concrete structures, corrosion of prestressing strands is a major durability concern. In advanced stages, corrosion may result in the rupture of strands. At early stages, corrosion of strands results in microcracking, deterioration of bond between strands and concrete, and therefore, in the loss of prestressing force. These effects, in turn, result in the change of dynamic response of prestressed elements. In this paper, we investigate whether the prestressing force of prestressed beams can be estimated indirectly using dynamic vibration test. For this purpose, six prestressed concrete beams were manufactured. Two beams were kept as control, two beams were corroded along the entire length of the strand, and two beams were corroded along one-third of the strand length. The induced accelerated corrosion was monitored by corrosion current measurements and passive acoustic emission. Two system identification approaches were developed where both utilize the free vibration response of an Euler-Bernoulli beam to estimate prestressing force of strands. Due to the ill-possedness of the identification problems and the presence of random and systematic errors in the experiment, Tikhonov regularization method was used. Finally, results were compared with analytical solution of vibration of a simply supported beam with external compressive force. It was concluded that using dynamic vibration of prestressed concrete beams and using indirect estimation approaches, it is possible to quantify the loss of prestressing force due to corrosion.

1. Introduction

Prestressed concrete elements are widely used in civil infrastructure. Corrosion in these elements can be a major concern since it may induce microcracking, and hence, adversely affects the mechanical properties of the concrete surrounding the stands, corrosion may result in longitudinal cracking and subsequent loss of prestressing force in strands, and corrosion may result in cracking and the rupture of the strands. The reduction of the prestressing force can severely compromise the serviceability of the structure and reduce the load carrying capacity of the elements. Estimating the load carrying capacity is important for example in determining the maximum allowable load on bridges suffering from corrosion. However, to estimate the load

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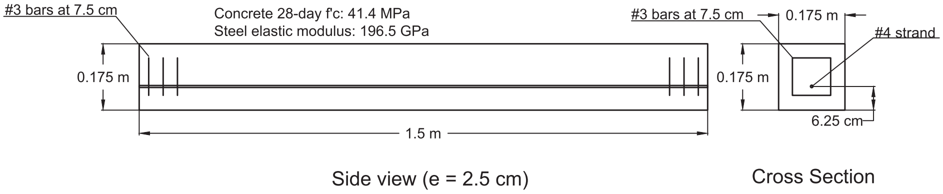

Fig. 1. Manufacturing details of the prestressed beams.

carrying capacity of the corroded prestressed elements, the prestressing loss should be quantified.

Several techniques have been implemented in recent years to detect and quantify the loss of pre-stressing force in prestressed concrete structures. These techniques include the use of ultrasonics [1–3], fiber optics [4] and vibration based methods [5–11]. While fiber optics have shown a great potential to detect the loss of pre-stressing in prestressed beams, this technique requires sensor installations at the time of construction and may be difficult to apply to existing structures. Similarly ultrasonic techniques have been also been successful however, they may be affected by the heterogeneity of the concrete materials; furthermore, the use of ultrasonic techniques may require access to the pre-stressing strands that may not be easily feasible in the field applications. On the other hand, using vibration based methods may be an efficient method to quantify the loss of pre-stressing force. Since they are relatively inexpensive, easy to apply, non-destructive and can be applied to existing structures. Therefore, this study focus on the use of vibration based methods to quantify the pre-stressing force loss.

Previously, several studies have attempted to correlate prestressing force to modal frequencies in prestressed concrete beams [5–11]. They showed that, the prestressing force can be directly estimated by modal frequencies, based on analytical solutions. Therefore, it can be concluded that, using the analytical solution of free vibration of a simply supported beam with an externally applied compressive force, which models prestressing force; we can estimate prestressing force of prestressed reinforced concrete beams. This analytical solution can be found in (e.g., [12,13]) and is shown in Equation (1)

$$\omega_i = \frac{i\pi}{L}\sqrt{\frac{1}{m}EI_0(\frac{i\pi}{L})^2 - F_c} \tag{1}$$

where ω_i are modal frequencies, EI_0 is the flexural rigidity of the beam, L is the length of the beam, m is the mass per unit length of the beam, i stands for the mode number and F_c is the axial compressive force. Equation (1) shows that the magnitude of modal frequencies of the beam decrease with the magnitude of the external compressive force.

Estimation of prestressing force loss using Equation (1) therefore is limited to simply supported prestressed beams with no complexity in geometry, materials and design and therefore does not support prestressed structures with different boundary and loading conditions, more detailed reinforcement, and structural behavior. Therefore, there is a need for more advanced inverse problem techniques such as the works by Law and Lu [14,15] for parameter estimation.

In this paper, we investigate the feasibility of using dynamic vibration response to quantify the prestressing loss due to corrosion in simply supported prestressed concrete beams. We use two parameter identification methods to estimate prestressing force. First, we developed a linear least-squares method to fit modal superposition to measured modal frequencies and estimate prestressing forces. Second, we implement an iso-parametric finite element based vibration of prestressed beams and fit simulated vibration responses of the beams to the measurements using Gauss-Newton nonlinear Least-Squares approach. The axial prestressing force in the strand is considered as an unknown parameter in these formulations and is estimated inversely from the experimental measurements. Further, we used Equation (1) to verify our framework by comparing the results of estimation to results of Equation (1).

In the following sections, the experimental setup and measurements are briefly presented. Then, the forward simulation and inverse problems as well as the solution strategies to identify prestressing force loss are discussed. Finally, the results and discussion, and the conclusions are presented.

2. Experimental setup

2.1. Specimen preparation

A total of six prestressed concrete beams were manufactured. All beams had square cross-section of 17.5 × 17.5 cm and were 1.50 m long. Prestressing was carried out using a 7-wire 12.5 mm diameter strand with ultimate tension capacity of F_{pu} = 1.86 GPa. In all beams, the prestressing strand was located 12.5 mm below the center of the cross-section and was tensioned to 70% of F_{pu} which resulted in a tension force of 128.5 kN. Each end of the beams had three ties with 10 mm diameter at 75 mm spacing, center to center. The prestressing strands were cut 72 h after casting. Fig. 1 shows schematic drawing of a prestressed beam, its cross section, prestressing strand location and the shear reinforcement details.

The concrete used in manufacturing the beams had a water-to-cement (w/c) ratio of 0.55, 60.0% aggregate volume fraction, and a maximum aggregate size of 1.5 cm. Ordinary Portland cement, Type I, was used in concrete. The concrete material was