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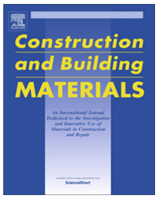

Differential axial shortening and its effects in high rise buildings with composite concrete filled tube columns

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HIGHLIGHTS

- Differential axial shortening in composite concrete filled tube columns is evaluated.
- Effects of creep, shrinkage and time dependent concrete properties are considered.
- Construction sequence, concrete levelling and stress relaxation are also included.
- Differential axial shortening of a CFT building is compared with a RC building.

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ABSTRACT

Use of concrete filled steel tube columns is becoming increasingly popular in high rise buildings due to their composite action, superior strength, seismic and fire resistance capacities and construction simplicity. These composite columns and the reinforced concrete (RC) lift core in the framing systems of high rise buildings are commonly coupled with reinforced concrete outrigger and belt systems to facilitate lateral load resistance. Axial shortening (AS) of the vertical structural components due to time dependent phenomena of basic creep, shrinkage and elastic deformation, is a common problem in concrete high rise construction. The creep and shrinkage of these composite columns develop more rapidly, but are comparatively lower in magnitude than for RC columns due to the concrete core having no direct exposure to the external environment. There is a need for a comprehensive understanding of the differential axial shortening (DAS) in concrete filled tube (CFT) buildings which will be different from that in a RC building. An appraisal of the DAS and accurate quantification of all the adverse effects that can occur in a building due to DAS, are required to facilitate a safe and efficient design. This paper develops and applies a comprehensive technique to evaluate the DAS in a high rise building with composite CFTs. This technique incorporates the effects of (i) construction sequence and concrete levelling (ii) stress relaxation of concrete due to the presence of the steel tube (iii) time dependent material properties and (iv) effects of belt and outrigger systems. The technique has been validated using experimental data and is then illustrated through its application to a 60 storey building with CFT columns. The DAS between the vertical members are evaluated and its effects on the structural components are studied. Finally, the technique is applied to a similar building with RC columns and the results compared with those from the CFT building. The technique developed in this paper and the new information on DAS generated will facilitate safer designs of buildings with composite CFT columns.

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1. Background

Concrete filled tube (CFT) columns have been successfully applied to many high rise buildings such as the Taipei 101 tower, the Two Union Square in Seattle USA, Shimizu Super High Rise Building in Tokyo, Guangzhou New TV Tower, China and 111 Eagle street, Brisbane, Australia. Axial shortening (AS) of these composite columns due to time dependent phenomena of basic creep, shrinkage and elastic deformations is an inherent challenge in high rise buildings. Moreover, the load migration that occurs between concrete and steel due to the creep and shrinkage needs to be considered as it can significantly affect the axial shortening of these composite CFT columns. Unfavourable effects of DAS in buildings constructed with concrete have been first observed in 1960s, in tall reinforced concrete buildings of more than 30 storeys [1]. More

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recently in a 45 storey RC building in Chicago, Illinois William D. Bast et al. [2] measured 4 in. of axial shortening of the core wall at the 45th floor as marked by the gap created between the condenser riser pipe and the top of the metal pipe support. They further measured similar high axial shortening values in a number of other floors by visual inspections of the building, including downward "scrape" on the elevator guide rail produced by the mounting bracket at the top floor of each elevator run, highlighting the necessity of making the axial shortening study an essential serviceability check for high rise buildings. Other studies including those of Baker et al. [3], Fragomeni et al. [4] and Russel et al. [5] have obtained similar observations by measuring deformations in a number of high rise buildings.

The creep and shrinkage of CFT columns develop more rapidly, but are comparatively lower in magnitude than that in RC columns [6] due to the concrete core having no direct exposure to the external environment. There is thus a need for a comprehensive understanding of trends in differential axial shortening (DAS) in CFT buildings which will be different from those in RC buildings. Also with current construction trends of (i) using higher strength concrete for columns, (ii) faster floor construction cycles, (iii) utilising form work systems such as the jump-form type with the core constructed 3–4 cycles before the columns and (iv) complex load paths due to irregular buildings, a new appraisal of the DAS and a detailed analysis with quantification of all the adverse effects that can occur due to DAS in a tall building is a timely requirement. To the best of the authors' knowledge this information is not currently available in the literature for the type of building considered in this study.

The effects of DAS that needs quantification include (i) the axial load redistribution through the stiff horizontal elements such as the outrigger and belt systems [7] and the consequent high transfer stresses which needs to be quantified at the design stage [8] and (ii) the serviceability problems in a high rise building such as the amount of tilt in floor plates and the distortion of non-structural elements such as claddings, facades and services. Since the absolute values of the DAS (the difference between the axial shortening of any two members considered) is of concern, it is important not to overestimate or under estimate the total axial shortening of individual composite columns for the success of the mitigating or compensation measures.

It is therefore necessary to conduct the axial shortening analysis with adequate details. The factors that need to be considered are accurate inclusion of the time dependent properties of creep and shrinkage and corresponding loading conditions and global structural effects by specific members such as outriggers, raking columns and transfers [10]. Moreover, accurate simulation of the real construction sequence with effects of the time dependent material responses impacts significantly on the accuracy of axial shortening prediction. This is evident from the typical time dependent loading on a column element in a high rise building as illustrated in Fig. 1(a) and the time varying material properties as depicted by Fig. 1(b). It is also important to include effects of concrete levelling in construction sequence modelling as evident in Fig. 2 which illustrates the axial shortening due to elastic strain component for a typical high rise building predicted with and without considering concrete levelling effects. Previous research on reinforced concrete structural components indicates that load migration occurs from concrete to steel due to the creep and shrinkage and this load migration significantly affects the axial shortening of those components [11]. The present study incorporates all these factors in the numerical procedure developed to quantify the axial shortening of CFT columns and shear walls in the high rise building and thereafter proceeds to make a comparison of these values with those in a similar building constructed entirely with RC.

2. Methodology

This study develops and applies a comprehensive procedure to predict the differential axial shortenings (DAS) in a CFT high rise building. The procedure includes the effects of reinforcement, time dependent material properties, construction sequence with concrete levelling effects and interaction of outrigger and belt system with the structural frame and therefore will provide accurate predictions. It uses the available material models in Euro Code 2 (EC2) [12] and knowledge on individual element behaviour for CFT, along with the finite element package ANSYS. The creep calculation is based on the Age Adjusted Effective Modulus (AAEM) method developed by Trost and Bazant [12] which includes the effects of aging of concrete and can be applied to the analysis of high rise building accurately with limited computational demand. This combination of material model and creep calculation method is selected based on outcomes of the research of Geng et al. [13] who compared the creep material models applicable to CFT, with results of 81 experimental tests on creep and shrinkage behaviour of CFT for a range of normal and high strength concrete mixtures. They used the large test data on CFT and recommended: (i) use of EC2 for the axial shortening predictions and (ii) use of coefficients developed by Bazant and Baweja [12] for AAEM calculations.

2.1. Time dependent material model of concrete

The present procedure incorporates the time dependent material model of concrete recommended by EC2. This material model considers the mean compressive strength f_{cm28} of concrete based on the cylinder strength at 28 days, the compressive strength $f_{cm}(t)$ at any time "t", the Young's modulus of elasticity E_{cm28} in 28 days and a coefficient S to incorporate the effect of cement type. Based on these, the following equations present the time dependent Young's modulus of elasticity $E_{cm}(t)$ of concrete. and further information on this material model can be obtained from Euro code2 [14]

$$E_{cm}(t) = \left(\frac{f_{cm}(t)}{f_{cm28}}\right)^{0.3} \cdot E_{cm28} \tag{2.1}$$

$$\left(\frac{f_{cm}(t)}{f_{cm28}}\right) = \beta_{cc}(t) = \exp\left\{s\left[1 - \left(\frac{28}{t}\right)^{0.5}\right]\right\} \tag{2.2}$$

2.2. Creep and shrinkage model of concrete

Creep material model presented in EC2 is incorporated into the methodology developed through the MPCHG command in ANSYS finite element code. The shrinkage material model is included as an equivalent thermal load. During construction and service stages, the Young's Modulus of concrete is replaced by the relevant age adjusted effective modulus to include the long term time dependent effects at each time step. In the creep calculation, time-dependent concrete behaviour is modelled by age adjusted effective modulus method developed by Trost and Bazant [12]. The age adjusted effective modulus; $\overline{E_e}(t, t_0)$ at any time t for first loading at t_0, is expressed by Eq. (2.3). The aging coefficient; $\chi(t, t_0)$ as defined by Trost and Bazant is given below in Eq. (2.4), relaxation function $R(t, t_0)$ in Eq. (2.5) and the compliance function $J(t, t_0)$ according to EC2 in Eq. (2.6).

$$\overline{E_e}(t, t_0) = \frac{E_c(t_0)}{1 + \chi(t, t_0)\phi(t, t_0)} \tag{2.3}$$

$$\chi(t, t_0) = \frac{E(t_0)}{E(t_0) - R(t, t_0)} - \frac{1}{\phi(t, t_0)} \tag{2.4}$$

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