Force and Deformation Responses of Tall Reinforced Concrete Building Frames

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***Abstract*— Tall reinforced concrete buildings have, at present, become common in urban areas due to high cost of land and other reasons. Linear elastic analysis, which is used for the analysis of buildings of small heights, is inappropriate for the analysis of tall and super tall buildings. The analysis of tall building frames must account for construction sequence, speed of construction, long term effects of creep and shrinkage of concrete among other factors. Many of the present day analysis software have facilities for performing complex nonlinear analysis to arrive at the true response of actual structures. One such software is ETABS. Using it, the present work determines and compares the deformation responses of columns and beams of tall building frames predicted by construction sequence analysis and linear static analysis. It also determines the effects of (i) speed of construction, (ii) grade of concrete, (iii) shrinkage of concrete and (iv) relative humidity of ambience on the force and deformation responses of the tall building frames at different ages of the structure using nonlinear analysis (P-delta analysis). It is observed that the deformation response of beams predicted by construction sequence analysis is considerably greater than that predicted by linear static analysis. It is also seen that the column shortening and beam deflection decrease as the relative humidity increases at all stages of loading. At any particular value of relative humidity, the rate of increase of column shortening and beam deflection decreases with time. The column shortening and beam deflection increase as the shrinkage coefficient increases at all ages of loading. At any particular value of shrinkage coefficient, the rate of increase of column shortening and beam deflection decrease with time. Studies on analysis of 40 storey building frame reveal that the column shortening decreases as the speed of construction decreases.**

Keywords—Tall Buildings; Reinforced Concrete; P-Delta Analysis; Creep; Shrinkage; Constrution Sequence Analysis.

I. INTRODUCTION

Many high rise commercial, residential and communication towers around the world have been constructed using reinforced concrete structural frames. Differential axial shortening of gravity load bearing components in tall buildings is a phenomenon that was first noticed in the 1960s for tall buildings. Axial shortening is cumulative over the height of a structure so that detrimental effects due to differential axial shortening become more pronounced with increasing building height. Methods for correcting instantaneous shortening such as construction of each floor to a corrected level or datum became common practice. Considering the example of an 80 storey concrete building, it has been reported that the elastic shortenings of columns is 65mm and that due to shrinkage and creep is 180 to 230mm [1]. Engineering the materials, components, size and configuration of 100 to 400 m buildings during the design process to control the impact of differential axial shortening and deformation is a well-established method [2]. Methods such as load balancing and axial stress equalization using elastic analytical procedures are convenient for symmetrical and regular building forms. However, controlling differential axial shortening and deformation becomes increasingly difficult for the new generation of super tall buildings in the 400 m to 1000 m range such as Burj Khalifa Tower, Dubai and those with complex geometric structural framing systems such as the Lagoons. Unacceptable cracking and deflection of floor plates, beams and secondary structural components, damage to facades, claddings, finishes, mechanical and plumbing installations and other non-structural walls can occur due to differential axial shortening. In addition, common effects on structural elements are sloping of floor plates, secondary bending moments and shear forces in framing beams [2].

The long term effects of shrinkage and creep did not have a significant impact on buildings up to about 20 storeys. However, tall buildings with more than 30 storeys showed detrimental effects of shrinkage and creep that could not be adequately compensated for by building each floor to a datum level. Concrete has three significant modes of volume change after pouring. Shrinkage as the name implies causes the concrete volume to decrease as the water within it dissipates and the chemical process of concrete causes hardening to occur. Elastic shortening occurs immediately as hardened concrete is loaded and is a function of the applied stress, length of the concrete element and modulus of elasticity. Creep is a long-term effect that causes the concrete to deform under exposure to sustained loading. These three phenomena occur in every concrete structure [3]. The combination of elastic, shrinkage and creep strains causes differential axial shortening, deformation and distortion of building frames. The load carrying capacity and integrity of structural frames are not adversely impacted by these effects as they are a natural phenomenon associated with loaded concrete structures.

When the building height is small or moderate, structural engineers determine the behavior of structures using linear static elastic finite element analysis. When the building height increases, the structural response, i.e. axial loads, shearing forces, bending moments and displacements, given by such typical linear analysis increasingly diverges from the actual behaviour. Time-dependent, long-term deformations can cause redistribution of response that would not be computed by conventional methods. Advances in finite element modelling and simulation have made nonlinear analysis easy, well managed and popular among structural engineers, which allows accurate and proper design of high-rise structures. Construction sequential analysis is becoming an essential part of analysis. Many well recognized analysis software include this facility in their analysis and design package. Construction sequential analysis deals with nonlinear behavior under static loads in the form of sequential load increment and its effects on structure considering that the structural members have started to respond to load prior to the completion of the whole structure.

In design, consideration of construction sequences (viz., sequential analysis) that account for the residual stress of each storey of the structure separately, step by step, to obtain the final displacement and other responses is important. Generally it yields greater displacement and greater structural effects for nonlinear behavior of materials than the simple linear static analysis. As linear static analysis yields the total effect of the final stage of the construction without considering step by step nonlinear effects of sequential construction, the results are not reliable for design of high-rise structures. Lack of knowledge about nonlinear behavior of materials and sequential analysis may lead to an improper design which may cause catastrophic destruction of structures. Thus it becomes obligatory to perform construction sequential analysis for high-rise structures.

A very brief survey of the literature on tall buildings is given here. Kim & Cho [4] measured axial shortenings of two reinforced concrete core walls and four steel embedded concrete columns (composite columns) in a 69 storey building. Axial shortenings of these composite columns were predicted using the numerical models of reinforced concrete. This work recommended further studies to develop a method to quantify axial deformations of composite columns with high steel ratios. Luong et al [5] demonstrated quantification of differential axial shortening at the design stage and strategies used to control the adverse effects of differential axial shortening of two international financial centres at Hong Kong. Shahdapuri, Mehrkar-AsI & Chandunni [6] presented a method to quantify axial shortenings of mega composite columns and cores of Al Mas tower. This method was based on material models of reinforced concrete given in ACI codes. Laser equipments were proposed to measure axial shortenings of the columns and the core shear walls during and after the construction. A. Vafaia et al. [7] calculated column shortening and differential shortening between columns and walls in concrete frames using a nonlinear staged construction analysis based on the Dirichlet series and direct integration methods. Prototype frame structures were idealized as two-dimensional and the finite element method (FEM) was used to calculate the creep and shrinkage strains. It was verified with respect to published experimental and analytical results.

H.S.Kim and H.S.Shin [8] proposed an analysis method with lumped construction sequences for the column shortening of tall buildings and its efficiency was investigated. Moragaspitiya et al [9] made an attempt to develop an accurate numerical procedure to quantify deformation and distortions of structure due to differential axial shortening. Additionally, a new practical concept based on the variation of vibration characteristic of structure during and after the construction was developed and used to quantify the axial shortening and to assess its performance. It was concluded that the combination of Finite Element Technique, time varying Young's Modulus, compression only elements, time history analysis method and the GL2000 method can be successfully used to quantify the differential axial shortening and the influence of the tributary areas can be captured accurately. F Molaand L M Pellegrini [10] discussed the problem of long time column shortening, derived approximate solutions and applied with reference to the case study of Palazzo Lombardiain Italy. The analysis of the long term column shortening in tall buildings was carried out assuming a viscoelastic rate of creep ageing behavior of concrete.

II. METHODOLOGY USED IN PRESENT WORK

A. *Creep and shrinkage prediction models*

Several prediction models on creep and shrinkage exist in the literature. Some of them are: EC 2 (2004), BS 8110 (1997), CEB 1990 (1993) and ACI-209 (1992). These empirical models yield different levels of accuracy using different parameters. The CEB-FIP model is used in the present work. The CEB-FIP Model Code 1990 is proposed by the Euro-International Concrete Committee and International Federation for Prestressing. The prediction of creep and shrinkage of concrete by the CEB-FIP 1990 is restricted to ordinary structural concretes having 28 days mean cylinder compressive strength varying from 12 to 80 MPa, mean relative humidity 40 to 100% and mean temperature 5 to 30^{o}C. The CEB-FIP 1990 model calculates a creep coefficient to predict the creep. It is based on the modulus of elasticity at 28 days. This model does not consider the effects of curing for the calculation of compliance. This model has a coefficient of variation of 20.4% for creep compliance. All the prediction equations are presented in Appendix A3 of the CEB-FIP1990 code.

B. *P-Delta effects*

P-Delta effect, also known as geometric nonlinearity, involves the equilibrium and compatibility relationships of a structural system loaded about its deflected configuration. The two sources of P-Delta effect are: (i) **P-δ effect** or **P-"small-delta"** associated with local deformation relative to the element chord between end nodes. Typically, P-δ only becomes significant at unreasonably large displacement values or in especially slender columns. So long as a structure adheres to the slenderness requirements pertinent to earthquake engineering, it is not advisable to model P-δ since it may significantly increase computational time without providing the benefit of useful information. An easier way to capture this behavior is to subdivide critical elements into multiple segments, transferring behavior into P-Δ effect and (ii) **P-Δ effect** or **P-"big-delta"** associated with displacements relative to member ends. Unlike P-δ, this type of P-Delta effect is critical to nonlinear modelling and analysis. Here

gravity loading will influence structural response under significant lateral displacement. P-Δ may contribute to loss of lateral resistance, etc. Effective lateral stiffness decreases, reducing strength capacity in all phases of the force-deformation relationship. To consider P-Δ effect directly, gravity loads should be present during nonlinear analysis.

C. Linear Static Analysis Versus Construction Sequence Analysis

Linear static analysis is performed in one step without considering the sequential construction of each floor. The construction sequence or stage analysis is performed after construction of each storey like real scenario.

In order to get the sequential construction effects each story should be analyzed with its prior stories assigning the vertical and lateral loads till that floor from the foundation of entire structure. The resulting output from analysis will represent the structural response of building till that floor. At present many structural analysis software have the capability to auto-perform the sequential analysis easily. Instead of considering one storey at a time in the staged analysis, a convenient small group of storeys may be considered. Structural analysis software ETABS 13.1.1 is used in the present work. This software has capabilities to perform linear analysis and nonlinear analysis. Provisions exist to account for axial shortening of columns, long-term effects of creep and shrinkage of concrete and construction sequence analysis.

III. PRESENT COMPUTATIONAL WORK

In the present study four tall building frames of 30, 40, 50 and 60 storeys are considered. The plan shape of all the tall building frames considered is same and the same is shown in Figure 1. The storey height and dimensions of the buildings are given in Table 1. One interior column is discontinued at first floor level in all the four buildings and the same starts again from second floor level and continues upwards as floating column. The 30 storey building frame is analyzed separately for M35, M40 and M50 grades of concrete to determine the influence of grade of concrete. The remaining building frames are analyzed for M40 grade of concrete. A value of 0.2 for the Poisson's ratio is used for all the grades of concrete. A value of 5.5 x 10^{-6} /^{o}C for the coefficient of thermal expansion is used for all the grades of concrete.

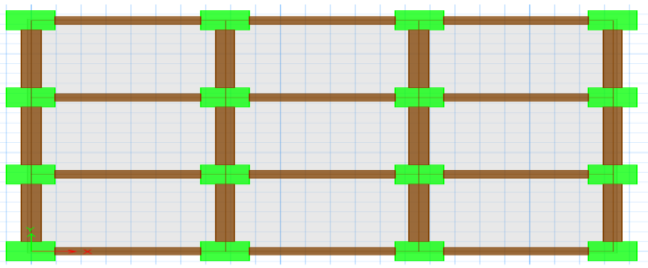

Figure 1: Plan of tall building frame

Table 1: Dimensions of Buildings

No of storeys / Dimensions	30 storeys	40 storeys	50 storeys	60 storeys
Height of Building (m)	90	120	150	180
Dimension in X-direction (m)	24	24	24	24
Dimension in Y-direction (m)	24	24	24	24
Typical Storey height (m)	3	3	3	3
Height of Storey just above foundation (m)	2	2	2	2

A dead load of 6 kN/m^2 and a live load of 4 kN/m^2 are assumed in the analysis. The building is assumed to be located at Mumbai. The thickness of floor and roof slabs is taken as 120 mm. In this study ETABS 13.1.1 is employed which accounts for time dependent parameters as well as construction sequence. In the present work staged analysis has been carried out for 30 storey building frame considering each stage to consist of 5 storeys for three different grades of concrete viz., M35, M40 and M50. For the other buildings of 40, 50 and 60 storeys this analysis has not been performed. The software computes the wind and seismic loads required in the analysis as per specifications of BIS Codes [11,12]. The values of relative humidity % used are 40, 50 and 60. The values of the shrinkage coefficient used are 4, 5 and 8. The cross-sectional dimensions of the columns are reduced as the height of the building increases. The details of column sections and beam sections used in the present work are given in Tables 2a through 2c.

Table 2a: Details of beams and columns of 30 storey building

Member	Size in mm (width x overall depth)	Slab thickness in mm
Beams	300 x 500, 350 x 600 and 800 x 800	120
Transfer beam	1200x1200	120
Columns	1000 x 1000 and 1200 x 1200	---

Table 2b: Details of beams and columns of 40 and 50 storey buildings

Member	Size in mm (width x overall depth)	Slab thickness in mm
Beams	400 x 400, 500 x 500 and 600 x 600	120
Transfer beam	1400x1400	120
Columns	1000 x 1000, 1200 x 1200 and 1400 x 1400	---

Table 2c: Details of beams and columns of 60 storey building

Member	Size in mm (width x overall depth)	Slab thickness in mm
Beams	400 x 400, 500 x 500, 600 x 600 and 700 x 700	120
Transfer beam	1600x1600	120
Columns	1000 x 1000, 1200 x 1200, 1400 x 1400 and 1600 x 1600	---

IV. RESULTS AND DISCUSSION

A. *Thirty-storeyed building frame*

a) Effect of construction sequence on force and deformation responses of critical beam

Construction sequence analysis has been carried out for 30 storey building frame considering three different grades of concrete viz., M35, M40 and M50 to determine the effect of construction sequence. The said analysis is performed by considering a group of 5 storeys as a stage. The number of storeys considered sequentially in the analysis is 5, 10, 15, 20, 25 and 30 storeys. At each stage of analysis, only the load increments occurring in that specific time-step are applied and analysis performed. The floors are assumed to be rigid in their plane. For the purpose of comparison with construction sequential analysis, the 30 storey frame is also analysed by static linear analysis. The first floor transfer beam spanning over the removed interior column is critical from both strength and serviceability points of view. It is hereafter referred to as **critical beam**. The responses of the critical beam during various stages of construction are given in Table 3 through 5.

Table 3: Structural responses of critical beam when M35 concrete is used

	Construction Sequential Analysis						Linear Static Analysis
	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	
Midspan Moment (kN-m)	2876	5996	8030	10327	12390	14340	13661
Shear (kN)	1040	1775	2256	2729	3283	3743	3465
Midspan Deflection (mm)	4.1	7.8	10.5	13.3	15.8	18.3	10.2

Table 4: Structural responses of critical beam when M40 concrete is used

	Construction Sequential Analysis						**Linear Static Analysis**
Response of critical beam	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	
Midspan Moment (kN-m)	2884	6008	8047	10350	12422	14382	13692
Shear (kN)	1039	1774	2256	2799	3287	3749	3471
Midspan Deflection (mm)	3.8	7.2	9.6	12.2	14.5	16.8	9.6

Table 5: Structural responses of critical beam when M50 concrete is used

Response of critical beam	Construction Sequential Analysis						Linear Static Analysis
	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	
Midspan Moment (kN-m)	2901	6041	8097	10426	12528	14525	13739
Shear (kN)	1036	1773	2259	2805	3299	3768	3481
Midspan Deflection (mm)	3.3	6.2	8.3	10.5	12.6	14.5	8.6

The following are the observations from Tables 3 through 5:

- The moment, shear and deflection values of critical beam increase with height during construction for all grades of concrete.
- The moment, shear and deflection values given by construction sequence analysis after completion of construction and full loading are higher compared to those given by linear static analysis. The moment value given by construction sequence analysis is greater than that given by linear static analysis by a small margin (4.9% when M35 is used, 5.04 % when M40 is used and 5.71% when M50 is used). The shear value given by construction sequence analysis is greater than that given by linear static analysis by a small margin (8.03% when M35 is used, 7.9 % when M40 is used and 8.23 % when M50 is used). The midspan deflection given by construction sequence analysis is considerably greater than that given by linear static analysis (79.4 % when M35 is used, 75 % when M40 is used and 68.6% when M50 is used).
- The midspan deflection of the critical beam is seen to decrease as the concrete grade increases. The decrease is 1.5 mm when the concrete grade is changed from M35 to M40 and 2.6 mm when the concrete grade is changed from M40 to M50. This decrease may be attributed to the increase in stiffness of the beam arising from the increase in Young's modulus of concrete.

b) ***Effect of humidity on deformation response of critical beam and selected interior columns***

Two interior columns are selected for the purpose of comparison. The first selected interior column is the one which extends from the foundation up to first floor level. It is discontinued later and designated here as **SC1**. The other selected interior column is the interior column next to SC1 and it is designated here as **SC2**. Separate nonlinear analyses have been carried out to determine the total column shortening in the selected columns and midspan deflection of critical beam at different ages of the building viz., (i) after completion of construction and occupation, (ii) 5 years after construction, (iii) 10 years after construction, (iv) 15 years after construction and (v) 20 years after construction for different percentages of relative humidity. The results for columns SC1and SC2 are shown in Tables 6 and 7.

Table 6: Column shortening of SC1

Relative Humidity	Column shortening in mm				
	After completion of construction	5 years after completion of construction	10 years after completion of construction	15 years after completion of construction	20 years after completion of construction
40%	32.9	43.3	54	60.3	64.2
50%	29.2	40.4	50.8	56.7	60.7
60%	26.6	37.3	46.6	52.3	55.2

Table 7: Column shortening of SC2

Relative Humidity	Column shortening in mm				
	After completion of construction	5 years after completion of construction	10 years after completion of construction	15 years after completion of construction	20 years after completion of construction
40%	30.8	42	53	59.9	63.2
50%	28.9	39.6	49.9	55.8	59.4
60%	26.4	35.3	45.8	51.1	54.8

The following observations are made from Tables 6 and 7:

- The column shortenings of SC1 and SC2 decrease as the relative humidity increases at all ages of loading.
- At any particular value of relative humidity, the column shortenings of SC1 and SC2 increase with time and the rate of increase of column shortening decreases with time

The midspan deflections of the critical beam are shown in Table 8.

Table 8: Midspan deflection of critical beam

Relative Humidity	Midspan Deflection in mm				
	After completion of construction	5 years after completion	10 years After completion	15 years after completion	20 years after completion
40%	16.8	19.6	20	20.2	**20.4**
50%	16.3	18.9	19.4	19.5	19.9
60%	15.8	18.3	18.7	19	19.2

From Table 8, the following observations are made:

- The midspan deflection of critical beam increases with time for all percentages of relative humidity.
- The midspan deflection of critical beam decreases as the relative humidity increases at all ages of loading since creep decreases as relative humidity increases.
- At any particular value of relative humidity, the midspan deflection of critical beam increases with time and the rate of increase of midspan deflection decreases with time.

*c) **Effect of shrinkage coefficient on deformation response of critical beam and selected interior columns***

Nonlinear analyses have been carried out to determine the effect of the shrinkage parameter $B_{sc.}$ on midspan deflection of critical beam and column shortening of selected columns. The shrinkage parameter B_{sc} depends on the type of cement. The values of shrinkage parameters [CEB –FIP] for different types of cement are as follows:

B_{sc} = 4 for low-speed hardening cement

B_{sc} = 5 for normal hardening or high speed hardening cement

B_{sc} = 8 for high strength and high speed hardening cement

In all these analyses, M40 grade concrete and 40 % relative humidity are assumed. The construction time for one storey is taken as 15 days. Separate nonlinear analyses have been carried out to determine the total column shortening in the selected columns and midspan deflection of critical beam at different ages of the building viz., (i) after completion of construction and occupation, (ii) 5 years after construction, (iii) 10 years after construction, (iv) 15 years after construction and (v) 20 years after construction for different percentages of relative humidity. The results for columns SC1 and SC2 are shown in Tables 9 and 10.

Table 9: Shortening of Column SC1

Shrinkage coefficient Bsc	Column shortening in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
4	31.1	41.1	51.1	56.8	60.7
5	32.9	43.3	54	60.3	64.2
8	37.1	48.8	63.1	71.4	77

Table 10: Shortening of Column SC2

Shrinkage coefficient Bsc	Column shortening in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
4	29	40.3	50.2	55.8	59.3
5	30.8	42	53	59.3	63.2
8	36.8	46.8	62.2	70.2	75.7

The following observations are made from Tables 9 and 10:

- The column shortenings of SC1 and SC2 increase as the shrinkage coefficient increases at all ages of loading.
- At any particular value of shrinkage coefficient, the column shortenings of SC1 and SC2 increase with time and the rate of increase of column shortening decreases with time

Table 11 shows the variation of midspan deflection of the critical beam with respect to age of structure for different shrinkage coefficients.

Table 11: Midspan deflection of critical beam

Shrinkage coefficient Bsc	Midspan deflection in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
4	15.7	18.8	19.1	19.4	19.5
5	16.8	19.6	20	20.2	20.4
8	19.1	22.3	23.1	23.4	23.6

The following observations are made from Table 11:

- The midspan deflection of critical beam increases with time for all shrinkage coefficients.
- At any particular value of shrinkage coefficient, the midspan deflection of critical beam increases with time and the rate of increase of midspan deflection decreases with time

d) ***Effect of grade of concrete on deformation response of critical beam and selected interior columns***

Three different concrete grades i.e., M35 M40 and M50 are considered. A shrinkage parameter of 5, construction time for one storey of 15 days and relative humidity of 40% are used in the performed nonlinear analyses. The effect of grade of concrete on column shortening of SC1 is shown in Table 12.

Table 12: Shortening of Column SC1

	Column Shortening (mm)		
	M35	M40	M50
After completion of construction	39.7	39.8	24.1
5 years after construction	42.9	43.6	33.5
10 years after construction	54	49.7	42.3
15 years after construction	60.3	55.6	47.4
20 years after construction	64.6	59.3	50.5

From Table 12, it is observed that the column shortening at any age of structure decreases as the grade of concrete increases.

The effect of grade of concrete on midspan deflection of critical beam is shown in Table 13.

Table 13: Midspan deflection of critical beam

	Midspan Deflection (mm)		
	M35	M40	M50
After completion of construction	18.3	16.8	14.5
5 years after construction	21.4	19.6	16.9
10 years after construction	21.9	20	17.3
15 years after construction	22.1	20.2	17.4
After 20 years	22.3	20.4	17.6

From Table 13, it is observed that the midspan deflection of critical beam decreases as grade of concrete increases at all ages of structure.

B. *Forty-storeyed building frame*

Nonlinear analyses have been performed to determine the effects of relative humidity, shrinkage coefficient and speed of construction on the responses of critical beam and selected interior columns

a) ***Effect of relative humidity on deformation response of critical beam and selected interior columns***

The midspan deflections of critical beam obtained from nonlinear analyses are shown in Table 14.

Table 14: Midspan deflection of critical beam

Relative Humidity	Midspan deflection in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
40%	41.5	47.7	48.7	49.5	49.8
50%	40.1	45.5	46.4	46.6	46.8
60%	38.9	44	44.8	45.2	45.4

From Table 14, the following observations are made:

The midspan deflection of critical beam increases with time at all percentages of relative humidity.
The midspan deflection of critical beam decreases as the relative humidity increases at all ages of loading. At any particular value of relative humidity, the midspan deflection of critical beam increases with time and the rate of increase of midspan deflection decreases with time

The shortenings of columns SC1 and SC2 obtained from nonlinear analyses are shown in Tables 15 and 16.

Table 15: Shortening of Column SC1

Relative Humidity	Column shortening in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
40%	42.8	54	67.5	75.9	81.7
50%	39	50.3	63.5	71.3	76.2
60%	35.8	46.5	58.5	65.5	70.5

Table 16: Shortening of Column SC2

Relative Humidity	Column shortening in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
40%	38.3	52	67.5	75.9	81.7
50%	35.8	48.9	62	69.7	74.6
60%	33.2	45.3	57.2	64	68.4

From Table 15 and 16, the following observations are made:

- The column shortenings of SC1 and SC2 decrease as the relative humidity increases at all ages of loading.
- At any particular value of relative humidity, the column shortenings of SC1 and SC2 increase with time; the rate of increase of column shortening decreases with time.

b) Effect of shrinkage factor on deformation response of critical beam and selected interior columns

Table 17: Midspan deflection of critical beam

Shrinkage coefficient Bsc	Midspan deflection in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
4	40	46	46.9	47.2	47.3
5	41.5	47.7	48.7	49.5	49.8
8	43.2	49.1	49.7	49.8	50.1

From Table 17, the following observations are made:

- The midspan deflection of critical beam increases with time for all values of shrinkage coefficient. The rate of increase of deflection with time decreases.
- The midspan deflection of critical beam decreases with increase in shrinkage coefficient value. The shortenings of column SC1 and SC2 obtained from nonlinear analyses are shown in Tables 18 and 19.

Table 18: Shortening of Column SC1

Shrinkage Coefficient Bsc	Column shortening in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
4	39.7	52	64.9	72.4	76.5
5	42.8	54	67.5	75.9	81.7
8	45.1	59.5	77.9	88.7	95.6

Table 19: Shortening of Column SC2

Shrinkage Coefficient Bsc	Column shortening in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
4	36.2	49.9	62.7	70.1	74.8
5	38.3	52	66	74.2	79.5
8	46.6	58.1	76	86.6	93.6

From Tables 18 and 19, the following observations are made:

- The column shortenings of SC1 and SC2 increase as the shrinkage coefficient increases at all ages of loading.
- At any particular value of shrinkage coefficient, the column shortenings of SC1 and SC2 increases with time and the rate of increase of column shortening decreases with time.

c) Effect of speed of construction on the deformation response of critical beam and selected interior column

The 40 storey building is analyzed for three different speeds of construction i.e., 15 days/ storey, 21 days/ storey and 28 days/ storey. M40 grade of concrete, shrinkage coefficient of 5and 40% relative humidity are considered in the analyses.

The effects of speed of construction on column shortening are shown in Table 20

Table20: Shortening of Column SC1

	Column Shortening (mm)		
	15 days / storey	21 days / storey	28 days / storey
After completion of construction	43.8	30.9	28.7
5 years after completion of construction	53.8	44.1	40.9
10 years after completion of construction	62.7	55.8	51.4
15 years after completion of construction	72.4	61.9	58
20 years after completion of construction	78.8	63.7	61.6

From Table 20, it is observed that the column shortening decreases as the speed of construction decreases. The effects of speed of construction on deformation response of critical beam are shown in Table 21.

Table 21: Midspan deflections of critical beam

	Midspan deflection (mm)		
	15 days / storey	21 days / storey	28 days / storey
After completion of construction	41.5	37.9	37.4
5 years after completion of construction	47.7	42	40.8
10 years after completion of construction	48.7	42.7	41.3
15 years after completion of construction	49.5	42.9	41.5
20 years after completion of construction	49.8	43.2	41.8

From Table 21, it is seen that the midspan deflection of critical beam decreases as the speed of construction decreases

C. *Fifty-storeyed building frame*

Nonlinear analyses have been performed to determine the effects of relative humidity and shrinkage coefficient on the responses of critical beam and selected interior columns.

a) Effect of relative humidity on deformation response of critical beam and selected interior columns

The midspan deflections of critical beam obtained from nonlinear analyses are shown in Table 22.

Table 22: Midspan deflection of critical beam

Relative Humidity	Midspan deflections in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
40%	44.9	49.8	50.6	50.8	51
50%	43.7	48.3	49	49.2	49.5
60%	42.5	46.7	47.4	47.6	47.9

From Table 22, the following observations are made:

- The midspan deflection of critical beam increases with time for all percentages of relative humidity.
- The midspan deflection of critical beam decreases as the relative humidity increases at all ages of loading.
- At any particular value of relative humidity , the Midspan deflection of critical beam increases with time; the rate of increase of midspan deflection decreases with time

The shortenings of columns SC1 and SC2 obtained from nonlinear analyses are shown in Table 23 and 24.

Table 23: Shortening of Column SC1

Relative Humidity	Column shortening in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
40%	51.2	70.4	87.9	98.1	104.5
50%	47.9	66.4	82.7	92.2	95.6
60%	43.9	61.6	76.3	82.5	90.3

Table 24: Shortening of Column SC2

Relative Humidity	Column shortening in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
40%	50.4	70	87.4	97.6	104
50%	47.1	65.9	82.2	91.7	95.1
60%	43.2	61.1	75.8	82.1	89.8

From Tables 23 and 24, the following observations are made:

- The column shortenings of SC1 and SC2 decrease as the relative humidity increases at all ages of loading.
- At any particular value of relative humidity, the column shortenings of SC1 and SC2 increase with time; the rate of increase of column shortening decreases with time.

*b) **Effect of shrinkage factor on deformation response of critical beam and selected interior columns***

The midspan deflections of critical beam obtained from nonlinear analyses are shown in Table25

Table 25: Midspan deflections of critical beam

Shrinkage coefficient Bsc	Midspan deflections in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
4	43.7	48.7	49.5	49.8	49.9
5	44.9	49.8	50.6	50.8	51
8	46.2	50.7	51.1	51.8	52

From Table 25, the following observations are made:

- The midspan deflection of critical beam increases with time for all values of shrinkage coefficient.
- The mispan deflection of critical beam increases as shrinkage coefficient increases at all stages of loading.
- At any particular value of shrinkage coefficient, the midspan deflection of critical beam increases with time; the rate of increase of midspan deflection decreases with time

The shortenings of columns SC1and SC2 obtained from nonlinear analyses are shown in Tables 26 and 27.

Table 26: Shortening of Column SC1

Shrinkage coefficient Bsc	Column shortening in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
4	48.6	68	83.9	90.3	98.8
5	51.2	70.4	87.9	98.1	104.5
8	58.8	75.7	97.4	113.1	121.5

Shrinkage coefficient Bsc	Column shortening in mm				
	After completion of structure	5 years after completion	10 years after completion	15 years after completion	20 years after completion
4	47.8	67.5	83.3	89.8	98.3
5	50.4	70	87.4	97.6	104
8	58.1	75.3	97	112.7	121.1

Table 27: Shortening of Column SC2

From Tables 26 and 27, the following observations are made:

a) The column shortenings of SC1 and SC2 increase as the shrinkage coefficient increases at all ages of loading.

b) At any particular value of shrinkage coefficient, the column shortenings of SC1 and SC2 increase with time and the rate of increase of column shortening decreases with time

*D. **Variation of force and deformation responses of critical beam with building height***

*a) **Variation of midspan deflection of critical beam***

Figure 2 shows midspan deflection of the critical beam. The deflection of critical beam considered immediately after completion of construction and occupation is observed to vary from 16.8 mm in 30 storey building frame to 30.8 mm in 60 storey building frame by construction sequential analysis while by linear static analysis it varies from 9.6 mm to 23.2 mm for 30 storey and 60 storey building frames respectively. The predictions made by the two said analyses differ significantly, the response predicted by stage analysis being greater than that predicted by linear static analysis.

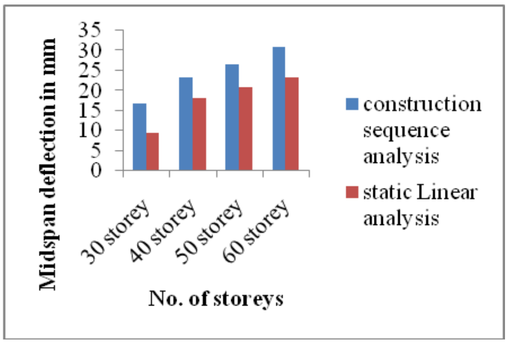

Figure 2: Variation of midspan deflection of the critical beam with height of building

b) Variation of midspan moment of critical beam

Figure 3 shows midspan moment values of the critical beam computed by the said analyses. The midspan moment of the critical beam is observed to vary from 13691.94 kNm in 30 storey building frame to 19038.336 kNm in 60 storey building frame by linear static analysis while it varies from 14382.05 kNm to 22282.514 kNm by construction sequential analysis for 30 storey and 60 storey building frames respectively. The predictions made by the two said analyses differ significantly, the response predicted by stage analysis being greater than that predicted by linear static analysis.

Figure 3: Variation of midspan moment of the critical beam with height of building

c) Variation of axial force in corner column

The variation of axial load for different storeys is shown in Figure 4 for both static linear analysis and construction sequence analysis.

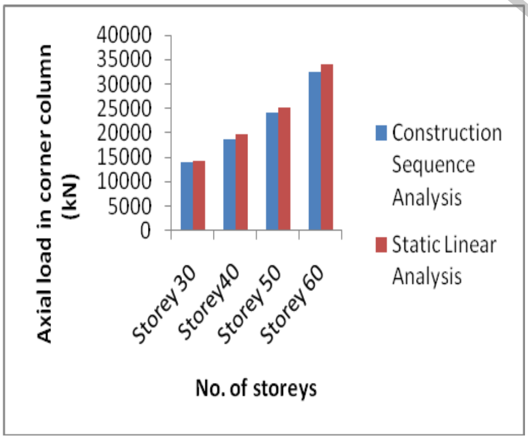

Figure 4: Variation of axial force of corner column with height of building

The axial load in corner column is observed to vary from 14169.99 kN in 30 storey building frame to 34084.27 kN in 60 storey building frame by linear static analysis while it varies from 13936.75 kN to 32383.93 kN by construction sequential analysis for 30 storey and 60 storey building frames respectively. It is observed that the axial load predicted by construction sequence analysis is slightly less than that predicted by linear static analysis

CONCLUSIONS

- The analyses made on 30 storey building frame reveal that midspan moment, end shear and midspan deflection values in critical beam increase with height during construction for all grades of concrete. The values given by construction sequence analysis after completion of construction and occupation are higher compared to those given by linear static analysis. The values predicted by construction sequence analysis are slightly greater than those predicted by linear static analysis in the case of midspan moments and end shears. The values predicted by construction sequence analysis are considerably greater than those predicted by linear static analysis in the case of midspan deflections. Similar results can be expected for 40, 50 and 60 storey building frames.

- The column shortening decreases as the relative humidity increases at all ages of loading in the case of all building frames. At any particular value of relative humidity, the column shortening increases with time and the rate of increase of column shortening decreases with time.

- The midspan deflection of critical beam increases with time for all percentages of relative humidity in the case of all building frames. At any particular value of relative humidity, the rate of increase of midspan deflection decreases with time. The midspan deflection of critical beam decreases as the relative humidity increases at all ages of loading since creep decreases as relative humidity increases.

- The column shortening increases as the shrinkage coefficient increases at all ages of loading in the case of all building frames. At any particular value of shrinkage coefficient, the column shortening increases with time and the rate of increase of column shortening decreases with time.

- The midspan deflection of critical beam increases with time for all shrinkage coefficients in the case of all building frames. At any particular value of shrinkage coefficient, the midspan deflection of critical beam increases with time and the rate of increase of midspan deflection decreases with time. To reduce the effects of shrinkage, it is advisable to use low speed cement for tall reinforced concrete structures.

- The column shortening decreases as the grade of concrete increases.

The midspan deflection of critical beam decreases as grade of concrete increases at all ages of structure. This decrease may be attributed to the increase in stiffness of the beam arising from the increase in Young's modulus of concrete.

The column shortening decreases as the speed of construction decreases.

This study has clearly brought the necessity of using nonlinear static analysis (P-Delta effects) in the design of tall building frames. The analysis must consider the effects of construction sequence, creep and shrinkage of concrete.

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