MONITORING OF A TALL BUILDING TO DEVELOP AXIAL SHORTENING MODELS INCORPORATING HIGH STRENGTH CONCRETE

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Abstract: This paper addresses axial shortening prediction of the vertical concrete elements of tall buildings with a particular focus on developing a reliable model for high strength concrete (HSC). An established reinforced concrete column shortening model used for normal strength concrete (NSC) is modified to predict axial shortening in vertical elements made of HSC. To compare with the theoretical model, the axial shortening measurements taken from the 83 storey World Tower Building, Sydney (WTS), obtained during the construction period, are used. The theoretical model having the best match with the actual measurements are recommended for predicting axial shortening of vertical elements using HSC.

Keywords: Axial shortening, column, high strength concrete, monitoring column, tall building

1. Introduction

There are two basic types of shortening of columns which affect the behaviour and functioning of tall buildings; (i) axial shortening and (ii) differential shortening. Axial shortening is the total cumulative shortening, which occurs due to elastic, shrinkage and creep deformations. Differential shortening is the difference between two axial shortening results at the same level. Axial shortening can potentially cause problems to infrastructure of buildings including ventilation, water and sewerage pipes, and heating systems, in addition to potential structural problems to facades, beams and slabs joining the columns. A major consequence of significant differential shortening of vertical elements (cores, columns and walls) of a building is slab tilt, which in turn rotates and distorts non-structural partitions.

It is essential that the problem of axial and differential shortening of vertical elements should be considered when building layout is designed to minimize the effect of this problem. For this, reliable methods are needed to accurately quantify the values of axial shortening. By judicially selecting appropriate column sizes, reinforcement percentages and concrete strengths, the problems of axial and differential shortening can be minimised. With the advent of advanced building technologies, use of high strength concrete (HSC) is becoming more common in the construction of vertical elements of tall buildings. Compared to conventional normal strength concrete (NSC), HSC offers significantly better structural engineering properties, such as higher compressive and tensile strengths, higher stiffness and better durability. For prediction of axial shortening in tall concrete buildings with HSC, equations of elastic modulus, shrinkage and creep based on HSC data are mentioned here. These include those proposed by Ahmad & Shah (1985), Carrasquillo et al. (1981), Gilbert (2002), Huo et al. (2001), McDonald & Roper (1993), Mendis et al. (1997) and Mokhtarzadeh & French (2000).

The idealisation of a building structure representing the complete sequential construction cycle, including the differential loading rates between adjacent structural elements, is essential. This enables an accurate definition of the loading history of each adjacent element to be employed in the prediction of differential behaviour. Thus, the final outcomes of a cumulative (axial) and differential shortening analysis of the columns depend mainly on two criteria: the idealisation of the building with its idealised construction cycle and the analytical column model containing the concrete and steel properties.

The aim of this paper is to conduct an analytical study of axial shortening of the selected vertical members in the World Tower Building, Sydney (WTS) with a view to develop a more reliable model for axial shortening. This analysis utilises the most reliable HSC equations of elastic modulus, shrinkage strain and creep coefficient to calculate the axial shortening of columns and cores.

2. Normal and high strength concrete models

NSC and HSC models for elastic modulus, shrinkage and creep prediction have been extensively reviewed by Baidya et al. (2010). A summary of the most applicable models for both NSC and HSC are given in Tables 1 and 2.

Table 1: *Normal strength concrete models.*

	Equation	Reference	Notation
Concrete compressive strength $f_c'(t)$	$f_c'(t) = \frac{t}{\alpha + \beta t} f_c'(28)$	ACI Committee 209 AS 3600 (2001)	t = age of concrete (days) α, β = constant used for compressive strength
Elastic modulus $E_c(t)$	$E_c(t) = 0.043 \rho^{1.5} \sqrt{f_c'(\mathrm{t})}$	ACI Committee 318 (2008) AS 3600 (2001) Pauw (1960)	ρ = density of concrete (kg/m^3)
Creep coefficient $\phi(t,\tau)$	$\phi(t,\tau) = \frac{(t-\tau)^{0.6}}{10 + (\mathrm{t} - \tau)^{0.6}} \phi^*(\tau)$	ACI 209R-92	τ = age of concrete (days) at loading $\phi^*(\tau)$ = final creep coefficient
	$\phi(t,\tau) = k_2\, k_3\, \phi_{cc.b}$	AS 3600 (2001)	k_2 , k_3 = modification factor $\phi_{cc.b}$ = basic creep
Shrinkage strain $\varepsilon_{sh}(t)$	$\varepsilon_{sh}(t) = \frac{t}{35 + t} \varepsilon^*_{sh}$	ACI 209R-92	ε^*_{sh} = final shrinkage strain at time infinity
	$\varepsilon_{sh}(t) = 0.00085\, k_1$	AS 3600 (2001)	k_1= modification factor

Table 2: *High strength concrete models.*

	Modified equations related to	Equation	Reference	Comments/Notation
Elastic modulus E_c	ACI	$E_c = 3320 \sqrt{f_c'} + 6900$	Carrasquillo et al. (1981)	$21 < f_c' < 83$ MPa
		$E_c = 3.385 \times 10^{-5} \rho^{2.5} (f_c')^{0.325}$	Ahmad & Shah (1985)	f_c'= compressive strength at 28-days (MPa)
	AS 3600	$E_c = 0.043 \eta \rho^{1.5} \sqrt{f_c'} \pm 20\%$	Mendis et al. (1997)	η = coefficient for modulus of elasticity $\eta = 1.1 - 0.002 f'_c \leq 1$
		$E_c = \rho^{1.5}(0.024\sqrt{f_{cm}} + 0.12)$	Gilbert (2002) AS 3600 (2009)	f_{cm}= mean compressive strength of concrete at 28 days (MPa) $f_{cm} \leq 100$ MPa

Creep coefficient **v_t** **φ_{cc}**	ACI	$v_t = (v)_u \dfrac{t^{0.6}}{K_c + t^{0.6}}$	Huo et al. (2001)	(v_u) = ultimate creep coefficient K_c = adjustment for early age creep coefficient
	AS 3600	$\varphi_{cc} = k_2\, k_3\, k_4\, k_5\, \varphi_{cc.b}$	Gilbert (2002) AS 3600 (2009)	k_2, k_3, k_4, k_5 = modification factor $\varphi_{cc.b}$ = basic creep coefficient
Shrinkage strain **$\varepsilon_{sh}(t)$** **ε_{sh}** **ε_r** **ε_{cs}**	ACI	$\varepsilon_{sh}(t) = \dfrac{t}{45 + t} (\varepsilon_{sh})_u$	Mokhtarzadeh & French (2000)	$(\varepsilon_{sh})_u$ = ultimate shrinkage strain $(\varepsilon_{sh})_u$ = 530 microstrain
		$\varepsilon_{sh} = (\varepsilon_{sh})_u \dfrac{t}{(K_s + t)}$	Huo et al. (2001)	K_s = adjustment for early age shrinkage
	AS 3600	$\varepsilon_r = \varepsilon_b\, k_e\, k_h$	McDonald & Roper (1993)	ε_b = basic shrinkage strain k_e, k_h = shrinkage strain coefficient
		$\varepsilon_{cs} = \varepsilon_{cse} + \varepsilon_{csd}$	Gilbert (2002) AS 3600 (2009)	ε_{cse} = endogenous shrinkage strain ε_{csd} = drying shrinkage strain

3. Reinforced concrete column HSC model

In this paper, a shortening model suitable for calculating long term vertical deformations of HSC columns obtained by modifying the existing NSC model is presented. A constant load P is applied to a short symmetrically reinforced concrete column at time *t*. For equilibrium, the load P must be resisted by internal forces as given in Equation (1):

$$P = N_c(t) + N_s(t)$$

(1)

where $N_c(t)$ is the internal force in concrete and $N_s(t)$ is the internal force in steel.

Using the age-adjusted effective modulus method (AEMM) proposed by Bazant (1972), total axial shortening strain of the column for *k* loadings is given by:

$$\delta_{total} = \delta_{elastic} + \delta_{creep} + \delta_{shrinkage} + \delta_{reinforcement} \tag{2}$$

In Equation (2) the elastic, creep and shrinkage strains can be estimated using corresponding ACI and AS equations (or other models) as given in Section 2. The full formulations of each component in Equation (2) are given by Koutsoukis & Beasley (1994).

For the j^th^ storey, the final cumulative column shortening is as follows:

$$\delta_{\text{cumulative}} = \sum_{i=1}^{j} \delta_{total\ \ for\ i^{th}\ storey} \tag{3}$$

Equation (3) summarises the application of the AEMM to obtain the final axial shortening predictions, for which the individual components (i.e. elastic, creep, shrinkage and reinforcement) are accumulated over the entire height of the column.

4. Measurement of world tower building, Sydney

The WTS building (230 m high and 83 storey) constructed in 2004, is one of the tallest buildings in Australia. This building provided an opportunity to monitor and record the axial shortening history of selected columns. At different levels of the WTS building, 28-day concrete strength varies from 32 to 60 MPa for the core and from 40 to 90 MPa for columns. Strain gauge points were installed and monitored mechanically on three columns TC1, TC4 and TC9 from levels 14 to 39. These gauge points were located in three stations on the face of the column at the base, at the top and in the middle. The data was collected using a demountable mechanical gauge system (Demec gauge), with some columns monitored for almost 200 days. Data were collected for columns with concrete strengths of 50, 60, 80 and 90 MPa, giving useful results for HSC columns. Also, internal strain gauges were installed on various floors to measure the transfer of stress from the concrete to the steel reinforcement. The extensive field measurement results were presented by Baidya (2005) and Bursle (2006).

5. Comparison of observed and predicted axial shortening

The cumulative strain data of the WTS building were used for comparison with theoretical results. A combination of three equations - one for each of elastic modulus, creep coefficient and shrinkage strain - is required to calculate column axial shortening model as shown in Equation (2). Thus, a number of empirical equations of elastic modulus, creep coefficient and shrinkage strain previously derived for HSC and NSC were combined randomly to form six AS and eight ACI models to calculate axial shortening of column. The combinations are given in Tables 3 and 4. In this study, only readings from level L26 to L33 of column TC1 were selected for the analysis because adequate experimental data were not as extensive for other levels and columns. The exterior column TC1 (corner column with two interior faces) was selected for monitoring based on the symmetry of the building. Following data were taken for all levels of the column TC1 (from L26 to L33): (i) 28-days concrete strength 80 MPa, (ii) cross-sectional area 1 m^2, (iii) perimeter 4 m, (iv) reinforcement 1.2%, (v) basic shrinkage strain 550 microstrain and (vi) average humidity 62%. It should be noted that the equations for elastic modulus, creep and shrinkage proposed by Gilbert (2002) are now incorporated in the recently released Australian standard AS 3600 (2009).

Table 3: *Different AS model combinations.*

Model	**Elastic Modulus**	**Creep Coefficient**	**Shrinkage Strain**
1	Gilbert, 2002	Gilbert, 2002	Gilbert, 2002
2	Gilbert, 2002	Gilbert, 2002	MacDonald and Roper, 1993
3	Mendis et al., 1997	AS 3600 (2001)	AS 3600 (2001)
4	Ahmad and Shah, 1985	AS 3600 (2001)	MacDonald and Roper, 1993
5	Carrasquillo et al., 1981	Gilbert, 2002	MacDonald and Roper, 1993
6	Pauw, 1960	AS 3600 (2001)	AS 3600 (2001)

Table 4: *Different ACI model combinations.*

Model	**Elastic Modulus**	**Creep Coefficient**	**Shrinkage Strain**
1	Gilbert, 2002	Huo et al., 2001	Huo et al., 2001
2	Mendis et al., 1997	Huo et al., 2001	Mokhtarzadeh and French, 2000
3	Pauw, 1960	Huo et al., 2001	ACI 209R-92
4	Carrasquillo et al., 1981	Huo et al., 2001	Huo et al., 2001
5	Ahmad and Shah, 1985	Huo et al., 2001	Huo et al., 2001
6	Mendis et al., 1997	Huo et al., 2001	Huo et al., 2001
7	Pauw, 1960	ACI 209R-92	ACI 209R-92
8	Carrasquillo et al., 1981	ACI 209R-92	ACI 209R-92

Model predictions were compared with the field data of the WTS building considering two different cases: a) Case 1 - comparison of all fourteen models (six models from AS and eight models from ACI) at level L33 for column TC1, and b) Case 2 - comparison of six selected models (the best three from AS and the best three from ACI) at levels L26 to L33 for column TC1.

Case 1 was used to select the six best models for further comparison in case 2. For Case1, column shortening predictions from the six AS models and eight ACI models were compared with the observed values of column TC1 at level L33 using time-trend, prediction error and observed-versus-predicted (scatter plots). From the analysis of the prediction errors Models 1, 3 and 5 from the AS group and Models 8, 4 and 2 from ACI group (see Table 3 and 4) were selected as the best models for further analysis for all levels L26 to L33. The full details are given by Baidya (2005).

For Case 2, in order to pinpoint the best model among the selected six models from the AS and ACI groups for column TC1, more analysis of the observed and predicted cumulative strains (predicted minus observed) were performed on a (i) level by level basis from L26 to L33 using time-trend and prediction error (see Figure 1 for L26) (ii) model by model basis from L26 to L33 and (iii) statistics of overall prediction error from L26 to L33 (see Figure 2).

The observed and predicted time-trends of cumulative strains for six models and their prediction errors for level L26 are shown in Figure 1. The observed values covered a period from 70 to 177 days after casting of concrete with observations made at irregular time intervals. Figure 1 shows that the AS (Models 1, 3 and 5) and ACI (Models 2, 4 and 8) group of models over-predict cumulative strain at early days (until ~150 days for AS Model 1, Models 3 and 5, and ~160 days for all ACI models – termed here as a “threshold period”), but after this threshold period, these models tend to under-predict cumulative strain. Even though this general trend is observed for all models, it is interesting to note that the predicted and observed trend lines do produce similar strains at various times.

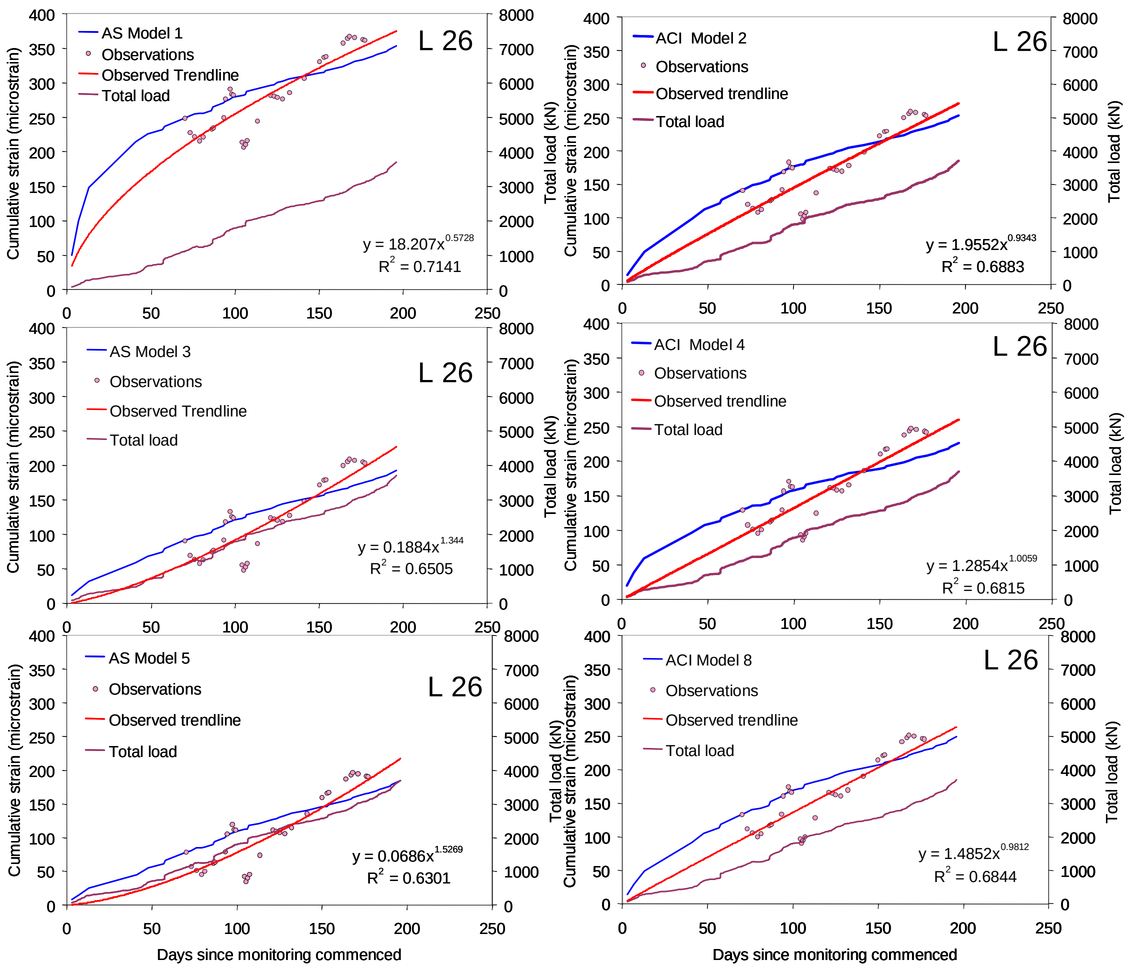

Figure 1: *Time-trend between the observed and predicted cumulative strains – Level L26. For AS and ACI model details, see Table 3 and 4.*

In the model wise analysis Baidya (2005) reported that all three AS models (1, 3 and 5) perform better in levels L29 and L31, and all ACI models (2, 4 and 8) are better in levels L30 and L31. It is noted that these models have high prediction errors in themselves and are considered relatively better or worse in this study from a subjective judgement. One model predicting better than other models in one level but performing poorly in other levels indicates that there is no universal model that is better and suitable for all levels.

When overall error statistics (mean, standard deviation and coefficient of variation of all levels from L26 to L33 of column TC1 combined together) are compared, some models do stand out from others in terms of their prediction ability (see Figure 2). Figure 2 provides error bands (mean ± std dev) for the six selected models, indicating that ACI Model 2 has the lowest overall mean error when prediction errors from all floors are put together. In contrast, AS Model 1 has the highest overall mean error.

Considering the ACI group Model 2, Model 4 and Model 8, and in the AS group Model 5, Model 3 and Model 1, are the best to worst models, respectively. If both ACI and AS groups are considered together then ACI Model 2 gives the best prediction. It is noted that these observations are based on comparing overall statistics of these selected six models only. Full details are given by Baidya (2005).

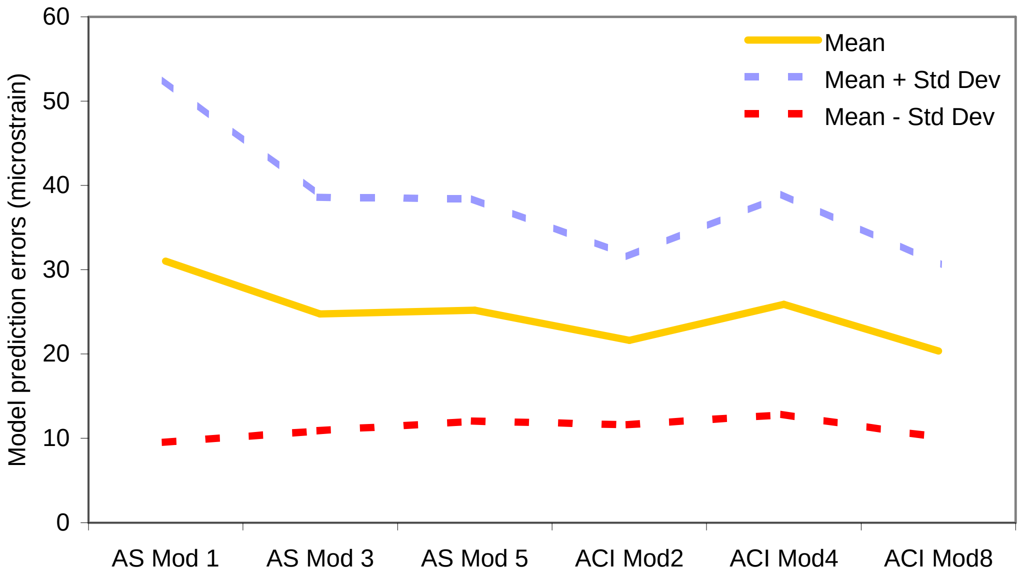

Figure 2: *Overall model prediction error: Overall mean ± Std Deviation.*

6 Conclusions

In addition to an analysis of prediction error values (level wise and model wise), overall error statistics (mean, standard deviation and coefficient of variation) are analysed to find out the best performing model for each of the selected six models of the AS and ACI groups. From this analysis, it can be concluded that ACI Model 2 and AS Model 5 are the best models (Figure 2). It is interesting to note that elastic modulus (Mendis et al., 1997 for AS and Carrasquillo et al., 1981 for ACI), creep coefficient (Gilbert, 2002 for AS and Huo et al., 2001 for ACI) and shrinkage strain (MacDonald & Roper, 1993 for AS and Mokhtarzadeh & French, 2000 for ACI) equations for these two best models are taken from the equations applicable to HSC. This indicates that equations applicable to HSC should be utilised when available.

Comparisons with field observations also show that development of accurate prediction methods that will have general relevance to deformations in buildings is complicated. This is partly due to the fact that the factors that influence the creep and shrinkage deformations of insitu concrete are very complex and highly variable and therefore it is difficult to specify them accurately. More field investigations generating quality data may help improve the prediction of elastic modulus, creep coefficients and shrinkage strains for HSC and NSC, and thereby the prediction of axial and differential shortening in vertical concrete members.

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