Figure 18. Circular Column with Type 4 Cracks in an Exterior Exposure. No Corrosion Observed on Any of the Columns in this Building Despite the Cracks Width and Length

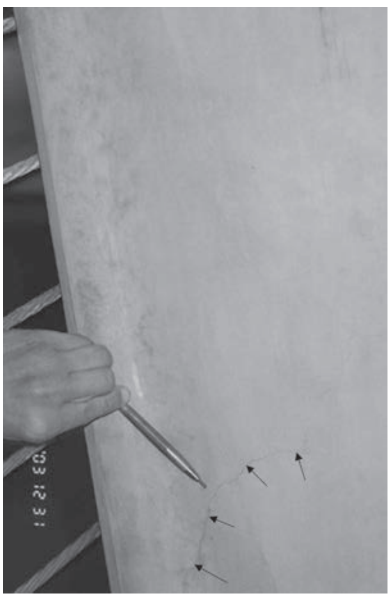

Figure 19. Type 5 Crack on a Column at the Ramp of a Parking Garage. This Crack Was Covered-Up with Stucco and Reappeared

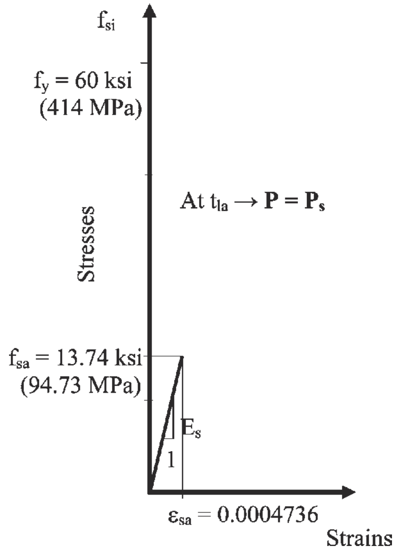

Figure A1. Instantaneous Reinforcement Stress and Strain at t_{la}

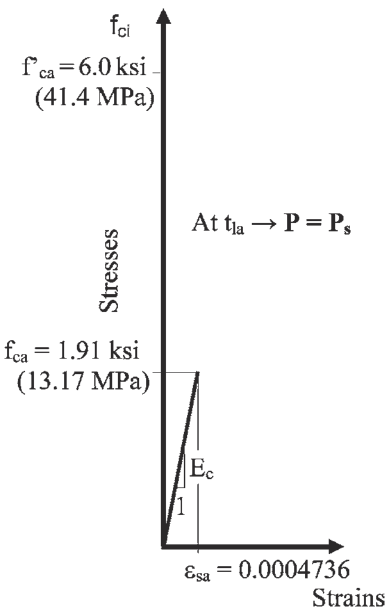

Figure A2. Instantaneous Concrete Stress and Strain at t_{la}

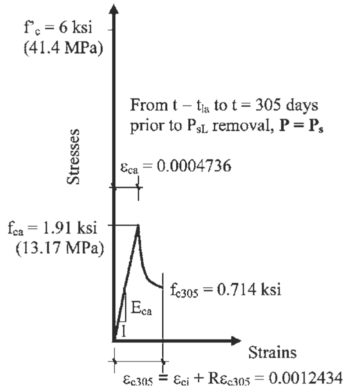

Figure A3. Concrete Stress and Strain History up to 305 days

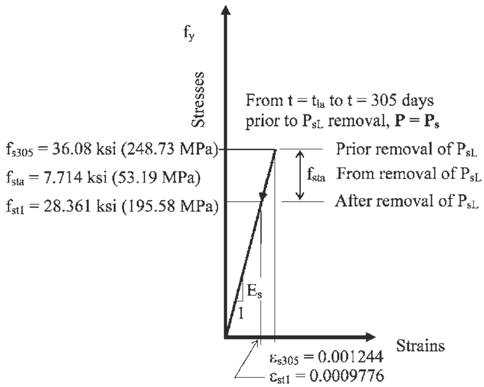

Figure A4. History of Reinforcement Stress and Strain up to 305 days

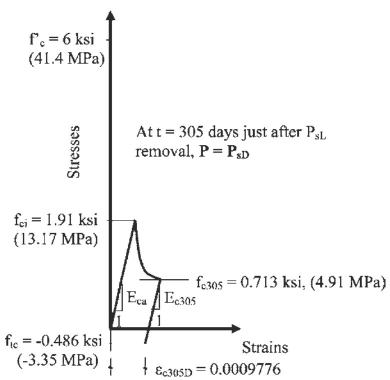

Figure A5. Concrete Stress and Strain History At t = 305 Days Just After P_{sL} Removal

Estimating Time-Dependent Deformations of Prestressed Elements: Accuracy and Variability

by M. W. Paulsen, S. D. B. Alexander, and D. M. Rogowsky

Synopsis: Continuous highway overpass structures are often governed by serviceability rather than ultimate conditions. Deflection prediction and control is vital to avoid cracking. A two span overpass in Calgary was chosen as a case study. Deflections and strains in two precast prestressed girders were monitored from fabrication to erection, and a comprehensive material testing program was done on the concrete mix. The results of the case study show that the CEB MC-90 model code underestimated the time-dependent response by a maximum of 16% while ACI 209 overestimated by 19%. By tuning ACI 209 and CEB MC-90 to the concrete material testing data, predictions were increased to within 8% and 7%, respectively. A variability analysis on the two tuned models showed that while they give nearly the same prediction, the CEB MC-90 format induces less uncertainty in predictions. In addition, extrapolation to long-term ages shows a substantial divergence between predictions of the two models.

Keywords: camber prediction; case study; creep, prestressed; shrinkage variability

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INTRODUCTION

A common structural system for bridges consists of precast, prestressed concrete girders made continuous through a cast-in-place deck and diaphragms. To assess the risk of cracking under service conditions the designer needs to estimate, with reasonable confidence, the internal stresses in the concrete. Time-dependent deformations associated with creep, shrinkage and prestress relaxation produce an internal stress redistribution on the section. The ability to accurately predict the time-dependent behaviour of prestressed elements may accelerate construction schedules, reduce serviceability issues, and increase confidence in designs.

The prediction of time-dependent response requires two components. The first is a material model to describe the time-dependent properties and the second is an analysis capable of incorporating the material model. Material models may be taken directly from codes or developed from extensive material testing, while analysis methods vary from the approximate to the highly refined.

The first objective of this paper is to compare, for one particular case study, differences in the time-dependent response predictions resulting from changes in the structural analysis methodology and/or the material models used to describe concrete behaviour.

The second objective of this paper is to assess the variability of the material models used in making predictions. A straightforward statistical approach is used to determine the 95% confidence intervals on predictions of the material properties critical to time-dependent deformations.

Two precast, prestressed girders were instrumented and monitored for strains and deflections for a five-month period from fabrication to erection. To describe the behaviour of the concrete used in the girders, laboratory tests were conducted to measure compressive strength, modulus of elasticity, creep and shrinkage.

EXPERIMENTAL WORK

In September 2003, an instrumentation program began to measure strain distributions and vertical deflections on two prestressed girders used in the 130th Avenue and Deerfoot Trail overpass in Calgary Alberta, Canada. The girders were monitored from fabrication to erection. Also, samples of the concrete mix used were obtained for a material testing program.

Overpass Description

Figure 1 shows the profile of the overpass and a typical section. A total of 12 precast girders were fabricated for this bridge. The construction sequence of the overpass is summarized as follows: 1) Erect pre-cast girders on piers (2 Spans), 2) Place deck and diaphragms to create continuity, 3) Post-tension longitudinally, 4) Make integral bridge/abutment connection.

The girders are 38 metres long, 1.65 metres deep and cast with a high-performance concrete. Each is prestressed with 56 - 15.2mm low-relaxation strands (tensile strength, f_{pu} = 1860 MPa) and contains a combination of welded-wire mesh and deformed bars for passive reinforcement. To avoid cracking at release, some of the prestressing strands were debonded. Figure 2 shows a typical girder cross-section, while Table 1 lists sectional and material properties for the concrete, the steel reinforcement and the prestressed reinforcement. The section was designed to remain uncracked throughout its service life.

Laboratory Testing

Properties of the concrete mix used in the main girders of the overpass were determined from nominally 150 x 300 mm cylinders. The cylinders were tested to determine compressive strength gain with time, modulus of elasticity, creep and shrinkage properties. The concrete specimens were steam cured for 12 hours to simulate the curing conditions the girders experience, then kept at a relative humidity of 50% ($\pm$ 4%) and a temperature of 23°C ($\pm$ 1.7°C).

The fabrication of one girder required 18 concrete batches. Strength gain, modulus of elasticity, creep and shrinkage tests were performed on two separate batches while compressive strength tests were performed on every batch to determine the mean strength of each mix. Refer to Appendix A for the results from the laboratory testing program.

Field Measurements

The instrumentation plan focused on monitoring curvatures and deflections. Five sets of demecs (demountable mechanical extensometers) were placed on each web of the girder, as shown in Figure 2, to measure strain distribution at a section. Five sections (marked I through V in Figure 1) were instrumented with demecs on each girder. Using a survey level, vertical deflection measurements were made at sections I through V as well as at the ends.

The load-histories and measurement sampling times for the test girders are summarized in Table 2. For each sampling time at each section, 10 strain readings were obtained. A curvature was estimated from the 10 readings by finding the best-fit plane section. Figure 3 shows the measured strain distributions at station III of Girder 273-01 at time t_1.

Curvatures were calculated at each section for each measurement period. These were numerically integrated to obtain deflections. Figure 5 shows the curvature measurements and deflections for both girders at the time of stressing.

PART 1 - ACCURACY

To predict the time-dependent response of concrete elements, two components are necessary. The first is a material model describing all necessary properties of the concrete. The second is a structural analysis method that incorporates the material model.

Material Model

Three models were used in this study to predict the mechanical properties of the concrete used. They are ACI 209 (1), AASHTO (2) and CEB MC-90 (3). These three models require similar information regarding the concrete's strength, the specimen's shape, and the environmental conditions. The ACI 209 formulation also has additional factors based on the composition of the concrete. In this paper, this formulation will be termed ACI 209 + Mix Factors.

In addition, two material models based on the laboratory data have also been used. The first termed Model A uses the CEB MC-90 format, and the second, Model B, uses the ACI 209 format. The empirical constants in these formulae were fitted to the measured test data. These models are described in Appendix A.

Structural Analysis Methodology

Two methodologies are used to predict the sectional responses with time. Both methods are accepted structural analysis methods, and are presented in a format so that differences may be noted. In both cases, plane-sections theory of uncracked elements set the compatibility requirements. The differences arise in how the time-dependent effects of creep, shrinkage and prestress loss are included.

At any time, the curvature is computed at a number of sections along the girder and is numerically integrated to obtain the deflected shape. With the assumption that creep strain varies linearly with applied stress, generally considered accurate for applied stresses up to 0.5 f_{cm}, superposition can be used in the analysis.

Elastic Response of a Section

The section forces considered are the normal force N acting at the reference point and the bending moment M, taken with respect to the reference point. For a section under the influence of prestressing and applied normal force and moment, the section forces are calculated as:

$$N = N_0 - \Sigma P_j \quad [1]$$

$$M = M_0 - \Sigma P_j y_{psj} \quad [2]$$

where P_j is the prestressing force in layer j, y_{psj} is the distance to the centroid of the prestressing force for layer j, N_0 is the applied normal load, and M_0 is the applied sectional moment, with N_0 and M_0 being independent of prestressing and acting through or about the reference axis. The prestressing force is usually specified as a percentage of the ultimate strength, f_{pu}, where the prestressing behaves in a linear elastic manner. Thus the prestressing force can be described by:

$$P_j = n_j A_{ps} E_{ps} \varepsilon_j \quad [3]$$

where n_j is the number of strands in layer j, A_{ps} is the area of one strand, E_{ps} is the elastic modulus of the prestressing and ε_j is the strain in the prestressing strand of layer j.

The response of a section to the loading defined by equations [1] to [3] can be described by its strain distribution. For a plane section the strain distribution is linear, and herein is described by the strain at the reference axis, ε_o, and curvature, ψ. The strain distribution for the section is calculated as:

$$\varepsilon = \varepsilon_0 + \psi y \quad [4]$$

while the strain in the prestressing layer j is calculated as:

$$\varepsilon_j = \varepsilon_{psj} + \varepsilon_0 + \psi y_{psj} \quad [5]$$

Then, for a section under a normal axial force, N and moment M, the elastic response at time t is given by:

$$\begin{Bmatrix} \varepsilon_0(t) \\ \psi(t) \end{Bmatrix} = \frac{1}{E_c(t)\left(\tilde{A}\tilde{I} - \tilde{B}^2\right)} \begin{bmatrix} \tilde{I} & -\tilde{B} \\ -\tilde{B} & \tilde{A} \end{bmatrix} \begin{Bmatrix} N \\ M \end{Bmatrix} \qquad [6]$$

where $\tilde{A}$, $\tilde{B}$ and $\tilde{I}$ are the transformed sectional properties calculated with respect to the concrete's elastic modulus, $E_c(t)$. The solution to equation [6] requires iteration until the strain compatibility defined by equations [4] and [5] is met. N is positive in tension and M is positive when causing tension on the bottom fibre.

Method 1 – Effective Modulus Method

The first of the methods considered is the simpler, and uses the effective modulus to calculate stress related strains. The use of this method assumes that any stresses applied on a section are done so instantaneously. The effect of creep on the section is considered directly proportional to the creep function $J(t,t_0)$ with free shrinkage and prestress relaxation being effectively treated as forces on the section. The procedure is adapted from Collins and Mitchell (4) and is summarised as follows. First the load vector is calculated as the sum of applied loads, shrinkage effects and prestressing.

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{Bmatrix} N_0 \\ M_0 \end{Bmatrix} + \begin{Bmatrix} N(t,t_i) \\ M(t,t_i) \end{Bmatrix}_{\text{shrinkage}} + \begin{Bmatrix} N(t,t_i) \\ M(t,t_i) \end{Bmatrix}_{\text{prestress}} \qquad [7]$$

where, the first vector on the right side of the equation is the applied forces on the section,

$$\begin{Bmatrix} N(t,t_i) \\ M(t,t_i) \end{Bmatrix}_{\text{shrinkage}} = E_{c,\text{eff}}(t,t_i)\varepsilon_{cs}(t,t_s)\begin{bmatrix} A_c \\ B_c \end{bmatrix} \qquad [8]$$

$$\begin{Bmatrix} N(t,t_i) \\ M(t,t_i) \end{Bmatrix}_{\text{prestress}} = \begin{Bmatrix} -\sum E_{p,\text{eff}} n_j A_{ps} \varepsilon_{psj} \\ -\sum E_{p,\text{eff}} n_j A_{ps} \varepsilon_{psj} y_{psj} \end{Bmatrix} \qquad [9]$$

The effective modulus of the prestressing, $E_{p,\text{eff}}$, accounts for relaxation by reducing the elastic modulus of the prestressing steel and is defined in the notation section. The strain distribution at any time t, after loading at t_i is then calculated as:

$$\begin{Bmatrix} \varepsilon_0(t,t_i) \\ \psi(t,t_i) \end{Bmatrix} = \frac{1}{E_{c,eff}(t,t_i)(A'I' - B'^2)} \begin{bmatrix} I' & -B' \\ -B' & A' \end{bmatrix} \begin{Bmatrix} N \\ M \end{Bmatrix} \quad [10]$$

where the prime symbol denotes an effective sectional property and is calculated as the transformed section property with respect to the effective modulus of the concrete, $E_{c,eff}(t,t_i)$. The effective Modulus is equal to the inverse of the creep function.

$$E_{c,eff}(t,t_i) = \frac{1}{J(t,t_i)} = \frac{E_c(t,t_i)}{1 + \phi_i(t,t_i)} \quad [11]$$

where $\phi_i(t,t_i)$ is the creep coefficient as defined by ACI 209.

Method 2 – Age-Adjusted Elastic Modulus Method

The second method follows the procedure described by Ghali et al (5). In this method the time-dependent effects on a section are expressed by a change in strain, $\Delta\varepsilon_o$, and curvature, $\Delta\psi$, that occur over the time period considered. This is done by first calculating the forces required to prevent unrestrained creep, unrestrained shrinkage and strand relaxation, then applying these forces to the age-adjusted transformed section. The restraining force is:

$$\begin{Bmatrix} \Delta N(t,t_i) \\ \Delta M(t,t_i) \end{Bmatrix} = \begin{Bmatrix} \Delta N(t,t_i) \\ \Delta M(t,t_i) \end{Bmatrix}_{creep} + \begin{Bmatrix} \Delta N(t,t_i) \\ \Delta M(t,t_i) \end{Bmatrix}_{shrinkage} + \begin{Bmatrix} \Delta N(t,t_i) \\ \Delta M(t,t_i) \end{Bmatrix}_{relaxation} \quad [12]$$

where the restraining forces for creep, shrinkage and relaxation are determined as follows:

$$\begin{Bmatrix} \Delta N(t,t_i) \\ \Delta M(t,t_i) \end{Bmatrix}_{creep} = -E_{c,aa}(t,t_i)\phi_i(t,t_i) \begin{bmatrix} A_c & B_c \\ B_c & I_c \end{bmatrix} \begin{Bmatrix} \varepsilon_0(t_i) \\ \psi(t_i) \end{Bmatrix} \quad [13]$$

$$\begin{Bmatrix} \Delta N(t,t_i) \\ \Delta M(t,t_i) \end{Bmatrix}_{shrinkage} = -E_{c,aa}(t,t_i)\varepsilon_{cs}(t,t_i) \begin{bmatrix} A_c \\ B_c \end{bmatrix} \quad [14]$$

$$\begin{Bmatrix} \Delta N(t,t_i) \\ \Delta M(t,t_i) \end{Bmatrix}_{relaxation} = \begin{Bmatrix} \sum A_{ps}\chi_r\Delta\sigma_{pr} \\ \sum A_{ps}y_{ps}\chi_r\Delta\sigma_{pr} \end{Bmatrix} \quad [15]$$