Study of Creep, Shrinkage and Column Shortening on Behavior of High-Rise Buildings

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Study of Creep, Shrinkage and Column Shortening on Behavior of High-Rise Buildings

Major Project

Submitted in partial fulfillment of the requirements

For the degree of

Master of Technology in Civil Engineering

(Computer Aided Structural Analysis & Design)

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MAY 2014

Declaration

This is to certify that

i) The thesis comprises my original work towards the Degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis and Design) at Nirma University and has not been submitted elsewhere for a degree or diploma.

ii) Due acknowledgement has been made in the text to all other materials used.

Snehal D. Poojara

Certificate

This is to certify that the Major Project entitled **"Study of Creep, Shrinkage and Column Shortening on Behavior of High-Rise Buildings"** submitted by **Mr. Snehal D. Poojara (12MCLC31)**, towards the partial fulfillment of the requirements for the degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis and Design) of Nirma University, Ahmedabad is the record of work carried out by him under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project, to the best of my knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

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Abstract

Axial shortening of columns affect the behavior of high-rise buildings. Differential axial shortening in the building structures causes axial force redistribution among columns and core walls and introduces additional forces in the horizontal members such as beams and slabs. Elastic as well as inelastic shortening of columns due to creep and shrinkage contributes a lot towards the axial shortening of columns and hence it need to be considered in the design and construction of medium to high-rise buildings. These effects increase with the height of the building and irregularity in vertical load paths resulting from geometric irregularity and complexity. General building codes do not give specific guidelines about consideration of differential column shortening. Consequently, column shortening is usually left to the judgment of structural engineers.

Analytical and experimental procedures available to quantify the magnitude of column shortening effects are limited to a very few parameters and are not adequate to capture the complexity of nonlinear time dependent material response. A present study is carried out to develop the understandings of the column shortening behavior in reinforced concrete buildings.

Parametric study is conducted to understand the influence of controlling parameters such as material properties, structural element sizes, construction sequence and rate, environmental conditions and structural systems. For studying effect of axial shortening, ETABS and MIDAS Gen software are used. Buildings with different structural systems like rigid frame structure and wall frame structure with different number of story are considered in the study. Generally, column shortening developed due to construction stages along with time dependent material properties and environmental conditions affect the design of beams and columns of mid height stories in high-rise buildings.

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I express my deep sense of gratitude and sincere thanks to my guide **Dr. P. V. Patel**, Professor & Head, Department of Civil Engineering, Institute of Technology, Nirma University, Ahmedabad. I express my hearty thanks to him who, right from the conceptualization of the problem to the finishing stage of the Major Project, molded my work. From the very beginning of the thesis, his valuable discussions and continuous reviews and suggestions helped me a lot during this study.

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Abbreviation Notation and Nomenclature

A_c .... Cross sectional area of concrete

A_s .... Cross sectional area of steel reinforcement

ε_c .... Strain in concrete

ε_{cso} .... Notional shrinkage coefficient

$\varepsilon_s(f_{cm})$ .... Shrinkage coefficient depending on concrete strength

σ_c .... Compressive stress in concrete

ε_{cc} .... Creep Strain in concrete

ε_{cs} .... Shrinkage strain in concrete

E_{ci} .... Modulus of elasticity of concrete at time of loading

E_{co} .... $2.15 \times 10^4 MPa$

f_{ck} .... Characteristic cylinderical compressive strength of concrete

f_{cm} .... Mean cylindrical compressive strength of concrete

$f_{cm(t)}$ .... Mean cylindrical compressive strength of concrete at time of loading

f_{cmo} .... 10 Mpa

β_{sc} .... Shrinkage coefficient depending on type of cement

β_{sRH} .... Shrinkage coefficient depending on relative humidity

β_{RH} .... Shrinkage coefficient depending on type of cement

s .... Strength coefficient depending on type of cement

t_s .... Age of concrete at the beginning of shrinkage

t_1 .... 1 day

t_0 .... 10 days

$\beta_{cc(t)}$ .... Coefficient depending on the age of concrete

β_{t_0} .... Notional Creep coefficient depending on the age of concrete

$\beta_{f_{cm}}$ .... Notional Creep coefficient depending on the concrete strength

ε_{so} .... Notional shrinkage coefficient

h .... Notional size of a cross-section

h_0 .... 100 mm

ϕ .... Creep coefficient

ϕ_{RH} ...... Notional creep coefficient depending on relative humidity
α_E ...... Coefficient depending on type of aggregate
t_0 ...... The age of concrete at the time of loading
Δ_f ...... Standard deviation
u ...... Perimeter of an element
RH ...... Relative humidity of climate
RH_0 ...... 100% Relative humidity
ECS ...... Element coordinate system
GCS ...... Global coordinate system
F_z ...... Downward axial force
U_z ...... Downward axial displacement
F ...... Floor
SQDL ...... Sequential dead load
OSA ...... One step analysis
CSA ...... Construction sequence analysis

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Chapter 1

Introduction

1.1 General

Creep, Shrinkage and Column shortening are the secondary effects which need to be considered in the construction and design of medium to high-rise buildings. During the construction of a building, columns and shear walls are subjected to a number of load increments. These load increments varies as the sequence of the construction varies. Each incremental load would cause instantaneous elastic shortening of columns and shear walls which would further lead to long term and time dependent creep and shrinkage shortening of such elements.

Axial shortening of vertical elements will affect more to horizontal elements such as beams and slabs. Axial shortening may change the level of beams and slabs, increase bending moments and shearing forces. These effects would be more devastating when beams and slabs are connected to the exterior columns and inner shear walls.

1.2 Necessity of the Column Shortening Prediction

Axial Shortening due to Creep and Shrinkage are Inelastic Shortening which grows with time either positively or negatively whereas Elastic shortening takes place instantaneously as soon as the first floor level is constructed of the frame. Sequence of the construction should include only the Dead Loads i.e. Self-weight and other finishes and not the Live Loads which is considered to be effective only after the whole frame is constructed.

Some important points which makes the prediction of axial shortening effect necessary are:

a. To determine the level adjustment amount in floors and columns.

b. To establish the construction tolerance or allowance.

c. To assess the impact on interfacing structures.

d. To maintain the construction sequence on site.

e. To reduce the increased bending moments and shear forces in the horizontal elements such as beams and slabs.

f. To reduce the risk of overloading of the structure.

g. To reduce the risk of weak story in the high rise buildings.

h. To maintain or limit the loadings on substructure i.e. foundations.

i. To consider the effect of stress transfer from concrete to steel reinforcement in high-rise RC buildings.

j. To achieve absolute safety of the building structure.

1.3 Column Shortening

Concrete is being used in high-rise buildings popularly with the improvements in concrete properties and innovation of high strength and high performance concrete. Adoption of ultimate strength design and replacement of traditional, load bearing heavy masonry partitions with lightweight partitions results in a significantly larger load increments on relatively smaller columns of modern high-rise buildings. Once the self weight and other dead loads act on the structure, a permanent, instantaneous shortening takes place in the column and creep commences from that point onward. Shrinkage, which is not affected by load applications, initiates from the moment of placement of concrete. Shortening due to live loads is temporary and disappears when the load is removed.

1.3.1 Creep

Creep of any building element depends on the loading history. Researcher found that creep strain becomes less with any delay in the application of loads. Creep varies with both, the dimension of the building elements and the percentage of reinforcement in the cross section of reinforced concrete members. Higher the amount of reinforcement, the lesser will be the creep deformation of the member, due to transfer of the stresses from concrete to reinforcing bars. Time dependent creep coefficient for a constant compressive stress applied at time t_0 according to CEB-FIP Model Code(1990) is shown in Fig.1.1 and Eq.1.1

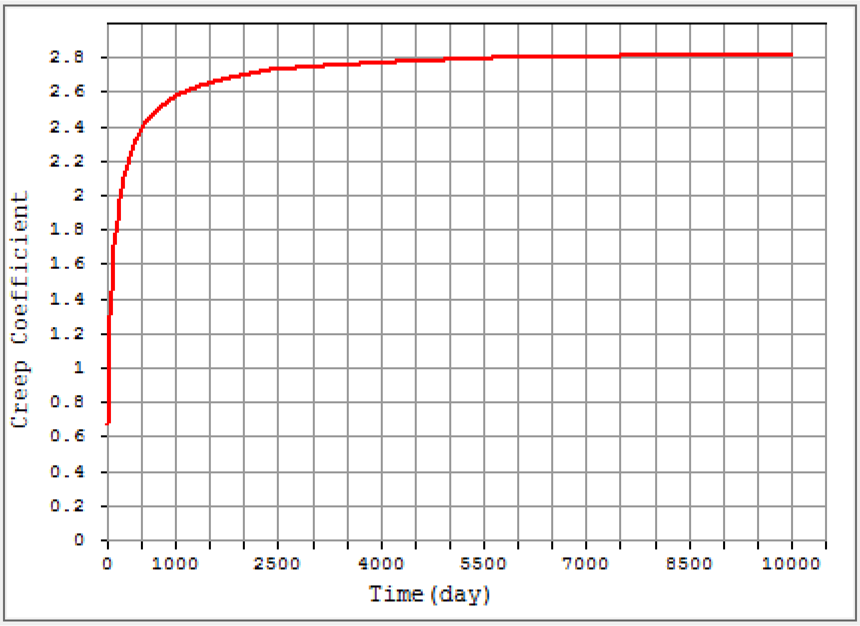


Figure 1.1: Time Dependent Creep function based on CEB - FIP model code

$$\epsilon_{cc}(t, t_0) = \frac{\sigma_c(t_0)}{E_{ci}} \Phi(t, t_0) \tag{1.1}$$

Where,

$\varepsilon_{cc}(t, t_0)$ = Creep Strain

$\sigma_c(t_0)$ = Compressive Stress

E_{ci} = Modulus of Elasticity at time of loading

$\Phi(t, t_0)$ = Creep Coefficient

1.3.2 Shrinkage

Shrinkage occurs in concrete due to hydration of cement without moisture evaporation from concrete which is known as **Autogenous Shrinkage** and due to moisture evaporation from concrete which is known as **Drying Shrinkage**. In case of autogenous shrinkage, no moisture exchange occurs with environmental medium at constant temperature. In majority of the cases, drying shrinkage plays a major role in shrinkage shortening of columns. Time dependent shrinkage strain according to CEB-FIP Model Code(1990) is shown in Fig.1.2 and Eq.1.2

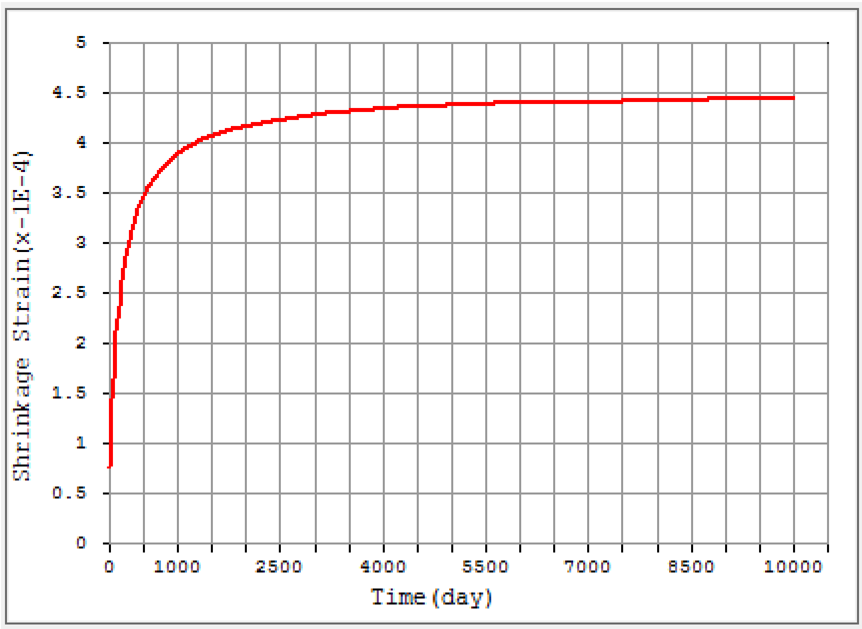


Figure 1.2: Time Dependent Shrinkage function based on CEB - FIP model code

$$\varepsilon_{cs}(t, t_s) = \varepsilon_{cso}\beta_s(t - t_s) \tag{1.2}$$

Where,

$\varepsilon_{cs}(t, t_s)$ = Shrinkage Strain

ε_{cso} = Notional Shrinkage Coefficient

β_s = Coefficient to describe development of shrinkage with time

t = Age of Concrete

t_s = Age of Concrete at beginning of shrinkage

Drying shrinkage increases with the surface area of the member and hence lower the volume to surface ratio, higher will be the shrinkage shortening. Environmental conditions also affects the shrinkage of concrete. As a lower relative humidity in surrounding environment absorbs water from possible sources, concrete in such areas is liable to shrink more.Similar to creep, the presence of reinforcement will reduce the amount of shrinkage strains in a concrete member.

Basic Driving force of **Autogenous shrinkage** is chemical shrinkage. As the hydration of the cement paste develops, the absolute volume decreases. The beginning of this deformation then starts with hydration, as soon as cement and water are in contact. Furthermore, Autogenous shrinkage can be split in two parts:

a. Autogenous plastic shrinkage that is generated during the induction period

b. Self desiccation that occurs after the setting.

Autogenous plastic shrinkage includes initial swelling action of cement paste whereas, Self desiccation includes Filling of capillary Porosity and Chemical Shrinkage.

1.3.3 Elastic

Elastic shortening is the instantaneous deformation that takes place in a member due to any gravity load. Any axially loaded member is likely to shorten at least in a very small amount. Material properties and structural element sizes affect the elastic shortening of members. Since adjacent columns and walls have dissimilar properties such as different cross sectional areas, different reinforcement percentage in case of reinforced concrete structures and different sequence of their construction, are differentially loaded at different ages, relative or differential shortening of vertical members is unavoidable. The relative shortening of columns and walls results in the tilting action of horizontal members such as beams and slabs and will be subjected to increased and redistributed moments and shears. If necessary precautions are not taken at an initial stage, the serviceability of the structures may get endangered.

Time dependent strength function according to CEB-FIP Model Code(1990) is shown in Fig.1.3 and Eq.1.3

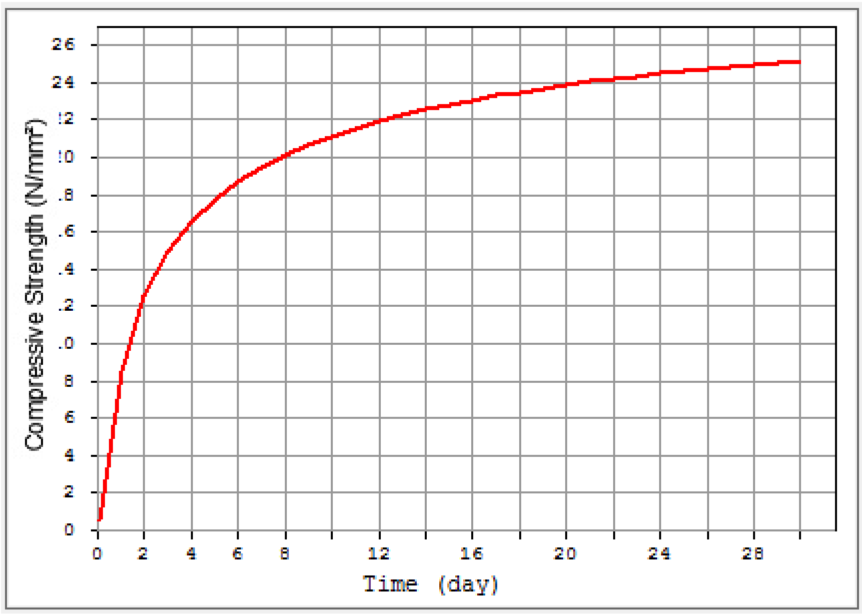


Figure 1.3: Time Dependent Strength function based on CEB - FIP model code

$$f_{cm}(t) = \beta_{cc}(t) f_{cm} \tag{1.3}$$

Where,

$f_{cm}(t)$ = Mean compressive strength at an age of t days

$\beta_{cc}(t)$ = Coefficient depending on age of concrete

f_{cm} = Mean compressive strength after 28 days curing

1.4 Column Shortening Prediction

Exact calculation of the axial shortening of the columns and shear walls is not possible as it is time dependent phenomena and is affected by the environmental conditions. Flow chart of column shortening analysis is shown in Fig.1.4

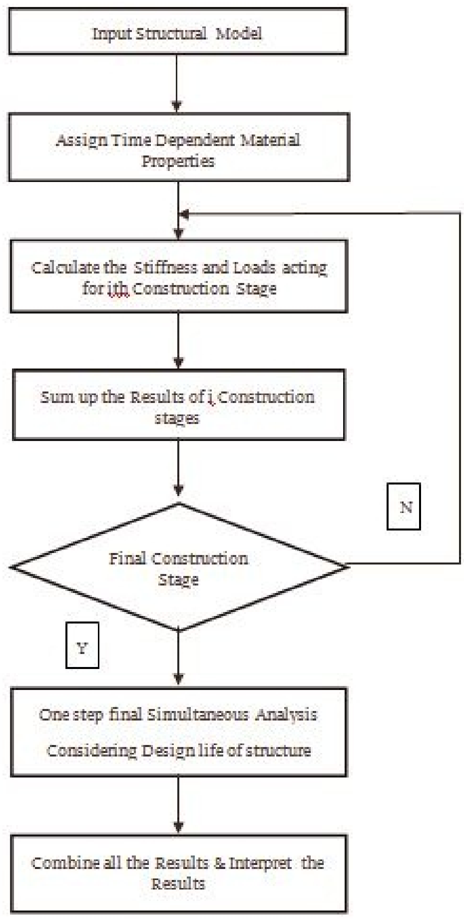


Figure 1.4: Flow Chart of Column Shortening Analysis [3]

Many researchers and authors have suggested various approximate methods to predict elastic as well as inelastic shortening of the columns and shear walls. In the prediction of axial shortening, Sequential nature of the Dead Load and Simultaneous nature of Live Load should be considered.

1.5 Objective of Study

The Present study aimed towards assessing the effects of the Creep, Shrinkage and Elastic Shortening of columns on behavior of High-Rise buildings.

Main objective of the study is to develop the guidelines for the prediction of the Axial Shortening of columns and their effects on the structural elements in High-Rise buildings due to Creep, Shrinkage and Elastic Deformation which can be useful to the Design engineers to achieve absolute safety of building structures and to the Construction Engineers who work on site for efficient execution of the construction.

1.6 Scope of Work

In order to achieve the objectives of the present study, the following scope of work is considered.
To study the effect of Creep, Shrinkage and Elastic Deformation of columns on design and construction of structural elements of High-Rise buildings. Variation in the following parameters are considered.

a. Structural Systems.

- Rigid Frame Buildings of 27m × 18m in plan
- Wall-Frame Buildings of 45.5m × 29.5m in plan

b. Building Heights.

- Building height varies from 32 meters up to 256 meters

c. Material Properties.

- Time dependent Creep
- Time dependent Shrinkage
- Development of Strength with time

d. Construction Sequence and Rate

- Lumping of floors: 1 Floor, 2 Floor, 3 Floor, 4 Floor and 5 Floor
- Construction Cycle: 7 days and 28 days

e. Environmental Conditions.

- Relative Humidity: 50%, 70% and 90%

1.7 Organization of Major Project

The content of Major Project is covered in different chapters as follows:

Chapter 1 includes general information, necessity of the study and causes of axial shortening of columns in high-rise buildings. Methods to predict the axial shortening of columns and its effect on building structures are discussed in this chapter. It also includes objective and scope of the present study.

Chapter 2 presents the review of the relevant literature available for understanding the concepts regarding elastic deformation, creep and shrinkage effects, importance of construction sequence to carry out axial shortening and applicability of the software to carry out the analytical work.

Chapter 3 describes the general procedure to carry out nonlinear construction stage analysis considering elastic deformation and time dependent creep and shrinkage effects using three dimensional finite element computer programs ETABS and MIDAS/Gen. Effects of Construction Stage is given the prime importance in this analytical procedures.

Chapter 4 presents the elastic shortening analysis results considering elastic shortening of columns using ETABS software. Effect of lumped construction sequence is considered in this chapter. Multi-storied rigid frame buildings are considered.

Chapter 5 presents the inelastic shortening analysis results considering time dependent material properties as well as elastic shortening of columns using MIDAS Gen software. Effect of material nonlinearities, construction rate and environmental conditions on design of elements are considered in this chapter. Multi-storied rigid as well as wall-frame buildings are considered for the proposed investigation.

Chapter 6 presents the summary of the work carried out and conclusions derived from the analytical study. It also includes future scope of work.

Chapter 2

Literature Review

2.1 General

Literature Review related to the Behavior of the High-Rise Buildings under Creep, Shrinkage and Elastic Shortening effects and the Methods of prediction of Axial Shortening effects in Column and Core walls is presented in this chapter. Various Research papers and Books have been referred to understand the behavior of the High-Rise buildings and methods to predict the axial shortening effects.

2.2 Column Shortening Analysis

As it is long perceived fact that creep of reinforced concrete columns result in gradual transfer of load from concrete to reinforcement, the method for prediction of the amount of creep and shrinkage strains was first outlined in the late 1969. **Fintel and Khan**[1] published first paper on this subject "Effects of Column Creep and Shrinkage in Tall structures - Prediction of Inelastic Column Shortening" in ACI Journal, December 1969.

Jayasinghe and Jayasena[2] suggested the effects of construction sequence, rate of construction, and grade of concrete on axial shortening of columns based on a number of case studies of the buildings covering 10 - 40 story range. They presented guidelines to include the effects of column shortening in preliminary design of buildings. They concluded that delay in construction of partition/frame reduces resultant axial shortening. They also concluded that the grade of concrete and cross sectional areas of columns do not have a significant effect on differential shortening values as reduction in shortening due to higher concrete grade and Cross Section cutoffs owing to the reduction of steel reinforcement. They recommended that allowance for differential shortening of vertical elements should be kept on construction site.

Serror and El-Din[3] presented parametric study on the influence of the variation of controlling parameters such as floor levels and type of statically system, using construction sequence analysis method. They analyzed wall-frame and outrigger buildings using MIDAS Gen for their investigation. They discussed the methodology for the modeling of construction sequence as shown in Fig.2.1. They found that in shear wall structure, maximum floor displacement occurred at a level around 2/3rd height of building. Results of the analytical study showed that outrigger separates the vertical structure and hence a local maximum floor displacement occurred at 0.5h to 0.8h. They concluded that differential displacement of local structure is same as the 20 story Shear wall structure and in stories less than 20, in shear wall structure, axial shortening effect can be neglected. As in 20 story outrigger structure, stiffness of outriggers was very high, exterior column behaved as a hanger column, hanging from the outriggers in ordinary analysis, which might not realistic, as outriggers were not in place until all lower column settlement occurred.

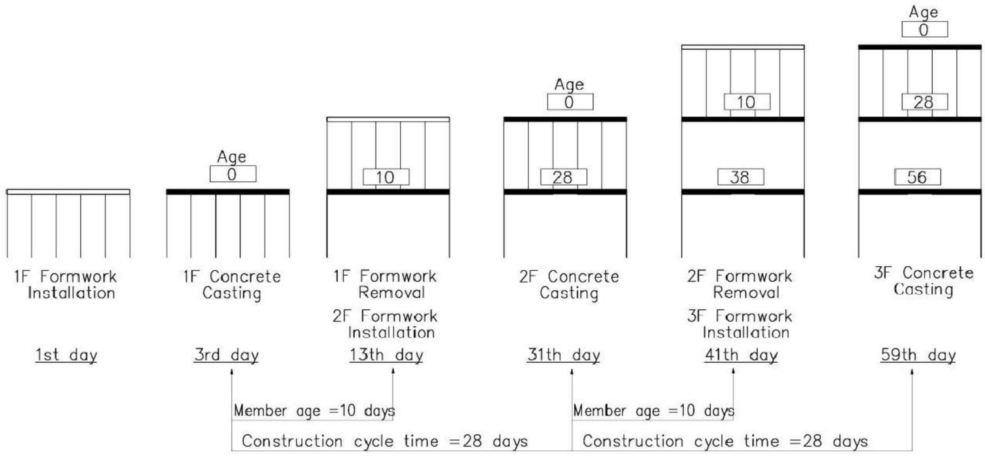


Figure 2.1: Construction Schedule of investigation models

Jayasinghe and Jayasena[4] presented a simple way of predicting the possible amounts of absolute and differential shortening in reinforced concrete wall-frame building structures. The effect of relative humidity on absolute and differential shortening of columns and core-walls was considered in study. They concluded that absolute shortening of column reduces with increase in relative humidity of the surrounding environment due to lower moisture evaporation from concrete surfaces. They showed that differential shortening between two adjacent members does not depend on the no. of stories of the building. They also suggested 10%, 17.5% and 20% reductions in shortening values can be assumed by increasing the construction rate from 7 dpf(days per floor) to 14, 21 and 28 dpf respectively. As per their analytical study, variation of the column dimensions or strength of concrete did not have much impact on absolute shortening. However, differential shortening was more sensitive to such changes.

Pan et al.[5] presented a simple procedure to predict long term shortening of concrete columns which followed the principle of incremental superposition. This method divided the whole concrete column in to no. of segments and applied the load at the intervals of time. The shortening values of each segment was then accumulated and the aggregate of the result over the intervals of time showed the good agreement with the practical measurements. The constant compressive stress at every intervals of time for each segment of columns tend to show some error in analysis results. If the column is divided into a considerably smaller segments, the assumption of constant stress may give good results with more accuracy and lesser required computing time.

Gao and Bradford[6] presented a method of analysis for the short term as well as long term response of slender R.C. columns using the Age-Adjusted Effective Modulus Method(AEMM). Stress-strain distribution on cross sections of columns and the prediction of lateral deflections caused by P - Δ effects under sustained loading was found. Also the influence of eccentricity and column length on the axial shortening predictions was studied. They concluded that eccentric loading cause the bending deformations of slender R.C. columns. The long term analysis produced final shortening values much greater than that obtained from short term analysis. In the case of section cracking with time, long term analysis results proved to be quite useful to obtain actual behavior of columns.

Mola and Pellegrini[7] discussed the effects of column shortening on construction and service life behavior of structural elements such as beams, slabs and columns. In order to simplify the complex calculations of column shortening, the author considered several assumptions such as the axial stress in the columns was not affected by variations of the stress distribution in the slabs and no interaction between the variations in the stress distribution in the various slabs. They concluded that the long term creep induced shortening values could be as high as two times of those of initial elastic deformation of columns. Their analytical study showed the resulting final moments after redistribution of forces considering the construction stage to be lower than those obtained from simple conventional static linear analysis.

Moragaspitiya et al.[8] presented a method to easily encounter the actual performance and behavior of concrete elements during and after construction of tall buildings. Author used a compact way of predicting column shortening through time history analysis using strategically located compression only/gap elements to simulate the impact of construction sequence and time based load application. They found that slip and jump forms, commonly used for core construction, increases the age difference and loading history of gravity load bearing elements on the same floor. For compressive stress due to dead load coming from top floors less than 0.5 * f_c, principle of superposition was used by the authors for the calculation of strain response showed good agreements with the test results. In case of high-rise buildings, having geometrically complex structural framing systems and irregular vertical load paths, finite element models can developed for separate floors and the dead loads of these sub models can be used to develop the finalized finite element model of whole structure.

2.3 Elastic Shortening

Lakshmi and Shanmugam[9] presented an interative method to obtain a nonlinear response of the infilled steel-concrete composite columns using moment-curvature-thrust relationships. Geometric and material nonlinearities were solved using generalized displacement control method. Analytical study was carried out on short and slender R.C. columns to investigate the influence of eccentricity considering uniaxial as well as biaxial bending. From their analytical study, moment carrying capacity of columns was found to be decreased with increased eccentricity of the load. They concluded that the concrete attains the crushing strain in compression earlier than the extreme fibre yield strain of steel in infilled steel concrete composite columns.

Kim and Shin[10] presented an analytical method to consider lumped construction sequences as shown in Fig.2.2. In this method, the effect of size of lumping in ultra tall buildings on accuracy of the sequential analysis and the time required to complete the repetitive analysis were studied. They concluded that about 1/15 of the total stories of the building could be considered as an effective size for lumping, considering accuracy of results and reduction in computing time as the accuracy achieved in this lumping size was more than 95% and reduction in the computing time was about 80 % of the total time. The method used by the authors can be implemented more effectively at the design stage of tall buildings when the data for the shortening analysis are not yet fixed and repetitive analysis is inevitable.

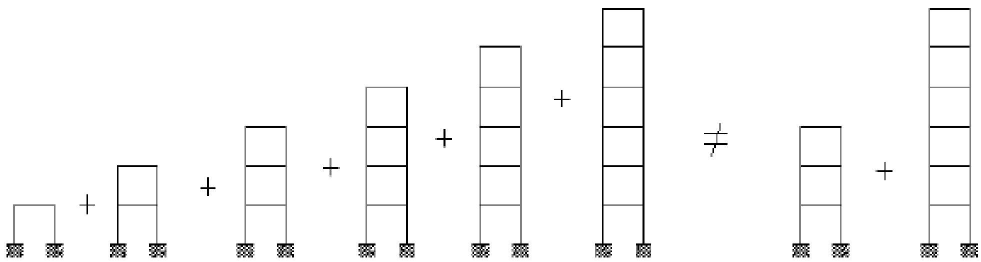


Figure 2.2: Lumped Construction Sequence of the High-Rise Building

2.4 Creep & Shrinkage

Barcelo et al.[11] discussed the causes of autogenous shrinkage of concrete by conducting experimental investigation and regression analysis on the cement paste models. The fact of the shrinkage mechanism that Autogenous shrinkage is a combined process of autogenous swelling and self-desiccation was explained by the them as shown in Fig.2.3. They explained through experimental investigation that autogenous shrinkage is the deformation occurring without moisture transfer with the environmental medium. In early stage, shrinkage of concrete governs with autogenous swelling action of concrete and goes on decreasing with time after pouring of concrete. They also suggested that sulphate to alkali ratio (SO_3/K_2O) and free lime in clinker lead to decrease in initial shrinkage and increase in initial swelling. The relative importance of swelling is stronger at the initial stage of pouring of concrete and goes on decreasing later on.

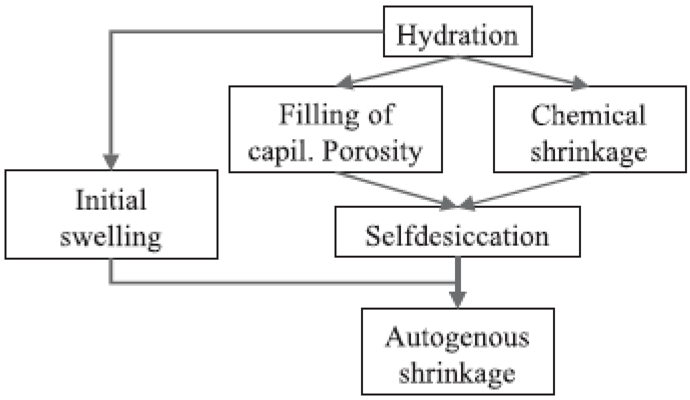


Figure 2.3: Proposed mechanism of autogenous shrinkage at early age

Maru et al.[12] presented the Consistent Procedure to take into account the sequential nature of application of dead load and simultaneous nature of application of live load as shown in fig.2.4 for determining creep and shrinkage effects in RC building frame. They suggested that shearing action of beams need to be considered for evaluation of elastic axial forces as well as redistribution of axial forces from creep and shrinkage deformations. For low beam stiffness and lower reinforcement in exterior columns, load transfer due to inelastic deformations takes place from 1st interior column to exterior column and hence differential deflection is positive. As lateral loading may cause increased reinforcement in exterior columns, the effect of stress transfer phenomena from concrete to steel demands full attention for its evaluation in free standing high-rise buildings deforming with cantilever action.

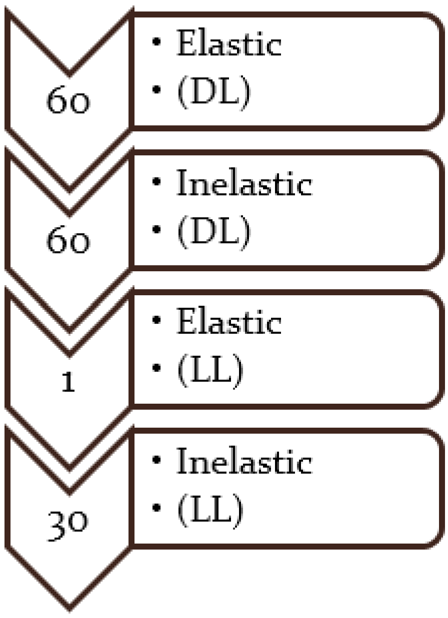


Figure 2.4: Sequence of Analysis suggested by author for 30 year considered life span

Sharma et al.[13] suggested the Simplified procedure known as AP2 for evaluating Creep and Shrinkage effects in Reinforced concrete Frames with low shear beam stiffness. This method was much more simplified than the previously discussed method CP. Studies were reported for the buildings covering range of 40/60/80 story. They discussed that the procedure (AP2) is simpler than the method suggested by Fintel and Khan:(AP1)[1] in 1969. They also concluded that the method is accurate for lower stiffness of beams as well.

Samra[14] presented a simple procedure to predict creep strain in axially loaded concrete columns. This method can be superposed with the method developed by Park & Pauley in 1975 to predict shrinkage behavior in concrete columns. The combined result of creep & shrinkage showed good agreement with the experimental and measured values. The procedure developed by him was limited to axially loaded columns only i.e. no provisions for eccentrically loaded columns was presented though the method was general and scope of this work could be expanded towards this. Effect of incremental loading was not included in this procedure to avoid extensively high or overestimated values number of input parameters were very few in the discussed method which may be readily available to design engineers at design stage.

Koutsoukis and Beasley[15] discussed the research carried out in the field of column shortening behavior of concrete columns by various researchers. Age Adjusted Effective Modulus Method (AEMM) and Effective Modulus Method (EMM) were the two methods used by researchers in their investigation. **Samra**[15] discussed the difference in procedure developed by the him and the other similar work carried out in this area of research by introducing a new equation for concrete stress which is compact and unique.

Vafai et al.[16] discussed the effect of relative humidity, rate of construction, cement types and concrete strength on axial as well as differential shortening of columns and walls. Accuracy of the various available methods to predict the creep and shrinkage effects was shown and compared with the finite element analysis results. They concluded that by increase in the relative humidity, construction rate and compressive strength of concrete, creep and shrinkage induced shortening of column decreases. They also found that higher, the rate of hardening of cement, the lower is the shrinkage strain of concrete.

2.5 Construction Rate & Sequence

Kwak and Kim[17] discussed the importance of the time dependent material properties and construction sequence in multi-storied R.C. buildings. Material nonlinearity effect was considered by including the cracking of concrete and geometric nonlinearity was considered by including P - Δ effect using stress matrices. They concluded that conventional one step analysis underestimates the structural response of building. The construction sequence and time dependent deformations due to creep and shrinkage increased the differential shortening of columns and hence material nonlinearities play an important role for the final design checks in a high-rise building structure.

Moragaspitiya et al.[18] observed that reinforcement content, variable material property, volume to surface area ratio of elements and environmental conditions influence the column shortening. They developed a numerical procedure for a 64 storey building that can accurately quantify the differential axial shortening of columns by taking into account Construction Sequence and Time dependant material Properties. The rigid outrigger system mitigates an impact of differential shortening between perimeter columns and core of the structure which is also influenced by the axial stiffness of columns in proportion to load tributary with assistance from the belt trusses.

Moragaspitiya et al.[19] presented a vibration based approach to update the axial shortening of vertical load bearing elements such as columns and core-walls in tall R.C. buildings during and after the construction. The proposed procedure to update the axial shortening values predicted at design stage can help avoiding the erroneous results and to obtain the actual and practical values of the axial shortening of columns by updating the actual flexibilities of them. **A**xial **S**hortening **I**ndex (ASI) developed by them has the ability to capture the flexibility variation and elastic deformation of vertical structural elements. They concluded that updated axial shortening during the construction are more accurate than that predicted at the design stage. They used accelerometers to access the vibration characteristics of the structural elements which avoids the need of mechanical as well as electrical strain gauges. They also suggested that updating axial shortening during and after construction of a building may provide valuable feedback to verify the actual performance in relation to the theoretical predictions.

Baker et al.[20] presented long-term construction sequence analysis procedure of the Burj Khalifa Tower. Effects considered for this sequential analysis were time dependent creep & shrinkage and construction sequence, variation of concrete stiffness with time, foundation settlements and stress transfer from rebar to concrete. The building was analyzed for 15 lumped models considering the lumping size to be $1/15^{th}$ of the total stories of the building. They suggested that for vertical compensation, modest increase in typical floor to floor height should be considered. Also for horizontal compensation, re-centering at each successive level should be done. They found that rebar attracts the additional stresses generated due to the sequential loading and transfers to the concrete. They also concluded that for 1 percent of the considered rebar reinforcement, the load to be supported by rebar and concrete is: 15% and 85% respectively.

2.6 Summary

In this chapter, review of the relevant literature is carried out. Concepts of creep, shrinkage and elastic deformation and the applicability of the prediction methods is studied. Moreover, methods to incorporate these secondary effects affecting the behavior of medium to high-rise buildings is studied. The concepts presented by various researchers help in understanding the behavior of tall reinforced concrete buildings under column shortening effect.

Chapter 3

Modeling of Construction Stage

3.1 General

Construction stage model divides a model into sub-models for each erection stage and assigns corresponding construction dead loads. The results for each stage are then superimposed to carry out the final construction stage analysis. Analysis for all remaining loads other than the construction dead loads are carried out on the basis of the one step analysis.

Modeling of construction stage includes various parameters that affects the construction of buildings, of which, important ones are:

- Construction Sequence
- Construction Rate
- Creep
- Shrinkage
- Strength of materials
- Relative Humidity

3.2 Use of ETABS

ETABS (Extended Three Dimensional Analysis of Building Systems) provides a facility to perform Construction Sequence Analysis of building. Construction Sequence Analysis is the Nonlinear Static analysis and hence time consuming and iterative in nature. Chronological order for performing construction sequence analysis is first to perform Linear static analysis and then to be followed by nonlinear construction sequence analysis.

Column sizes are determined by gravity loads. To take into account additional load increment due to wind and seismic loads, Seismic load is applied according to IS 1893:2002 Part-I considering zone 2 and medium soil condition. Wind load is calculated and applied according to IS 875: Part III to the structure considering basic wind speed as 39 m/s (i.e. Ahmadabad Region)

Lumping of floor is an important parameter to achieve a better accuracy and less time to complete an analysis. To reduce the time taken by a computer program to perform an iterative analysis lumping size can be increased from 1F up to 5F and effective size of lumping is found from various models.

Material Property, Column Sizes and Total height of the building is varied for Different Structural System e.g. Rigid frame structure and Wall-Frame Structure.

3.2.1 Modeling in ETABS

Stepwise procedure to perform Construction Sequence Analysis of a structure in ETABS Software is explained below:

Step 1: Prepare Appropriate Model and Define Static load cases.

Step 2: Define Construction Sequence Case as shown in Fig.3.1.

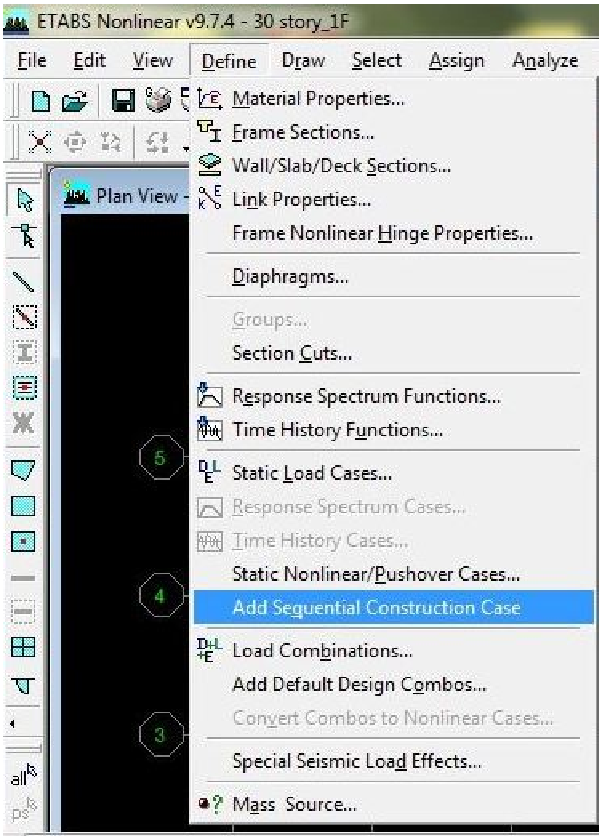


Figure 3.1: Add Construction Sequence Case

Keep the name of the case as it is **(DEAD-SQ).**

If the result of Construction Sequence is to be considered in design instead the dead load case check the box of **Replace Dead Type Cases with this Case in All Default Design Combos.** as shown in Fig.3.2.

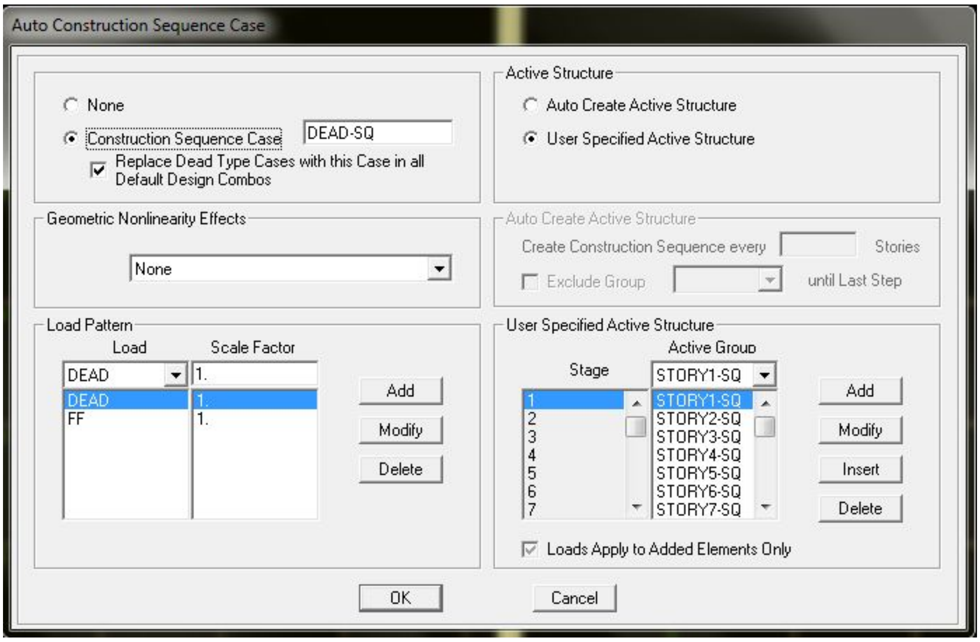


Figure 3.2: Construction Sequence Input

Step 3: From **Geometric Nonlinearity Effects** drop-down list as shown in Fig.3.3, choose **None** as it is recommended that the analysis to be performed first without P-delta.

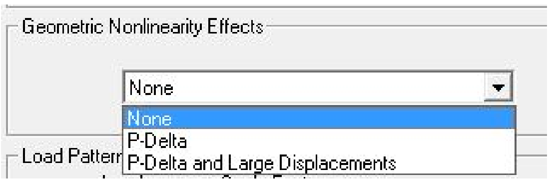


Figure 3.3: Geometric Nonlinearity

Step 4: In Load Pattern area, use the edit boxes, buttons and display lists in this area to specify the Load Pattern that will be used with the default of the program Dead load case with scale factor 1.

Step 5: From **Active Structure** option, One should choose how the structure will be defined.

Auto Create Active Structure option should be chosen if one wants to have the program automatically create the active structure to include the predefined construction sequence as shown in Fig.3.4.

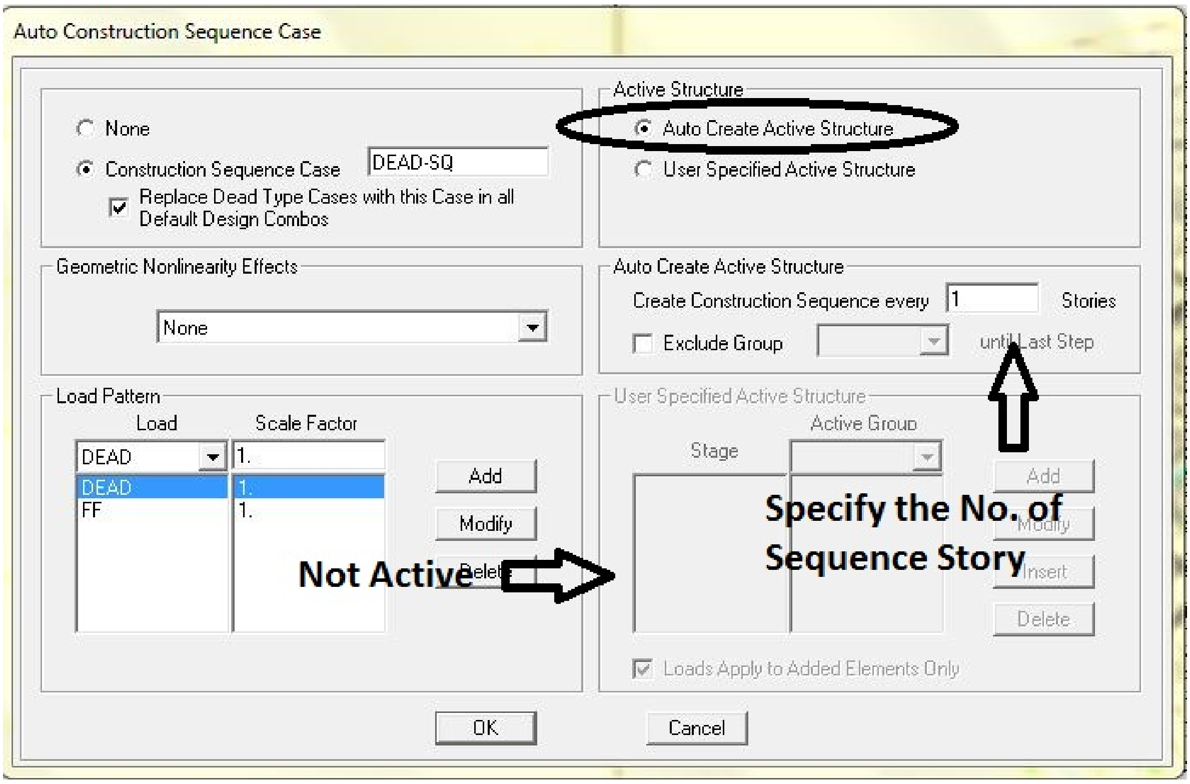


Figure 3.4: Program Generated Construction Sequence

User Specified Active Structure option should be chosen if one wants to create sequence on the basis of Story Levels (e.g., Story 1-SQ, Story 2-SQ and so on)

If the structure has different sequence of construction, make each as a group, then add in active Group cell.

Step 6: When **Loads Apply to Added Elements Only** check box is checked, the specified load pattern will be applied to the added elements only. This box usually should be checked if more than one construction stage exists as shown in Fig.3.5.

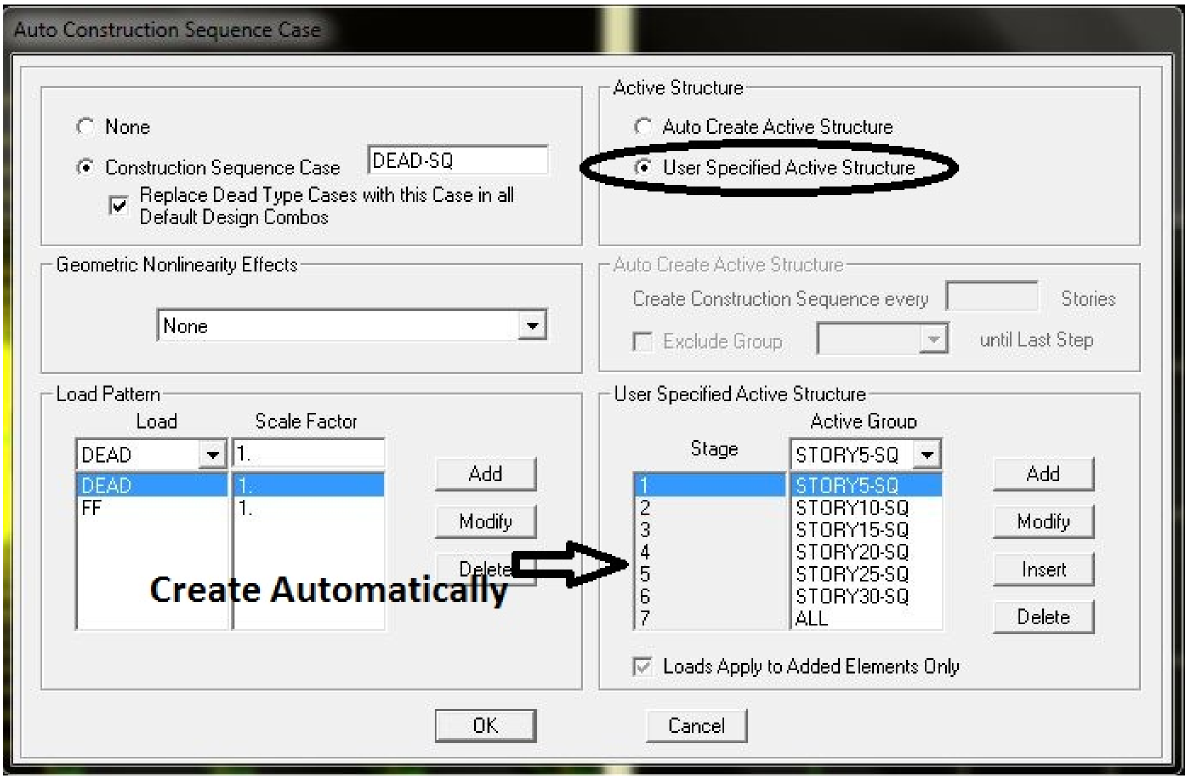


Figure 3.5: User Defined Construction Sequence

Step 7: Perform Static linear Analysis and then **Perform Construction Sequence Analysis.** from the dialogue box shown in Fig.3.6.

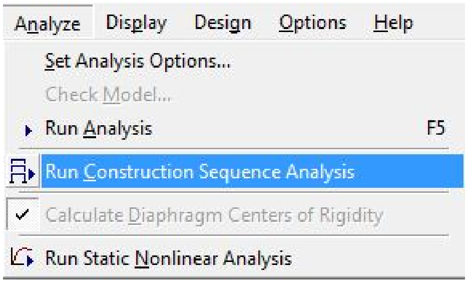


Figure 3.6: Sequential Analysis

Step 8: Check the point displacements of columns as shown in Fig.3.7 and beam forces to interpret the results.

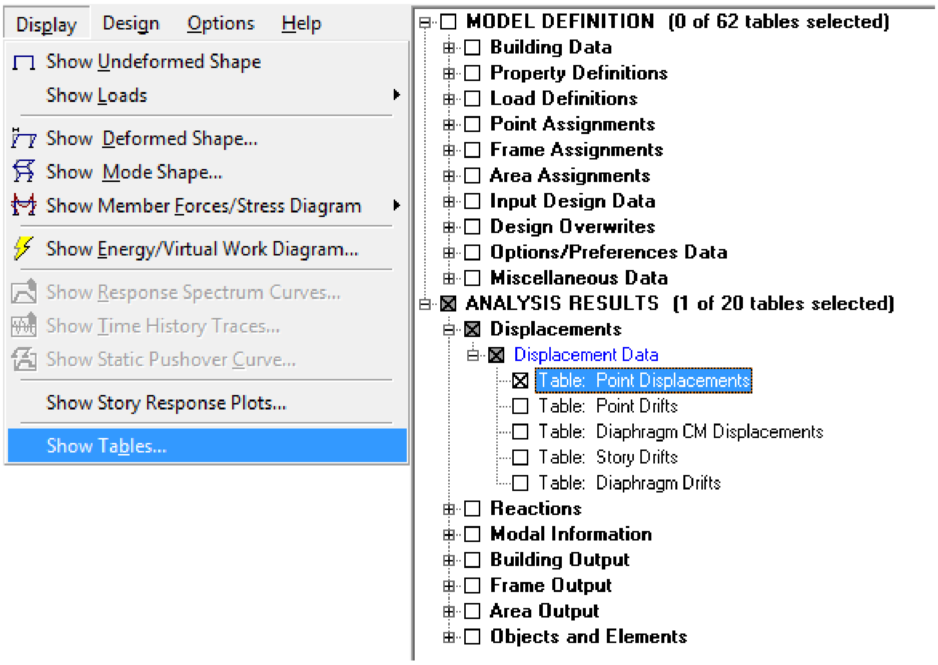


Figure 3.7: Axial Displacement of Columns

3.3 Use of MIDAS Gen

MIDAS Gen (Modeling, Integrated Design & Analysis Software) is a Three Dimensional Finite Element Analysis & Design Program for Buildings and General Structures. MIDAS Gen incorporates modeling of the various structural elements such as:

- Truss Element
- Tension-only Element (Hook and Cable function included)
- Compression-only Element (Gap function included)
- Beam Element/Tapered Beam Element
- Plane Stress Element
- Plate Element
- Two-dimensional Plane Strain Element
- Two-dimensional Axisymmetric Element
- Solid Element
- Wall Element

Defining the types of elements, element material properties and element stiffness data completes data entry for finite elements. Connecting node numbers are then specified to define the locations, shapes and sizes of elements.

3.3.1 Beam Element

Beam Elements are used to model beams and columns. Two nodes define a Prismatic/Non-prismatic, three-dimensional beam element. Its formulation is founded on the Timoshenko Beam theory taking into account the stiffness effects of tension/compression, shear, bending and torsional deformations. In the Section Dialog Box, only one section is defined for a prismatic beam element whereas, two sections corresponding to each end are required for a non-prismatic beam element. Each node retains three translational and three rotational d.o.f. as shown in Fig.3.8

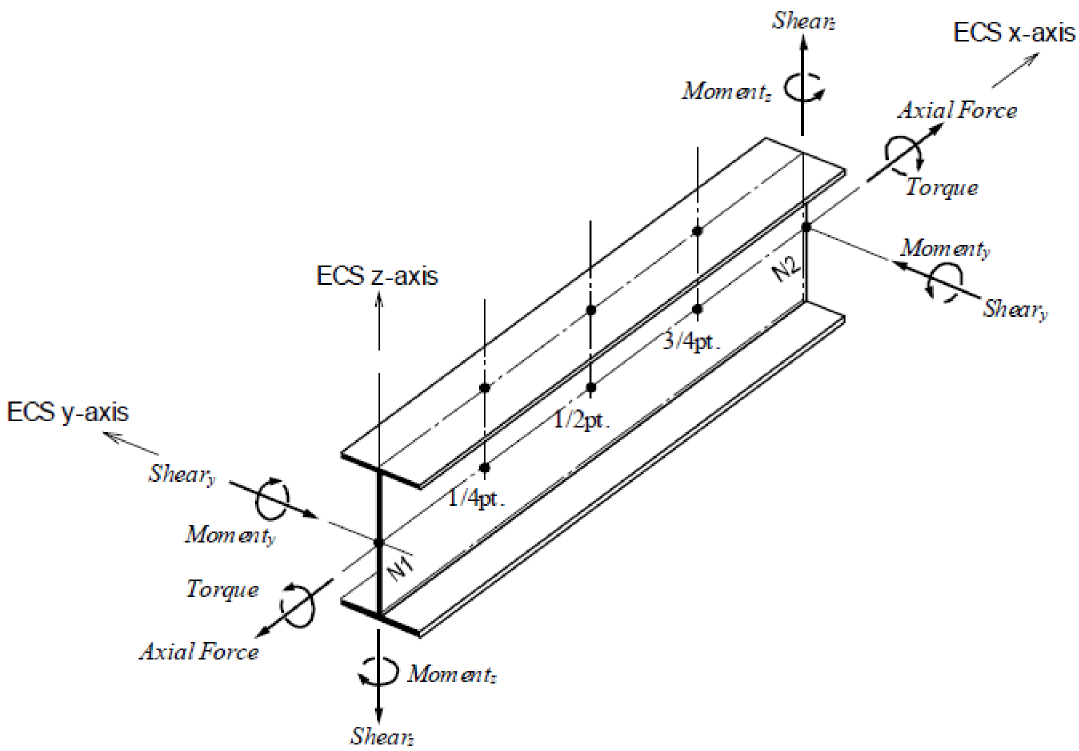


Figure 3.8: Sign convention for element forces and local axis of a beam element [29]

3.3.2 Plate Element

Plate elements are used to model floors and slabs. Three or four nodes placed in the same plane define a plate element. The element is capable of accounting for in-plane tension/compression, in-plane/out-of-plane shear and out-of-plane bending behaviors.

The out-of-plane stiffness used in MIDAS/Gen includes two types, DKT/DKQ (Discrete Kirchhoff element) and DKMT/DKMQ (Discrete Kirchhoff-Mindlin element).

DKT and DKQ are developed on the basis of a thin plate theory, i.e. Kirchhoff Plate theory. Whereas, DKMT and DKMQ are developed on the basis of a thick plate theory, Mindlin-Reissner Plate theory, which exhibits better performance for thick plates as well as thin plates by assuming appropriate shear strain fields to resolve the shear-locking problem. The in-plane stiffness is formulated according to the Linear Strain Triangle theory for the triangular element.

Separate thicknesses can be used for the calculation of in-plane stiffness and out-of-plane stiffness. In general, the thickness specified for the in-plane stiffness is used for calculating self-weight and mass. When it is not specified, the thickness for the out-of-plane stiffness will be used. The element's translational d.o.f. exists in x, y and z-directions and rotational d.o.f. exists in the x and y-axes of the Element Coordinate System (ECS). Plate element local axis and nodal forces are shown in Fig.3.9 & 3.10 respectively.

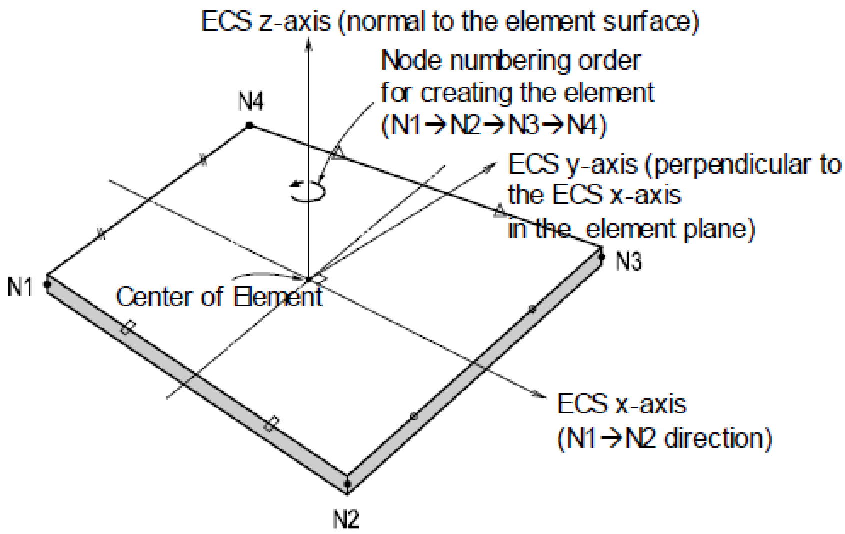


Figure 3.9: Sign convention and local axis of a quadrilateral plate element [29]

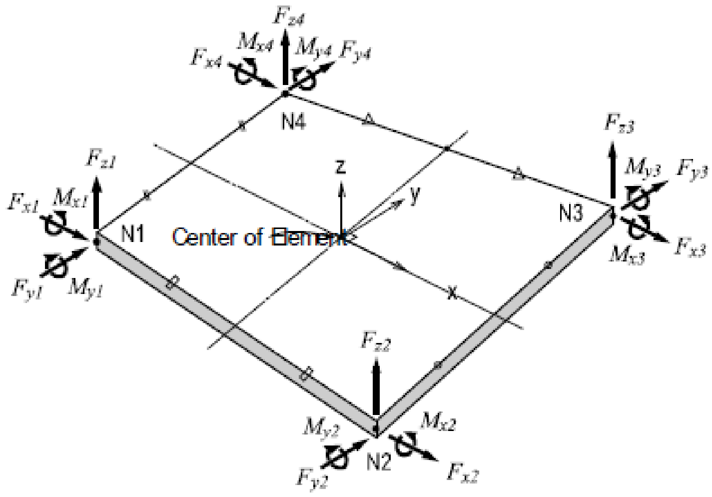


Figure 3.10: Nodal forces for a quadrilateral plate element [29]

3.3.3 Wall Element

Wall elements are used to model shear walls, which retain the shape of a rectangle or square. The direction of gravity must be set opposite to the direction of the Z-axis of Global Coordinate System (GCS). The elements retain in-plane tension/compression stiffness in the vertical direction, in-plane shear stiffness in the horizontal direction, out-of-plane bending stiffness and rotational stiffness about the vertical direction.

Two types of wall elements included in MIDAS/Gen are:

- Membrane type (in-plane stiffness + rotational stiffness about the vertical direction)

- Plate type (in-plane stiffness + rotational stiffness about the vertical direction + out-of-plane bending stiffness)

Membrane type element is generally used to model shear walls subjected to in-plane loads only. Whereas, Wall or plate type element is suitable for modeling common walls intended to resist in-plane loads as well as out-of-plane bending moments. Plate type Wall element local axis and nodal forces are shown in Fig.3.11 & 3.12

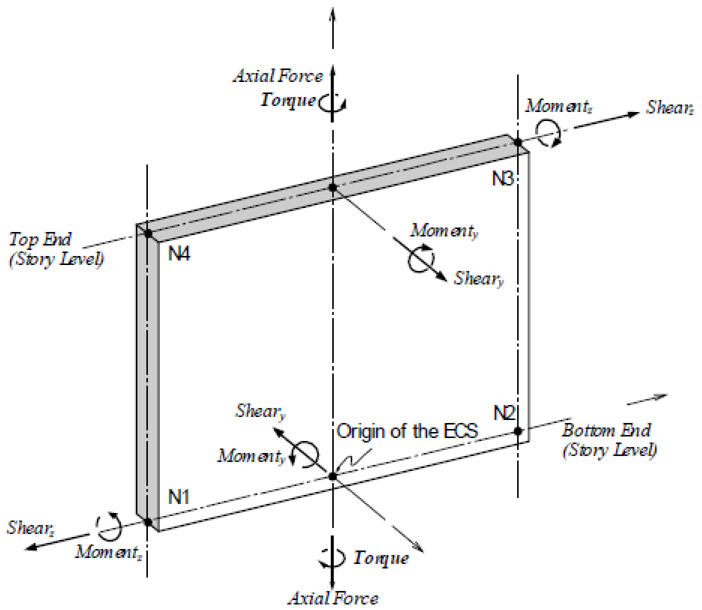


Figure 3.11: Sign convention and local axis of a wall element [29]

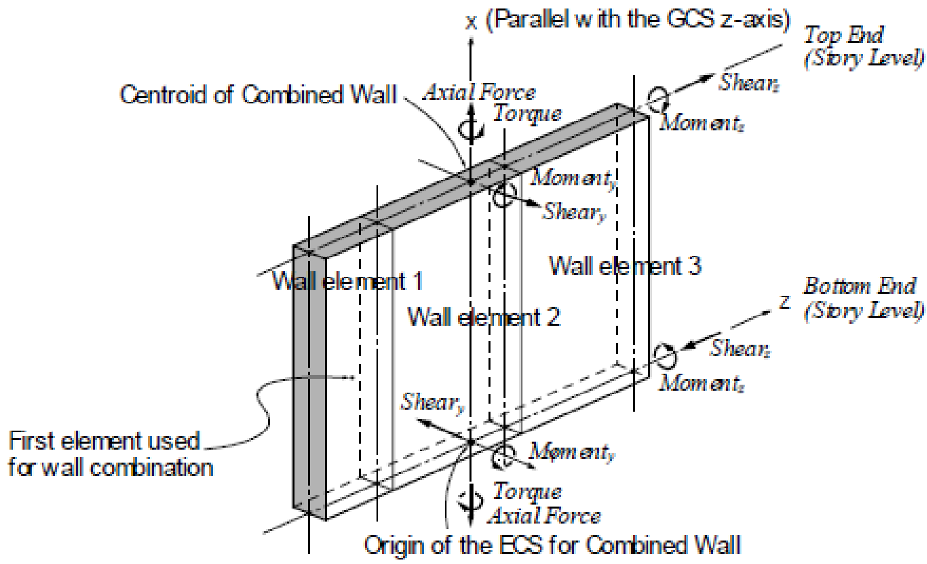


Figure 3.12: Nodal forces for a wall element [29]

3.3.4 Modeling in MIDAS GEN

Modeling in MIDAS Gen includes time dependent material properties such as Strength, Modulus of Elasticity, Creep Coefficient & Shrinkage Strain. To generate the construction sequence in MIDAS Gen, structure groups, boundary groups and load groups are required to be assigned to the building model. CEB-FIP Model Code (1990) is used to model the material nonlinearity in order to consider inelastic shortening of members.

⇒ **Strength & Elasticity**

Characteristic Compressive Strength of Cylinder is taken as 0.8 times that of Cube Characteristic Compressive Strength.

Hence, Mean Compressive Strength of Cylinder for M25 Grade of Concrete is,

$$f_{cm} = f_{ck}(cyl.) + \Delta f \tag{3.1}$$

$$= 0.8 * f_{ck}(cube) + \Delta f$$
$$= 0.8 * 25 + \Delta f$$
$$= 20 + 8$$
$$= 28\ N/mm^2$$

Time dependent strength and elasticity are calculated according to the codal provisions and assigned to the building model as shown in the Fig.3.13 & 3.14. Input parameter for strength function are given in Table 3.1 and 3.2.

Table 3.1: Required Input to Model Strength

Strength Input Parameters		
Parameter	Value	Unit
s	0.25	-
t_1	1	days

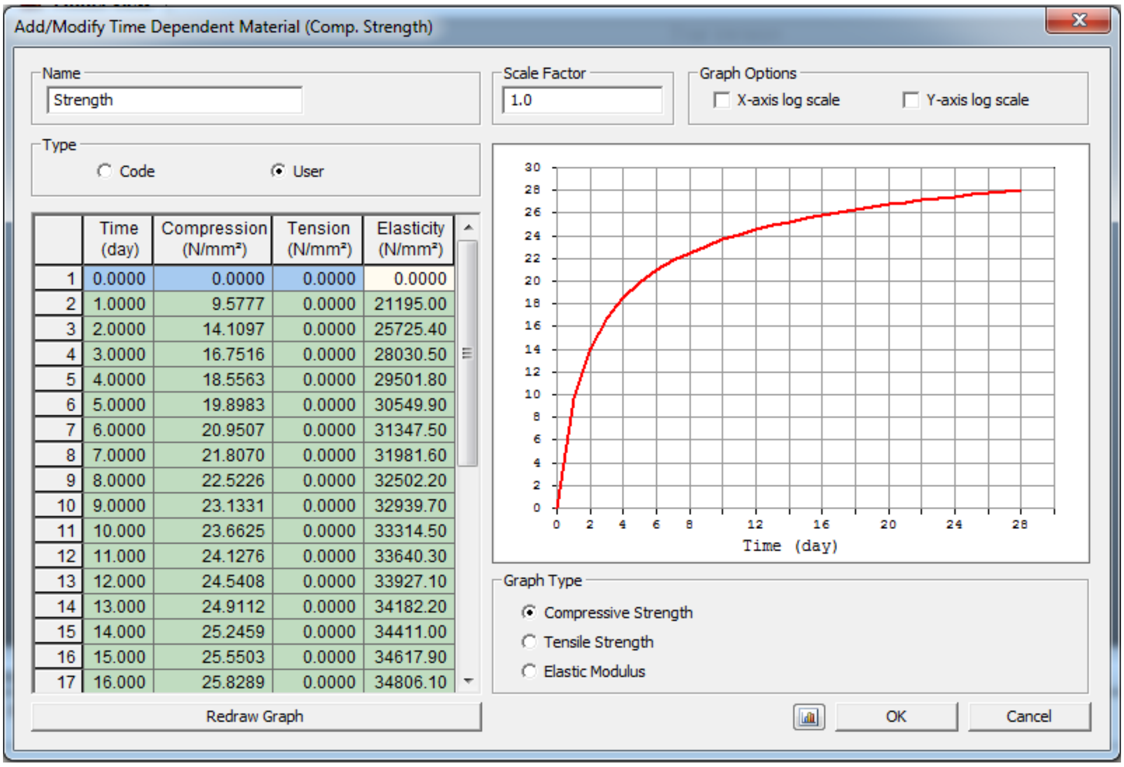


Figure 3.13: Development of Strength with Time

Table 3.2: Required Input to Model Elasticity

Elasticity Input Parameters		
Parameter	Value	Unit
Aggregate	Basalt	-
E_{co}	21500	N/mm^2

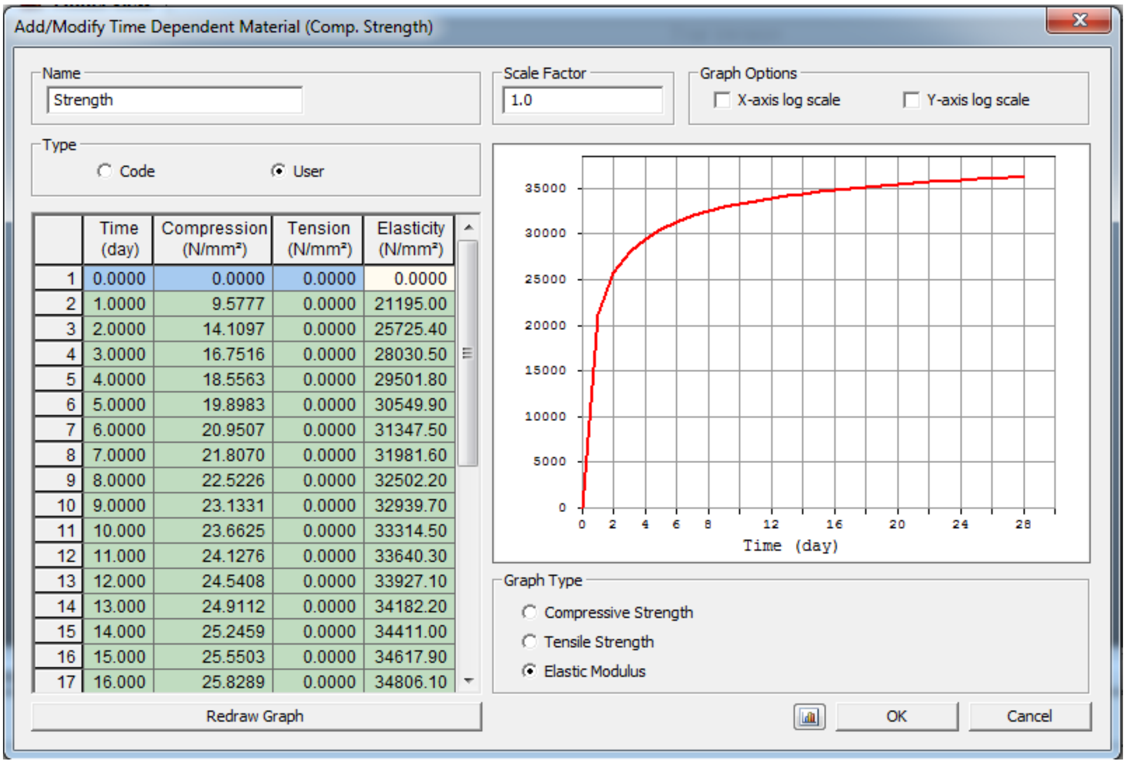


Figure 3.14: Development of Elasticity with Time

⇒ Creep & Shrinkage

Creep Coefficient and Shrinkage Strains calculated according to the codal provisions and applied to the building model as shown in Fig.3.15, 3.16 & 3.17. Input parameters for creep and shrinkage functions are given in Table 3.3 and 3.4.

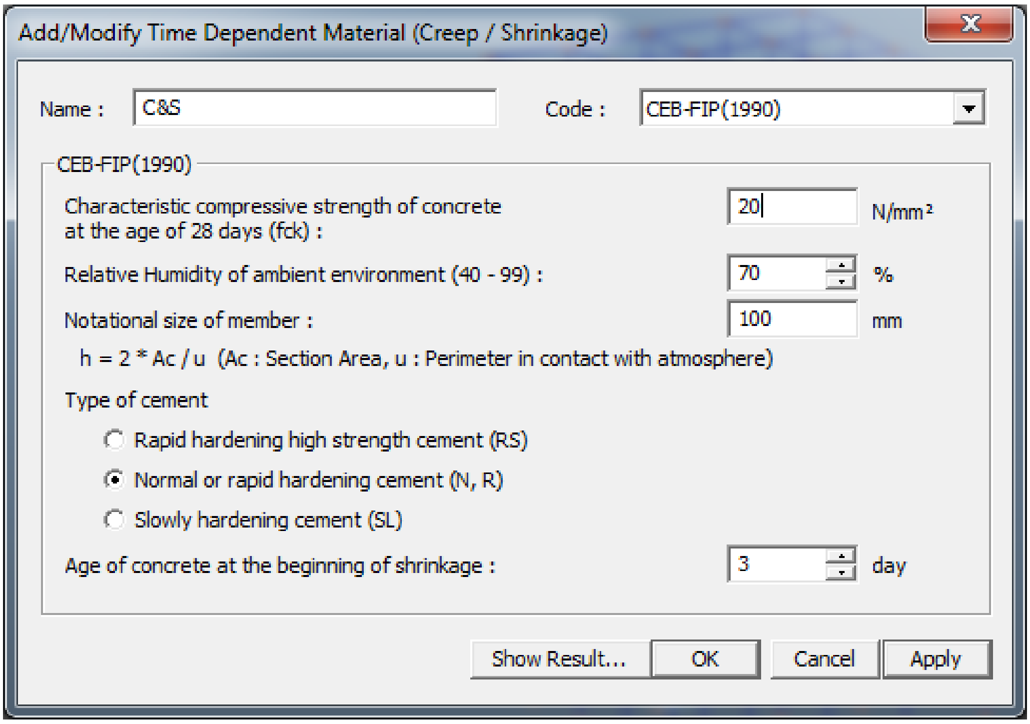


Figure 3.15: Creep & Shrinkage function definition

Table 3.3: Required Input to Model Creep Coefficient

Creep Input Parameters		
Parameter	Value	Unit
RH	70	%
RH_0	100	%
h_0	100	mm
h_b	176.47	mm
h_c	500	mm
h	100	mm
t_1	1	days
f_{cmo}	10	N/mm^2
$f_{ck(cube)}$	25	N/mm^2
t_0	10	days

Table 3.4: Required Input to Model Shrinkage Strain

Shrinkage Input Parameters		
Parameter	Value	Unit
t_S	3	days
ßsc	5	-

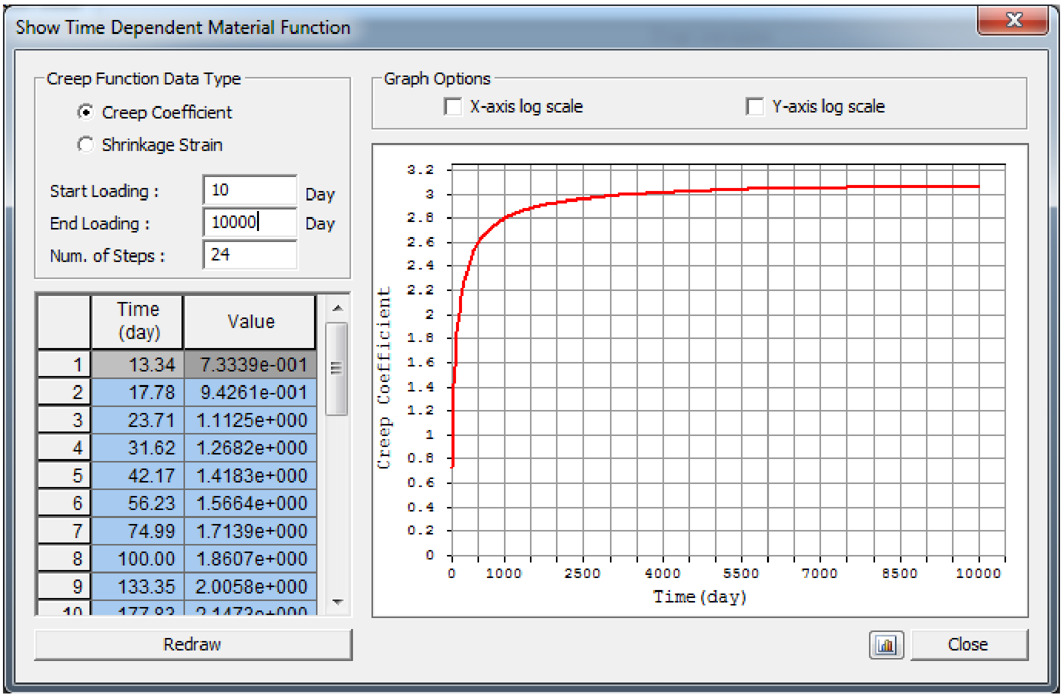


Figure 3.16: Variation of Creep Coefficient with time

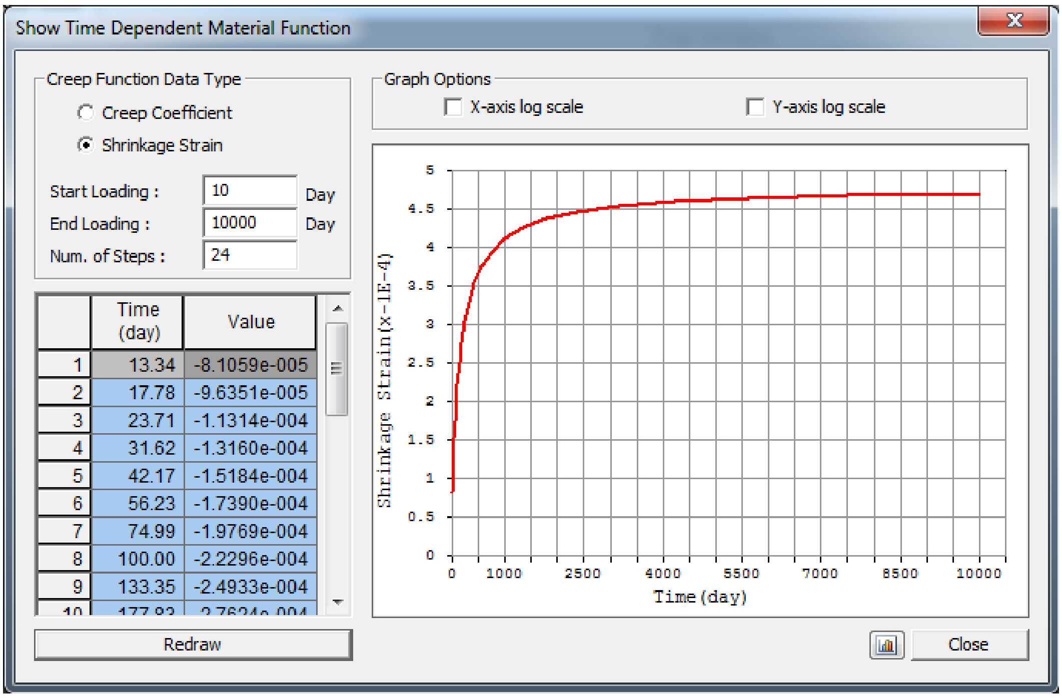


Figure 3.17: Variation of Shrinkage Strain with time

⇒ Construction Sequence

To model the construction sequence in MIDAS Gen, a model is divided into sub models for each construction stage. Here, for example, 10 story(G+9) building is assumed and the required Structure Groups as shown in **Fig.3.18**, Boundary Groups as shown in **Fig.3.19** and Load Groups as shown in **Fig.3.20** are assigned to the building model.

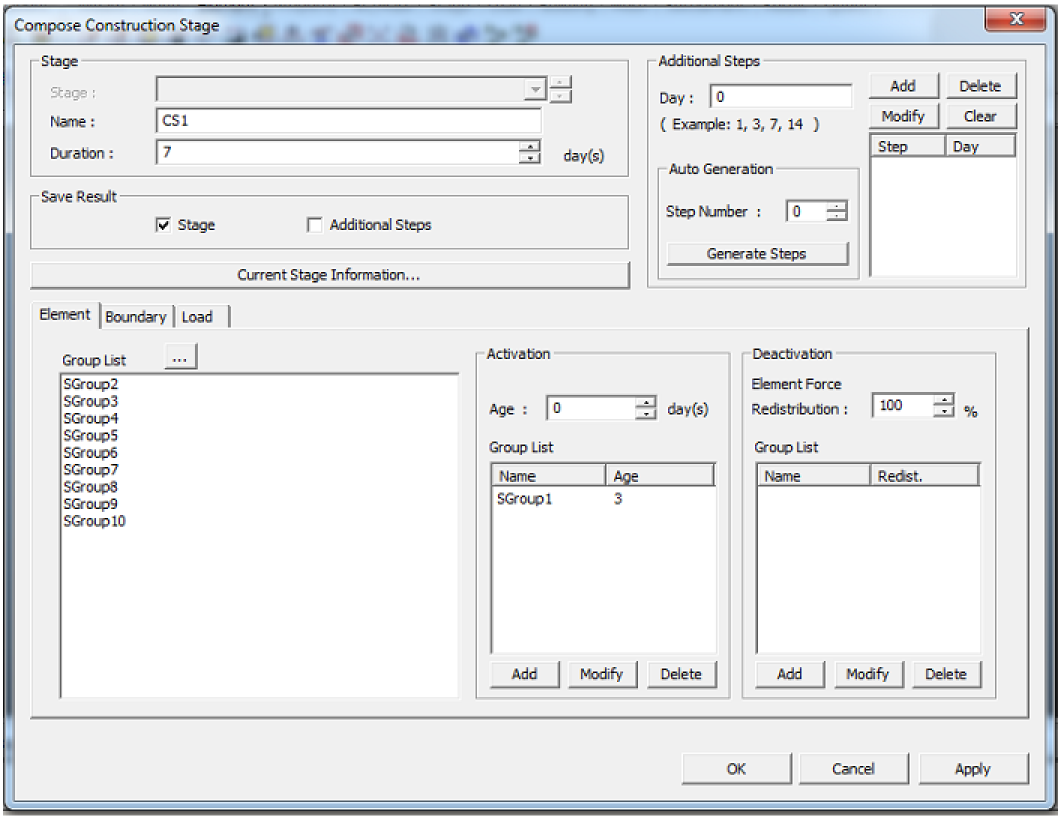


Figure 3.18: Structure Groups Assigned to Model

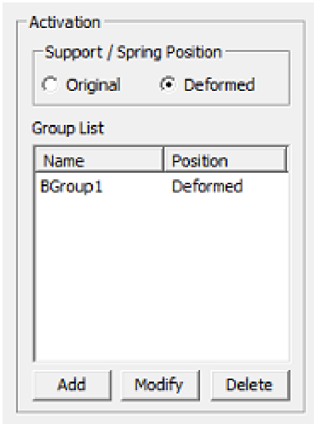


Figure 3.19: Boundry/Support Groups Assigned to Model

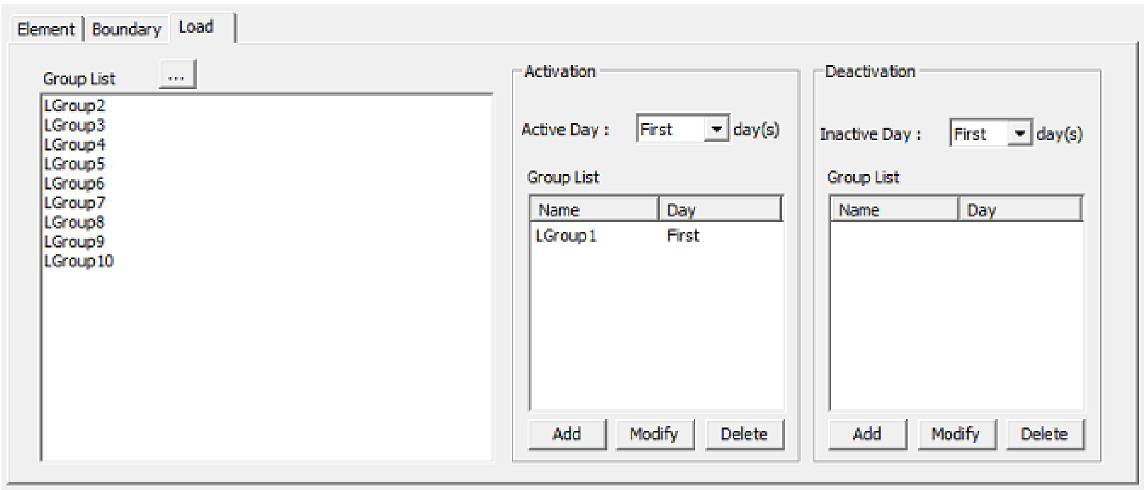


Figure 3.20: Load Groups Assigned to Model

3.4 Summary

Construction stage analysis procedure is discussed in this chapter, by incorporating the numerical model and methodology. Application of the finite element computer programs such as ETABS & MIDAS Gen in the column shortening prediction is presented. Application of the CEB-FIP model code to model time dependent material properties such as creep, shrinkage & strength functions is presented. Methodology to incorporate the construction sequence effect in building structures to perform the construction stage analysis is also discussed in this chapter.

Chapter 4

Elastic Shortening Analysis

4.1 General

During construction of high rise buildings, the vertical elements are subjected to a number of load increments. Each load increment causes elastic shortening of columns and shear walls. In high rise buildings, design of some of the columns is governed by gravity and lateral load requirements, whereas some other columns are designed for gravity loads with different tributary areas. This means that adjacent columns may have different percentages of reinforcement which carry different axial loads and have different volume to surface ratios. As a result, differential axial shortening, which is the relative movement between adjacent vertical members occurs in these structural members.

Focus of the investigation is 10, 20 & 30 storied Rigid Frame buildings. To perform column shortening analysis of building models, finite element computer program ETABS (Extended Three Dimensional Analysis of Buildings) is used. ETABS divides a model into sub models for each construction stage considering lumping of floors. The size of lumping is increased from **One Floor**, up to **Five Floor** lumping in order to save the time required in the iterative analysis and to achieve the accuracy in results. Elastic shortening effect is considered to carry out the sequential analysis. Material properties, Column sizes and height of building are varied.

4.2 Buildings Configuration

Schematic floor plan of the rigid frame building models is shown in the Fig.4.1. Column sizes are decided by considering the gravity load with the arbitrary increment due to lateral loads. Two set of member sizes are considered for analysis to understand the effect of cross sectional area of column on column shortening. The member sizes considered for analysis are shown in Table 4.1 & 4.2. Beam sizes and slab thickness are kept same but column sizes are different.

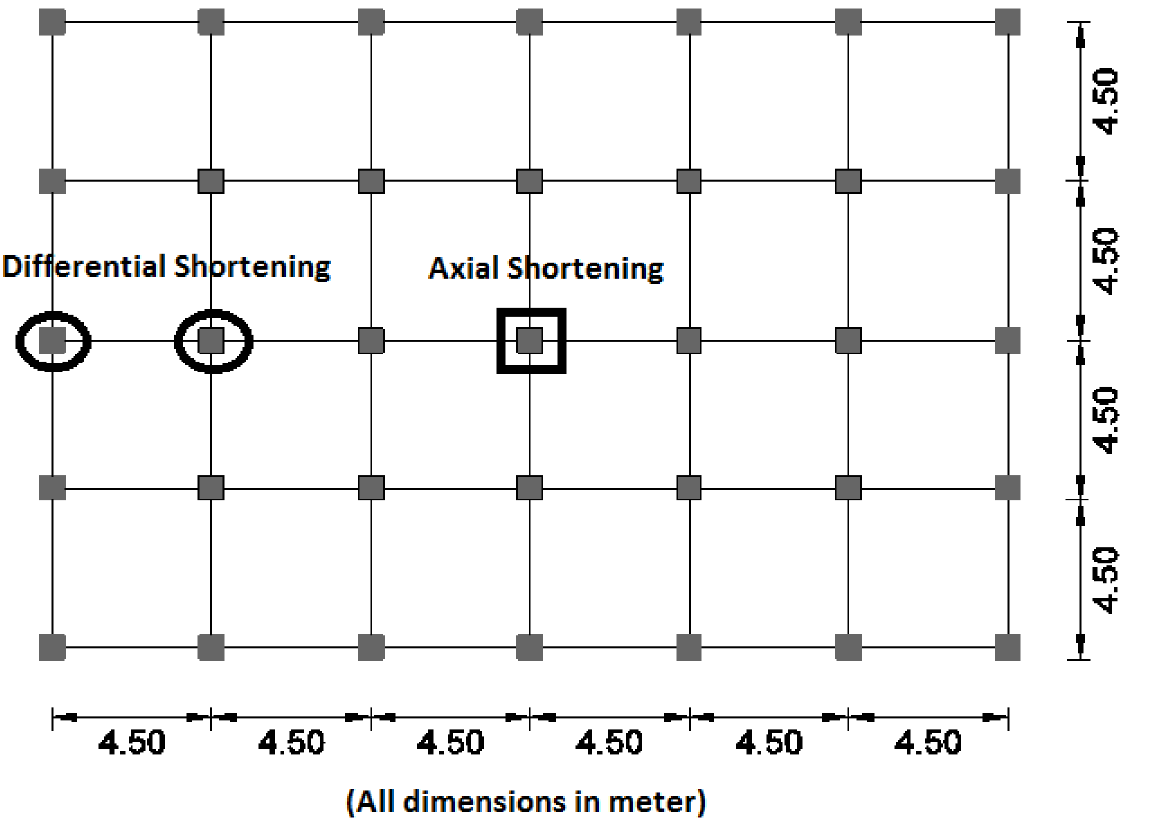


Figure 4.1: Schematic floor Plan of 10, 20 & 30 Story building models

Table 4.1: Structural element sizes (smaller size of column)

No. of Story	10	20	30
Beam (mm)	250 x 600	250 x 600	250 x 600
Column (mm)	450 x 450	750 x 750	1200 x 1200
Slab thickness (mm)	150	150	150
Story Height (m)	3.2	3.2	3.2

Table 4.2: Structural element sizes (larger size of column)

No. of Story	10	20	30
Beam (mm)	250 × 600	250 × 600	250 × 600
Column (mm)	600 × 600	1000 × 1000	1450 × 1450
Slab thickness (mm)	150	150	150
Story Height (m)	3.2	3.2	3.2

Axial shortening of column at the center of the building is considered, because central column is subjected to maximum axial force. The column marked with Square in Fig.4.1 is considered to compare the axial shortening. For differential axial shortening between adjacent columns, it is found that exterior column and first interior column along the longer lateral side of building shows maximum differential axial shortening. Columns marked with Circles in Fig.4.1 are considered to compare differential axial shortening. For sequential analysis, Concrete Grade M25 and Dead loads which includes Self Weight and Load due to Finishes of 1.5 kN/m^2 are considered.

4.3 Effect of Column Cross Section

Column cross sectional area is increased for investigation and its effect on axial as well as differential axial shortening is presented in Table 4.3 & 4.4 and Fig.4.2 & 4.3. Analysis results are obtained by considering only dead loads. Analysis results in terms of axial load considering One Step Analysis (OSA) Sequential Analysis, maximum axial shortening of central column marked with square and maximum differential axial shortening of adjacent columns marked with circle in Fig.4.1 are presented.

Table 4.3: Analysis results with smaller cross section of columns

Number of Story	10	20	30
Column Sizes (mm)	450x450	750x750	1200x1200
Axial Force - OSA (kN)	1555.36	3039.64	6670.17
Sequential Axial Force (kN)	1563	3114.20	6776.97
Axial Shortening (mm)	2.96	3.85	4.77
Diff. Shortening (mm)	0.99	0.71	0.62

Table 4.4: Analysis results with larger cross section of column

Number of Story	10	20	30
Column Sizes (mm)	600x600	1000x1000	1450x1450
Axial Force - OSA (kN)	1677.97	3794.88	8324.17
Sequential Axial Force (kN)	1685.55	3842.71	8402.39
Axial Shortening (mm)	1.79	2.69	4.07
Diff. Shortening (mm)	0.56	0.47	0.48

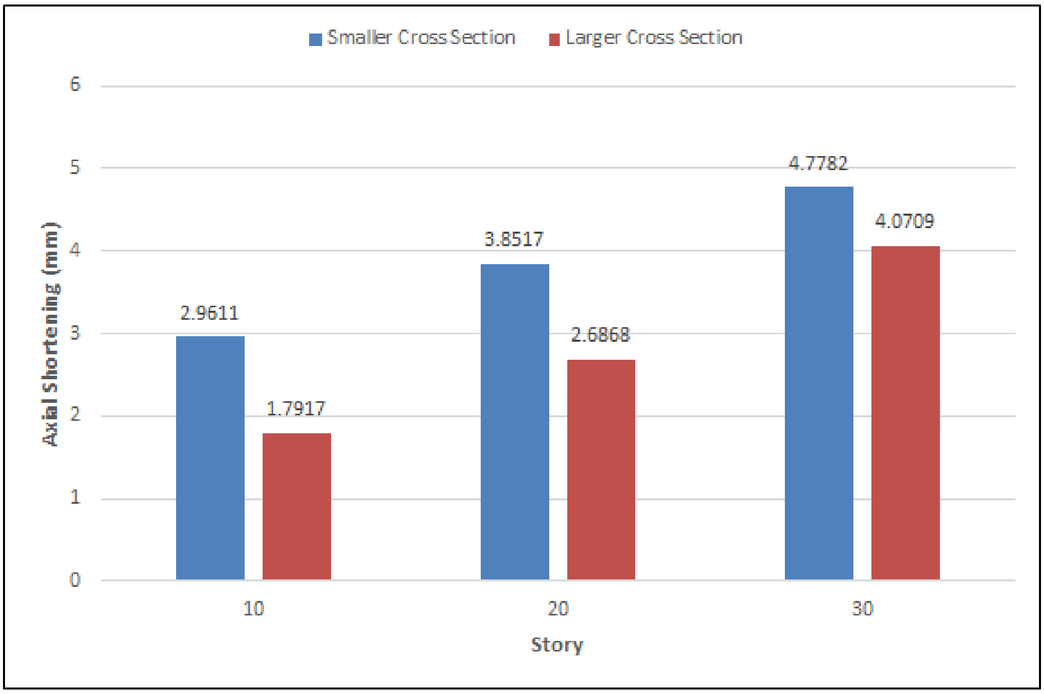


Figure 4.2: Effect of column cross section on axial shortening

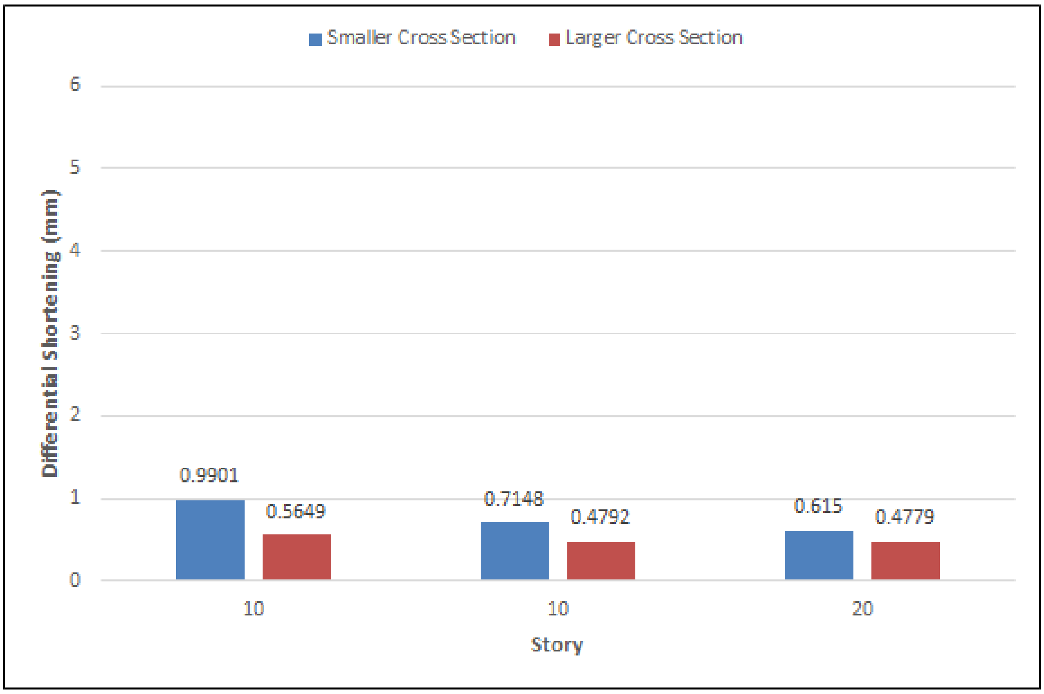


Figure 4.3: Effect of column cross section on differential shortening

From the analysis results shown in Fig.4.2 and 4.3, it is observed that, with increase in cross sectional area of column, axial as well as differential axial shortening of column reduces. Effect of column cross section reduces with the increasing building height and the number of stories in the building.

4.4 Effect of Lumping of Floors

Lumping of number of floors indicates that the dead load of floors considered for lumping are assumed to act at a time. Effect of lumping of different number floors on axial as well as differential shortening along the height of the buildings is shown in Fig.4.4 to 4.9. Axial shortening of central column with Square Mark, as shown in Fig.4.1, is presented, while differential axial shortening of columns with Circular Mark, as shown in Fig.4.1, is presented. OSA means One Step Analysis and 1F to 5F represents One Floor to Five Floor lumping in sequential analysis.

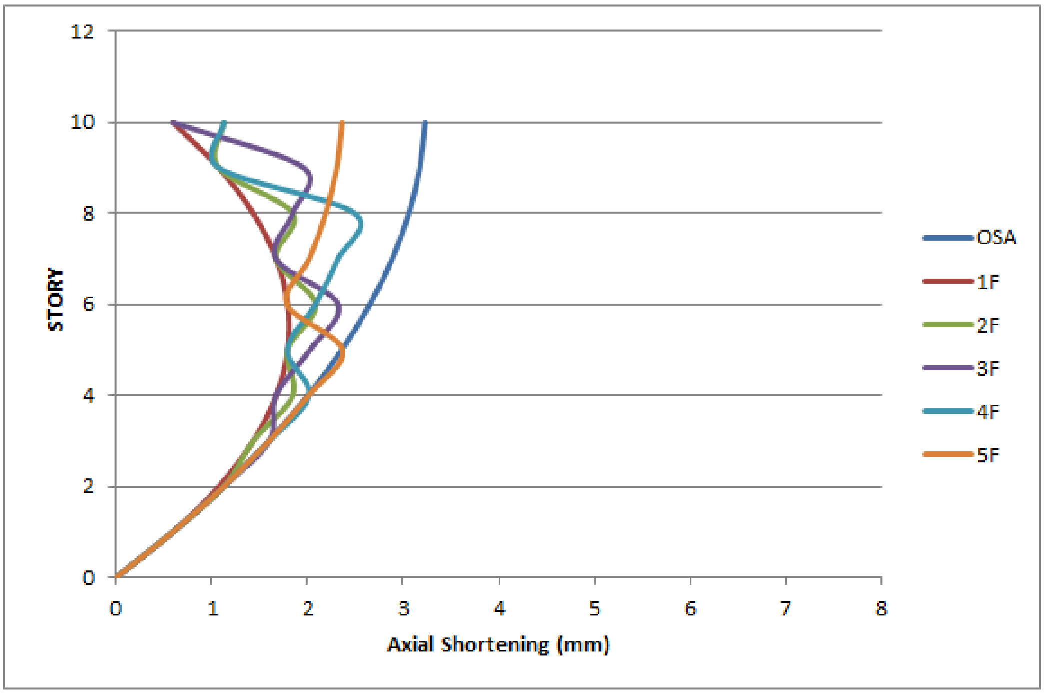


Figure 4.4: Axial Shortening of Column in 10 Story Building

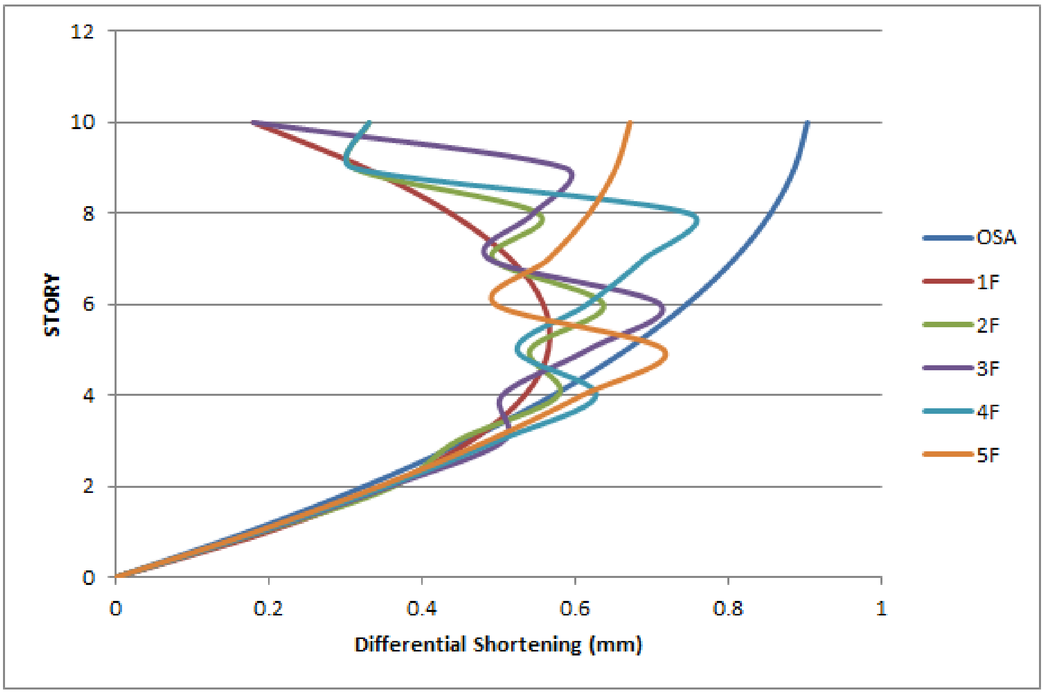


Figure 4.5: Differential Shortening of Columns in 10 Story Building

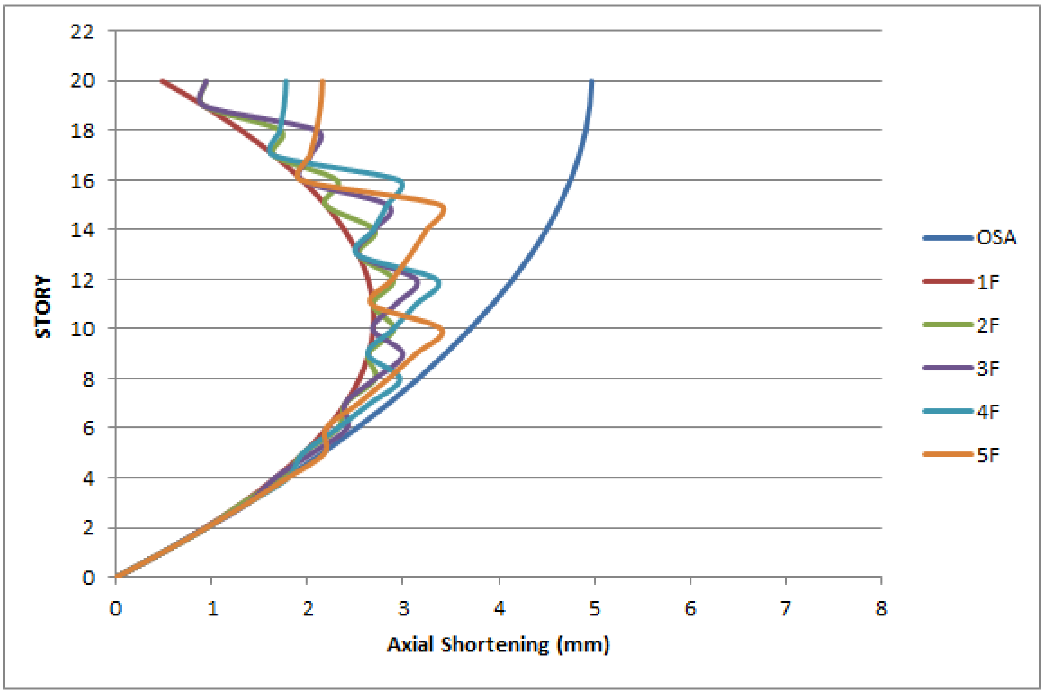


Figure 4.6: Axial Shortening of Column in 20 Story Building

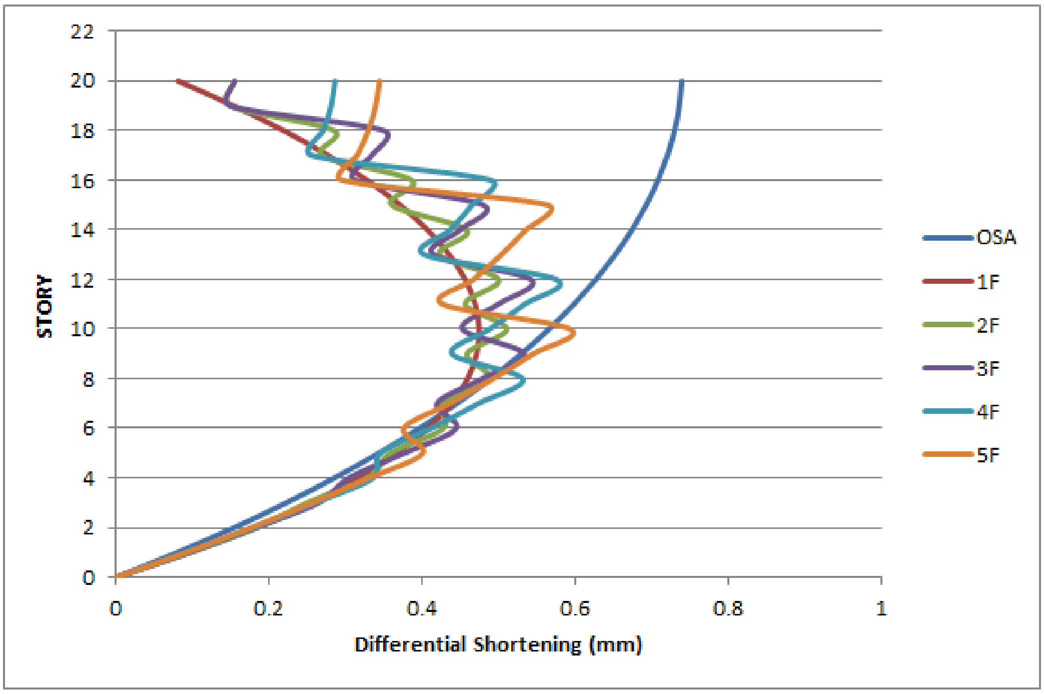


Figure 4.7: Differential Shortening of Columns in 20 Story Building

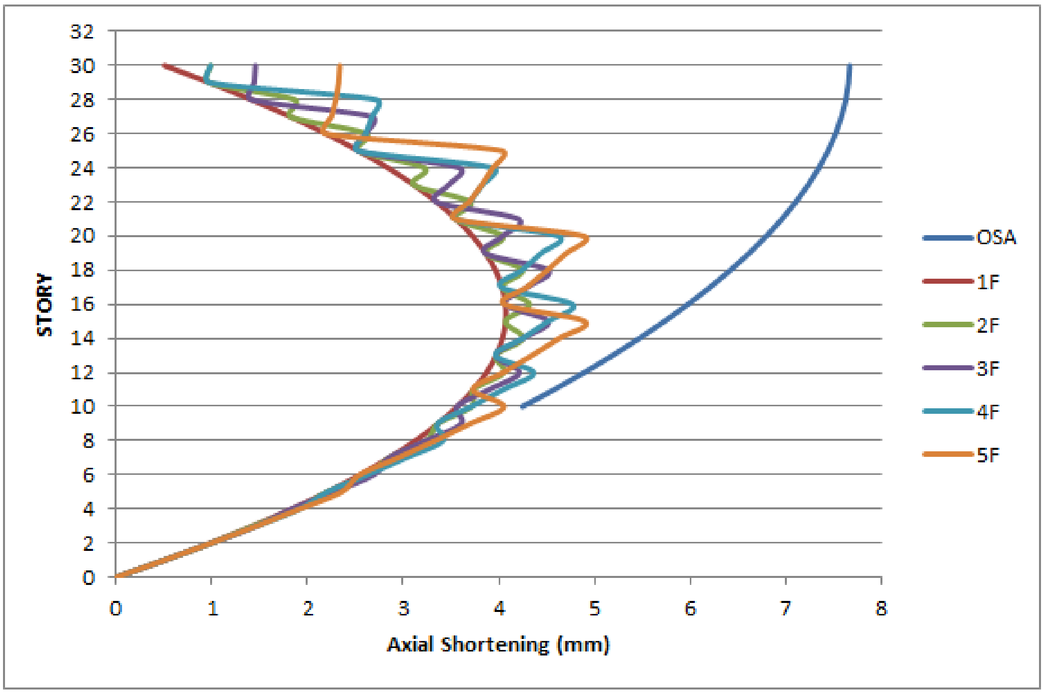


Figure 4.8: Axial Shortening of Column in 30 Story Building

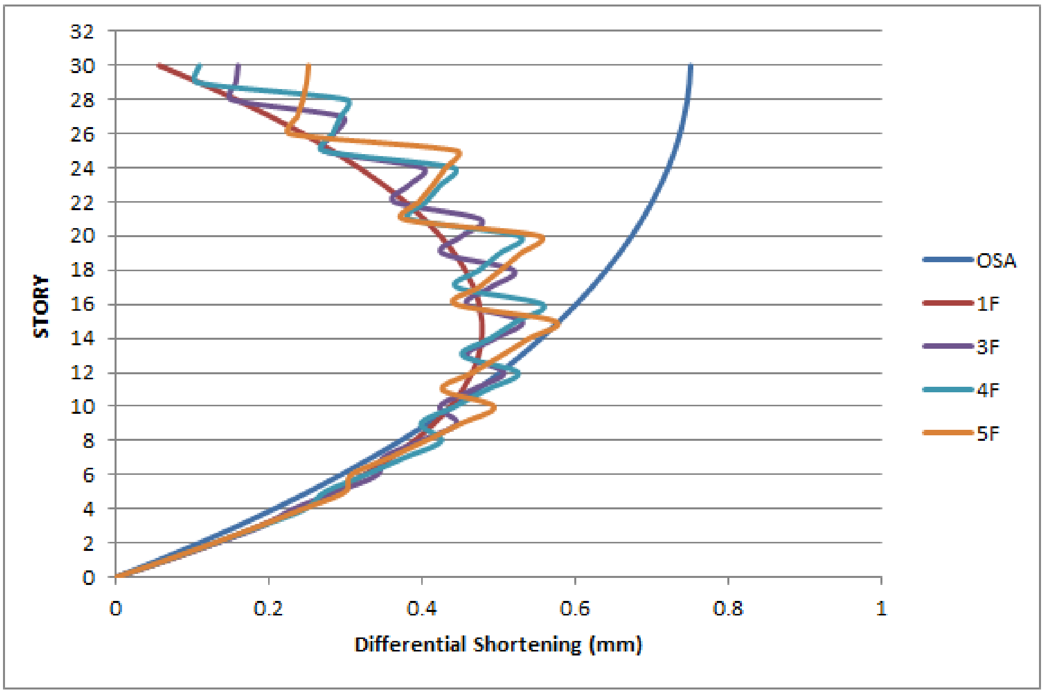


Figure 4.9: Differential Shortening of Columns in 30 Story Building

4.5 Results and Discussion

In rigid frame structures, effect of **cross sectional area of columns** on axial as well as differential axial shortening is studied and the results are presented in Table 4.5. In this study, column sizes shown in Table 4.1 and 4.2 are considered.

Table 4.5: Effect of column cross section on column shortening

Number of Story	10	20	30
% Change in Column Cross Sectional Area	+77.77	+77.77	+46.00
% Change in Axial Shortening	-39.49	-30.24	-14.80
% Change in Differential Shortening	-42.95	-32.96	-22.29

Analysis results presented in Table 4.5 include percentage change in maximum axial shortening and maximum differential shortening of columns when compared with the percentage increase in the cross sectional area of column.

Effect of the **change in size of lumped floor mass** is studied and the results are presented in Table 4.6, 4.7 and 4.8. Lumping sizes considered are varied from 1F, 2F, 3F, 4F, to 5F. Element sizes shown in Table 4.1 are considered for analysis.

Table 4.6: Effect of Lumped Mass Models in 10 Story Building

Number of Floors	Sequential Axial Dead Load (kN)	Axial Shortening (mm)	Differential Shortening (mm)
1	1685.55	1.79	0.56
2	1685.21	2.01	0.63
3	1684.93	2.32	0.71
4	1684.43	2.49	0.75
5	1682.04	2.57	0.78

Table 4.7: Effect of Lumped Mass Models in 20 Story Building

Number of Floors	Sequential Axial Dead Load (kN)	Axial Shortening (mm)	Differential Shortening (mm)
1	3842.71	2.69	0.47
2	3839.17	2.90	0.51
3	3836.58	3.14	0.54
4	3832.71	3.35	0.58
5	3829.60	3.40	0.59

Table 4.8: Effect of Lumped Mass Models in 30 Story Building

Number of Floors	Sequential Axial Dead Load (kN)	Axial Shortening (mm)	Differential Shortening (mm)
1	8402.39	4.07	0.47
2	8398.65	4.31	0.50
3	8395.06	4.51	0.53
4	8392.50	4.77	0.56
5	8388.04	4.90	0.57

Analysis results presented in Table 4.6, 4.7 & 4.8 include maximum values of sequential axial load due to dead load, maximum axial shortening of column and maximum differential shortening of column with different number of lumping.

Table 4.9, 4.10 and 4.11 show the percentage error in axial shortening and differential shortening when different floor lumping is considered in comparison of floor lumping sequence.

Table 4.9: Different Lumped Sequence in 10 story Rigid Frame Structure

Floor Sequence	Error in Axial Shortening	Error in Diff. Shortening
1F-2F	16.35%	12.71%
1F-3F	29.45%	25.83%
1F-4F	39.09%	32.47%
1F-5F	43.18%	37.30%

Table 4.10: Different Lumped Sequence in 20 story Rigid Frame Structure

Floor Sequence	Error in Axial Shortening	Error in Diff. Shortening
1F-2F	7.96%	7.61%
1F-3F	16.725%	14.28%
1F-4F	24.63%	21.27%
1F-5F	26.37%	25.05%

Table 4.11: Different Lumped Sequence in 30 story Rigid Frame Structure

Floor Sequence	Error in Axial Shortening	Error in Diff. Shortening
1F-2F	06.08%	05.31%
1F-3F	10.97%	10.96%
1F-4F	17.07%	16.46%
1F-5F	20.27%	20.00%

From the analysis results of present study, following observations are made:

- Axial and differential shortening of columns decreases by 50% with increase in the column cross sectional area by 100%, approximately, as larger column cross section helps transferring the compressive stresses along the vertical load path. Moreover, the effect of column cross section on column shortening goes on decreasing with the increasing building height.

- Static linear analysis assumes the whole mass of the building to be lumped at once whereas in construction stage analysis which is a nonlinear iterative analysis, the building is lumped into various number of floors or elements. By decreasing the size of lumping up to One Floor Lumping (1F), increases the accuracy of the results and show the realistic response of the structure to gravity loadings.

- Decreased lumped floor mass increases the time to perform an iterative analysis but eliminates the possible error in the column shortening evaluation.
- The error in the column shortening analysis results decreases with the increasing height of the building. Due to increased height, vertical load path to transfer the axial load increases, which eventually decreases the error in the analysis results.
- Two floor lumping (2F) is an effective lumping size which gives the accuracy of the results as high as 95 % and reduces the time required to complete the iterative analysis.

4.6 Summary

In this chapter, effect of column cross section and lumping of floor mass on axial as well as differential shortening of columns is studied. Columns with larger cross sectional area reduce the resultant differential shortening of columns. Linear static analysis considers the whole mass of the building to act at a time, whereas in construction sequence analysis, the building is divided in to the desired number of floor lumping. The increased size of lumped floor mass could reduce the time required to perform nonlinear iterative analysis in ETABS. Reduced size of lumping could increase the accuracy of the analysis results. Lower number of floor lumping reflect the actual loading condition as the actual construction on site.

Chapter 5

Inelastic Shortening Analysis

5.1 General

To predict the strength and serviceability of the high-rise reinforced concrete structures, appropriate description of the material properties along with the time dependent strains of concrete is required. The prediction of inelastic strains such as creep and shrinkage is important to assess the risk of concrete deflection and cracking. Among the time-dependent material properties of concrete that are of interest to the structural engineers are the shrinkage due to self-desiccation(cement hydration), loss of moisture to the environment and creep under sustained loadings. While there is a lot of data available on shrinkage and compressive nature of creep, very few data are available for creep recovery, and very limited data are available for relaxation and tensile creep under environmental effect.

In this chapter, effect of time dependent creep, shrinkage and elastic shortening on behavior of reinforced concrete high-rise building design is studied by conducting the parametric study. The parameters considered for the present study are **Construction Rate** and **Relative Humidity** in order to capture the realistic time dependent material response in the Rigid Frame and Wall-Frame Buildings of varying height.

5.2 CEB MC90-99 Prediction Model

In 1990, CEB presented a model for the prediction of creep and shrinkage in concrete. The model is revised in 1999(CEB 1999) and published as a first complete draft in 2010 [24] to include normal and high strength concrete structures and to separate the total shrinkage into its autogenous and drying shrinkage as shown in Fig.5.1. The revised model for the drying shrinkage component is closely related to the approach in CEB MC90 [23] as shown in Fig.5.1. The CEB models do not require any information regarding to the duration of curing and curing condition. The correction term used for relative humidity in the creep equation is extremely sensitive to any variation in relative humidity of the environment.

The method requires the following details:

- Age of concrete when drying starts, usually taken as the age at the end of moist curing
- Age of concrete at loading
- Concrete mean compressive strength at 28 days
- Relative humidity
- cement type
- effective size of member

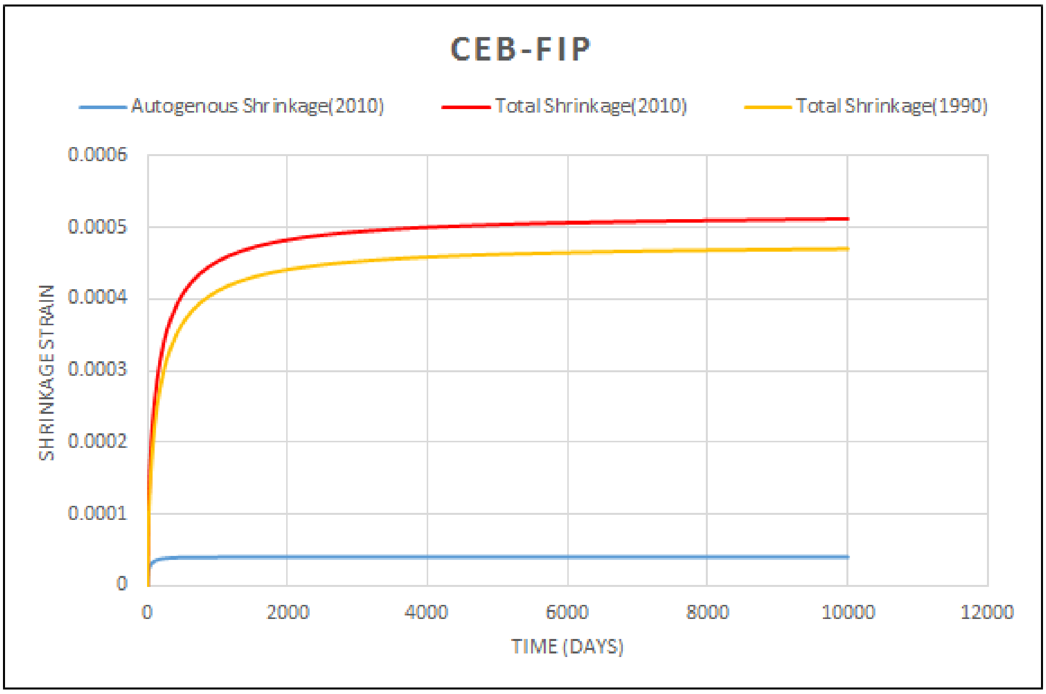


Figure 5.1: Components of total shrinkage

The shrinkage model does not respond well to early age extrapolation due to omittance of autogenous shrinkage in CEB MC90 model. The other prediction models available are **ACI 209R-92 model**, **Bazant-Baweja B3 model** and **Gardner-Lockman GL2000 model**.

5.3 Buildings Configuration

Schematic floor plan of rigid frame buildings with 10, 20, 30 story and wall-frame buildings with 40 and 60 story considered to study the effect of inelastic shortening are shown in Fig.5.2, 5.3 and 5.4. Sizes of structural elements are shown in Table 5.1 and 5.2. For deciding sizes of column, gravity load with arbitrary increment due to lateral load are considered.

Axial shortening of column at the center of the building is considered, because central column is subjected to maximum axial force. The columns marked with Square in Fig.5.2, 5.3 and 5.4 are considered to compare the axial shortening. For differential axial shortening between adjacent columns, it is found that exterior column and first interior column along the longer lateral side of building shows maximum differential axial shortening. Columns marked with Circles in Fig.5.2, 5.3 and 5.4 are considered to compare differential axial shortening. For sequential analysis, Concrete Grade M25 and Dead loads which includes Self Weight and Load due to Finishes of 1.5 kN/m^2 are considered.

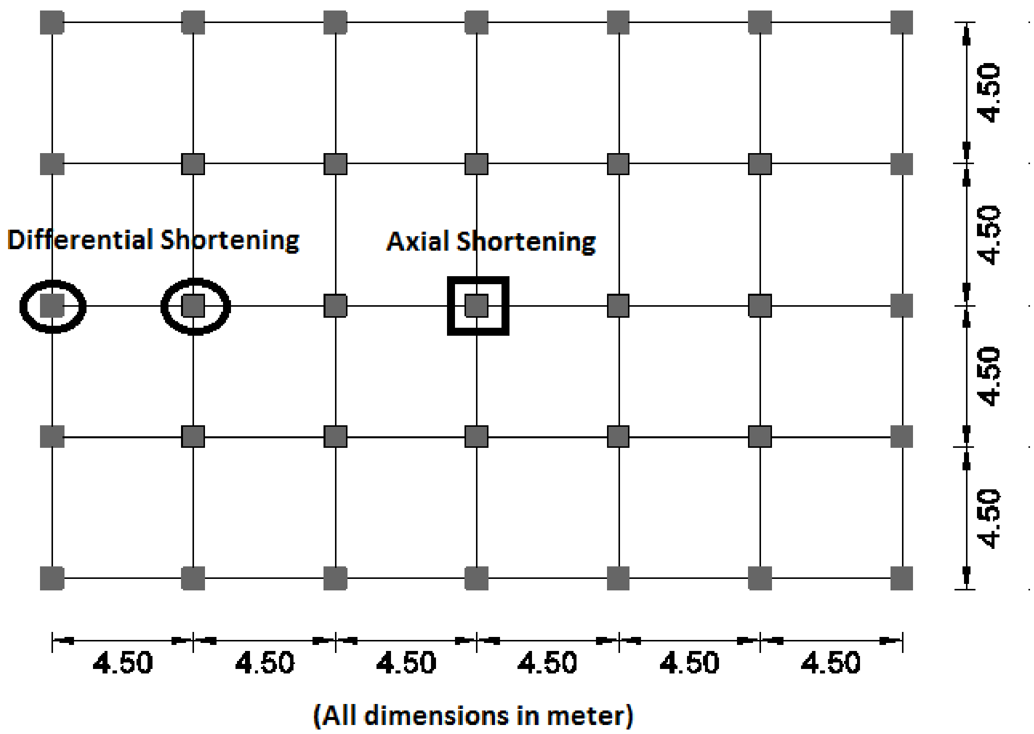


Figure 5.2: Schematic Plan of 10, 20 & 30 Storied Buildings

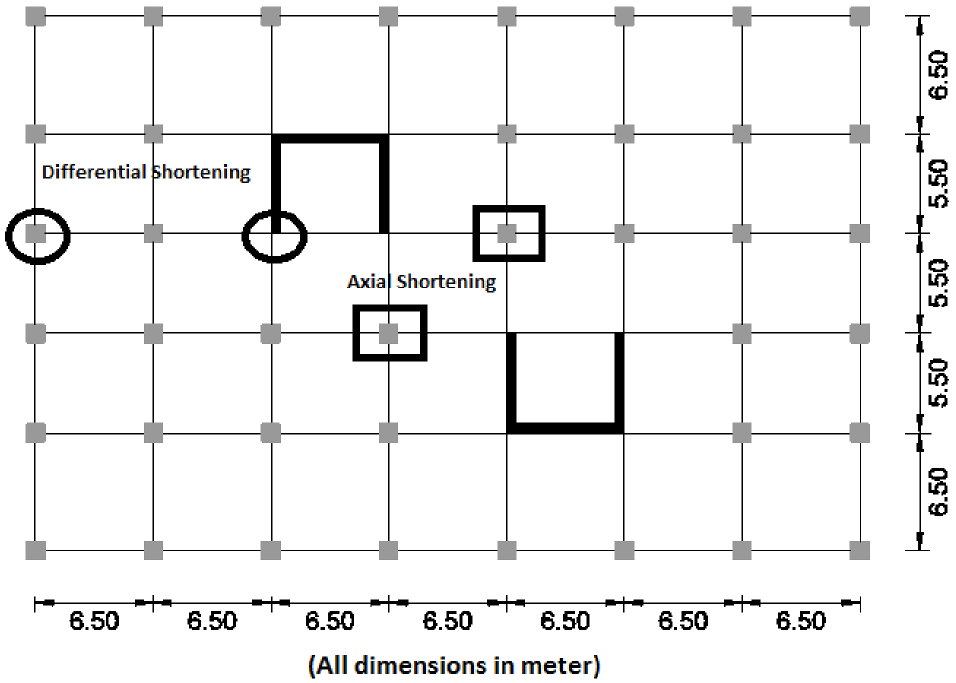


Figure 5.3: Schematic Plan of 40 Storied Wall-Frame Building

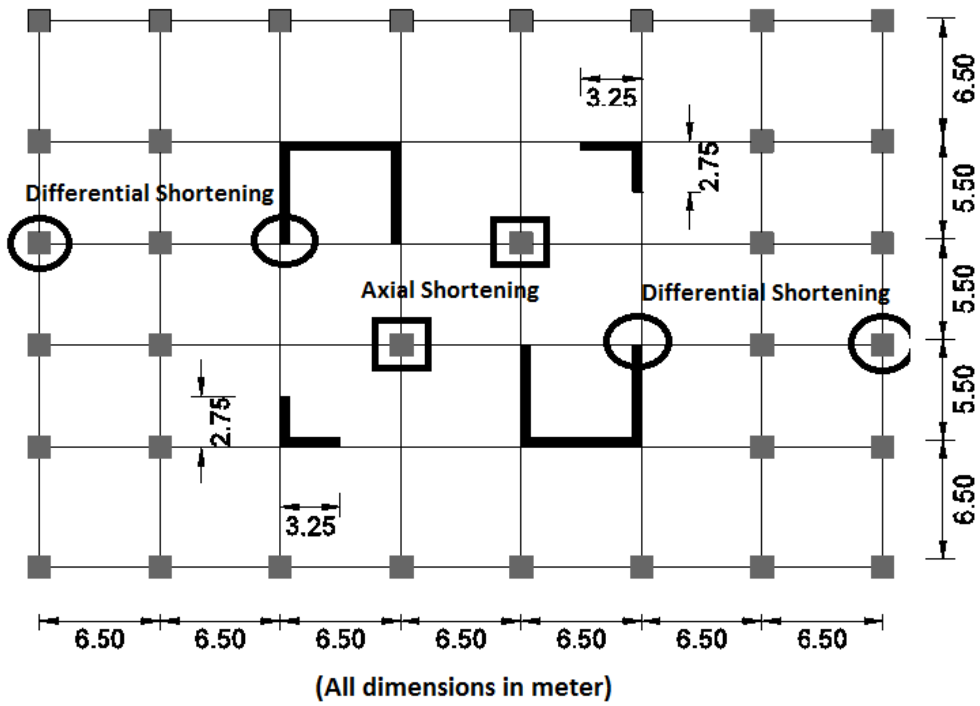


Figure 5.4: Schematic Plan of 60 Storied Wall-Frame Building

Table 5.1: Structural Element Sizes in Rigid Frame Buildings

Number of Story	10	20	30
Beam (mm)	250 x 600	250 x 600	250 x 600
Column (mm)	450 x 450	750 x 750	1000 x 1000
Slab thickness (mm)	150	150	150
Story height (m)	3.2	3.2	3.2

Table 5.2: Structural Element Sizes in Wall-Frame Buildings

Number of Story	40	60
Beam (mm)	350 x 650	350 x 700
Column (mm)	1000 x 1000	1250 x 1250
Shearwall thickness (mm)	350	400
Slab thickness (mm)	160	170
Story height (m)	3.2	3.2

5.4 Effect of Construction Rate

To incorporate the effect of construction rate , Creep, Shrinkage and Strength input parameters are required to be specified. In this study, construction rate is kept as 7 days per floor and 28 days per floor to study the effect of construction rate on column shortening analysis results. The term dpf means “days per floor”. In case of 7dpf and 28dpf construction rate, duration of each structure group is kept as 7 days and 28 days respectively, while defining the structure groups in MIDAS Gen. Structure group activation is kept as 3 days and 7 days while considering 7dpf and 28dpf construction rate, respectively, to consider the time required for the installation of formwork and other required arrangements. The effect of each structure group last till the end of design life of the building. Boundary groups and Load groups are defined similarly as discussed in Chapter 3.

5.4.1 Axial and Differential Shortening

To study the effect of Construction Rate on Building Structures, 10, 20 and 30 Storied Rigid Frame Building are considered. Construction rate of the buildings affects the axial as well as differential shortening of columns and hence eventually the gravity load induced bending moments in beams. In this study, construction rate is varied from 7 Days Per Floor to 28 Days Per Floor considering single floor lumping and the its effects on axial shortening, differential shortening and gravity load induced beam end moments are studied. For the study, time dependent creep, shrinkage and elastic strains are considered. Fig.5.5 to 5.10 shows the effect of construction rate on elastic, creep and shrinkage induced shortening of columns. Fig.5.11 to 5.16 shows the effect of construction rate on elastic, creep and shrinkage induced differential shortening of adjacent columns in rigid frame structures. Fig.5.17 and Fig.5.18 shows the effect of construction rate on total (elastic + inelastic) axial as well as differential axial shortening of columns in rigid frame structures. Axial shortening of central columns with Square Mark, as shown in Fig.5.1, 5.2 and 5.3 are presented, while differential axial shortening of columns with Circular Mark, as shown in Fig.5.1, 5.2 and 5.3 are presented.

Analysis results for axial and differential axial shortening show that by decreasing the construction rate from 7dpf to 28dpf, creep and shrinkage induced shortening increases due to increased environmental exposure of the columns where as elastic shortening decreases due to relaxation of stresses with time. Though the effect of construction stage on column shortening increases with the height of the buildings, the effect of change of construction rate on column shortening decreases with the height of the building due to more number of load increments in buildings with more number of stories.

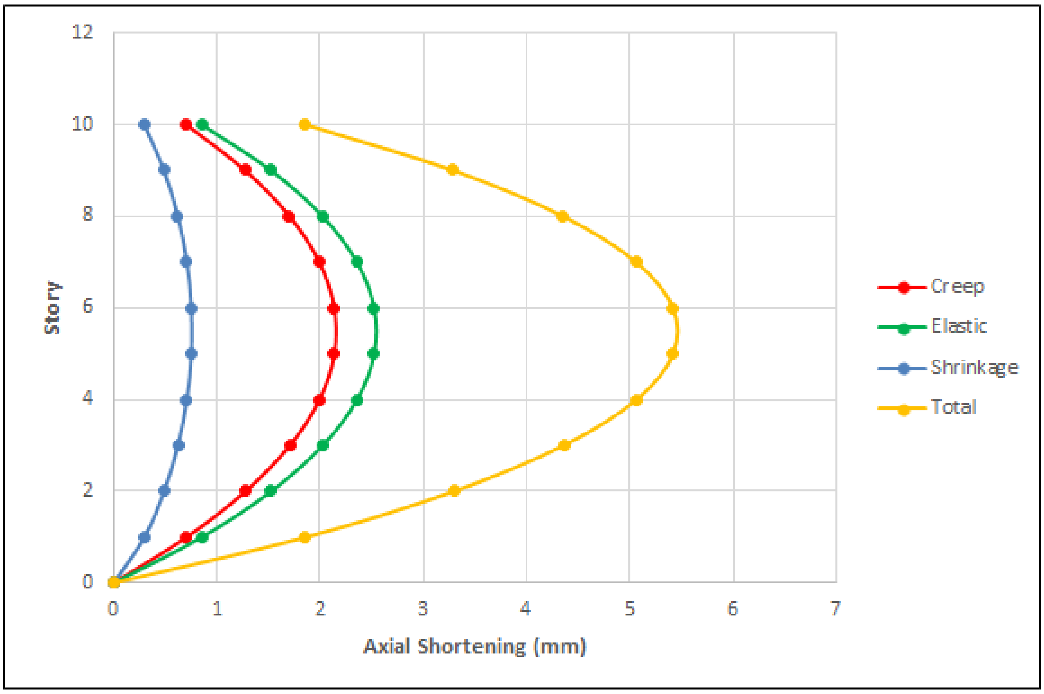


Figure 5.5: Axial Shortening in 10 Storied Building with 7dpf Construction Rate

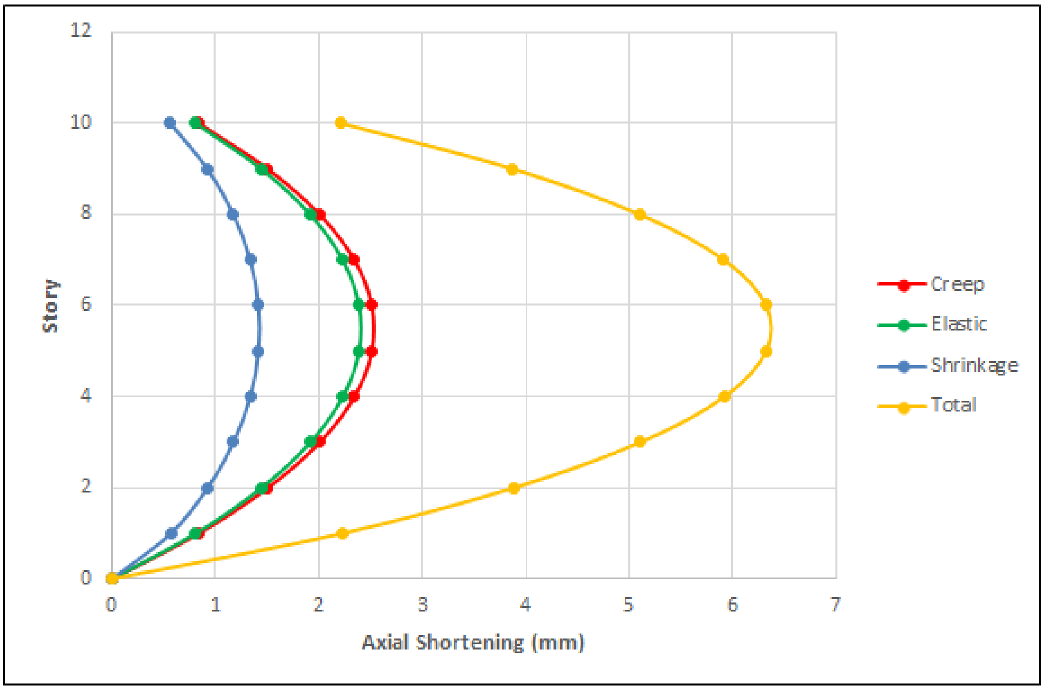


Figure 5.6: Axial Shortening in 10 Storied Building with 28dpf Construction Rate

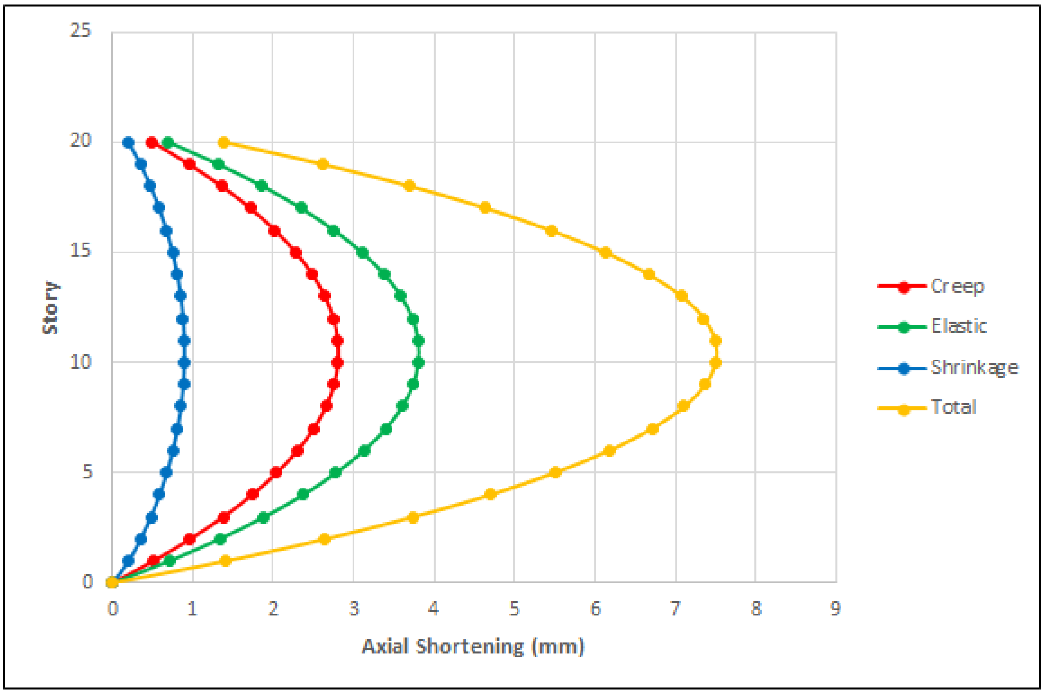


Figure 5.7: Axial Shortening in 20 Storied Building with 7dpf Construction Rate

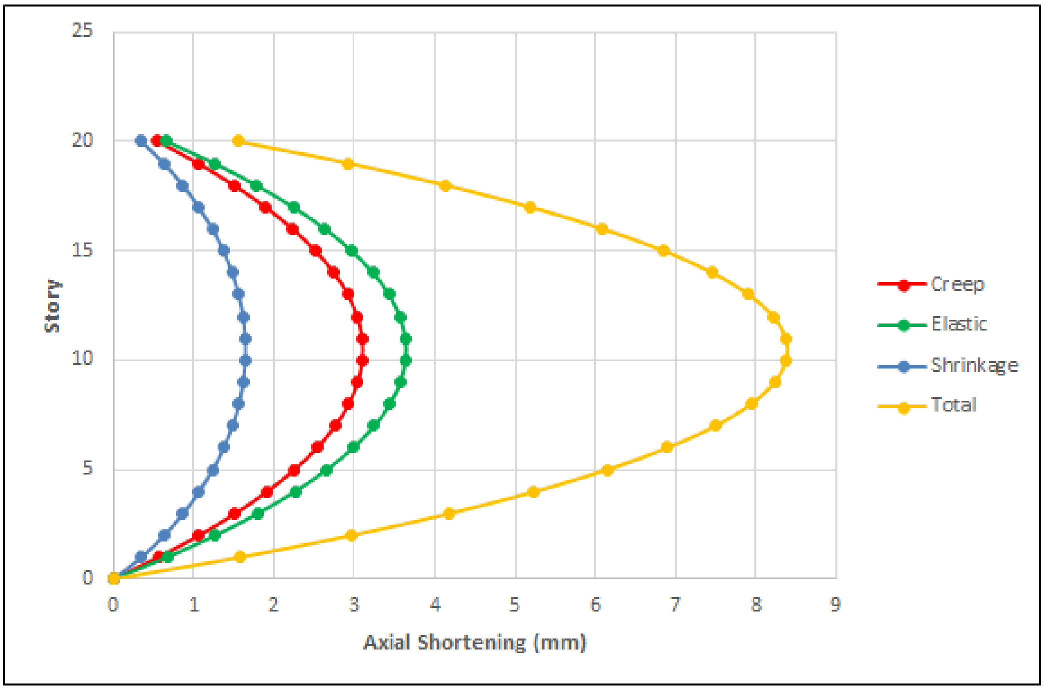


Figure 5.8: Axial Shortening in 20 Storied Building with 28dpf Construction Rate

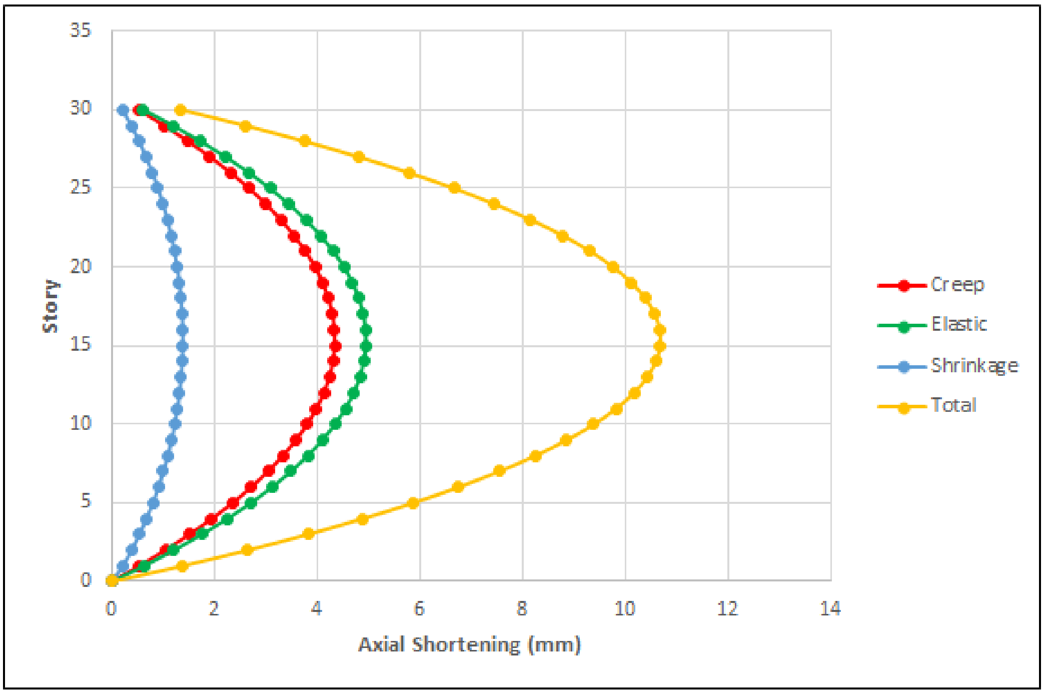


Figure 5.9: Axial Shortening in 30 Storied Building with 7dpf Construction Rate

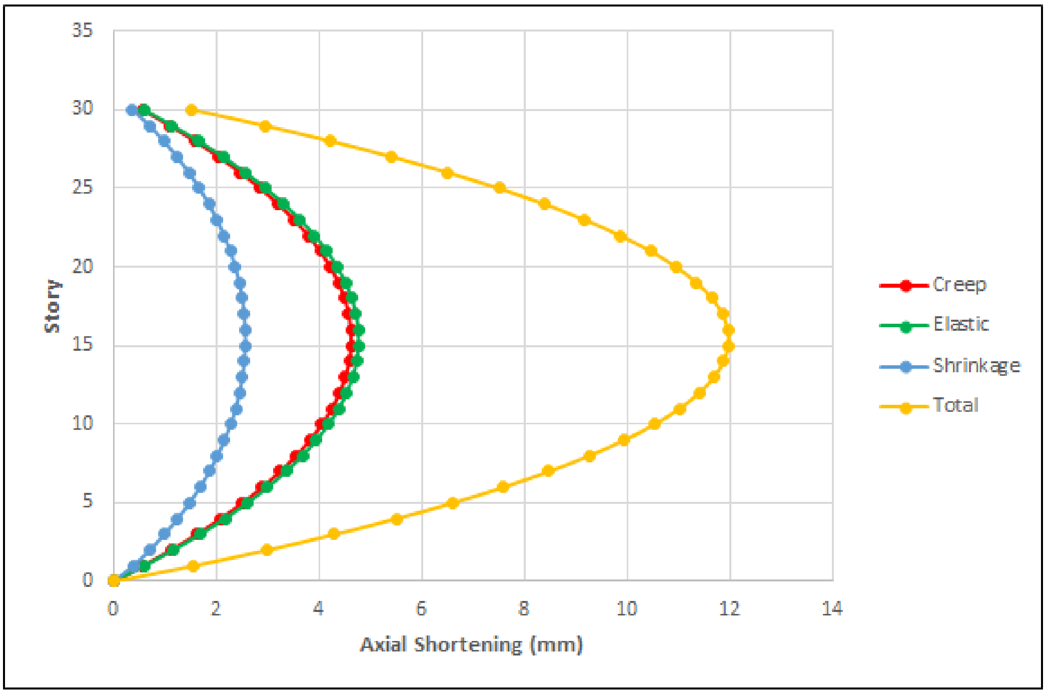


Figure 5.10: Axial Shortening in 30 Storied Building with 28dpf Construction Rate

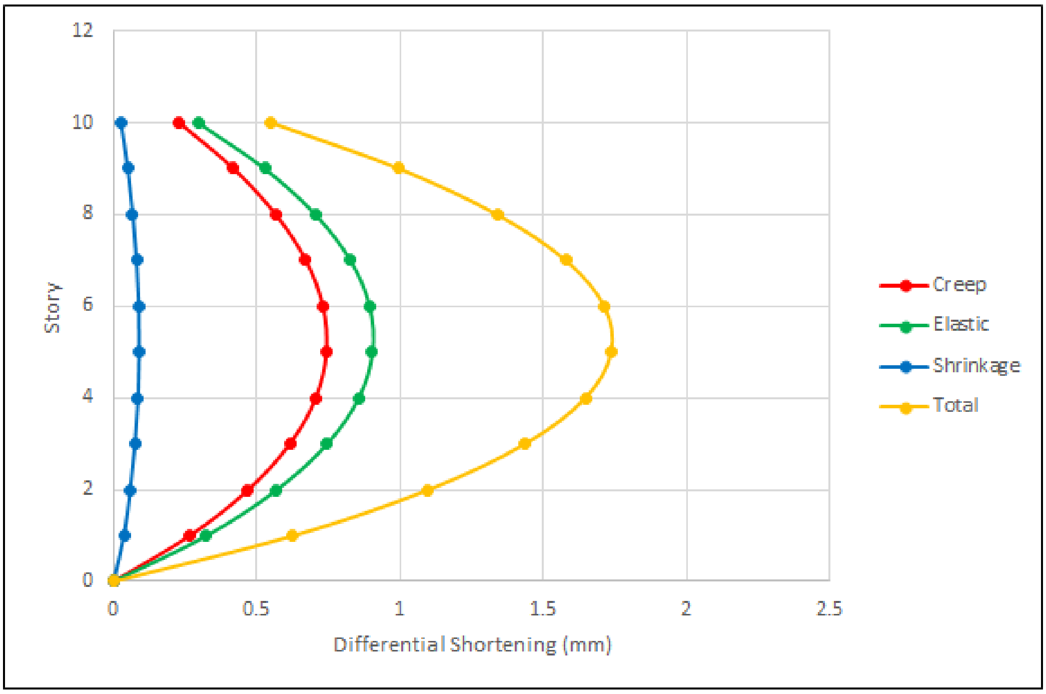


Figure 5.11: Differential Shortening in 10 Storied Building with 7dpf Construction Rate

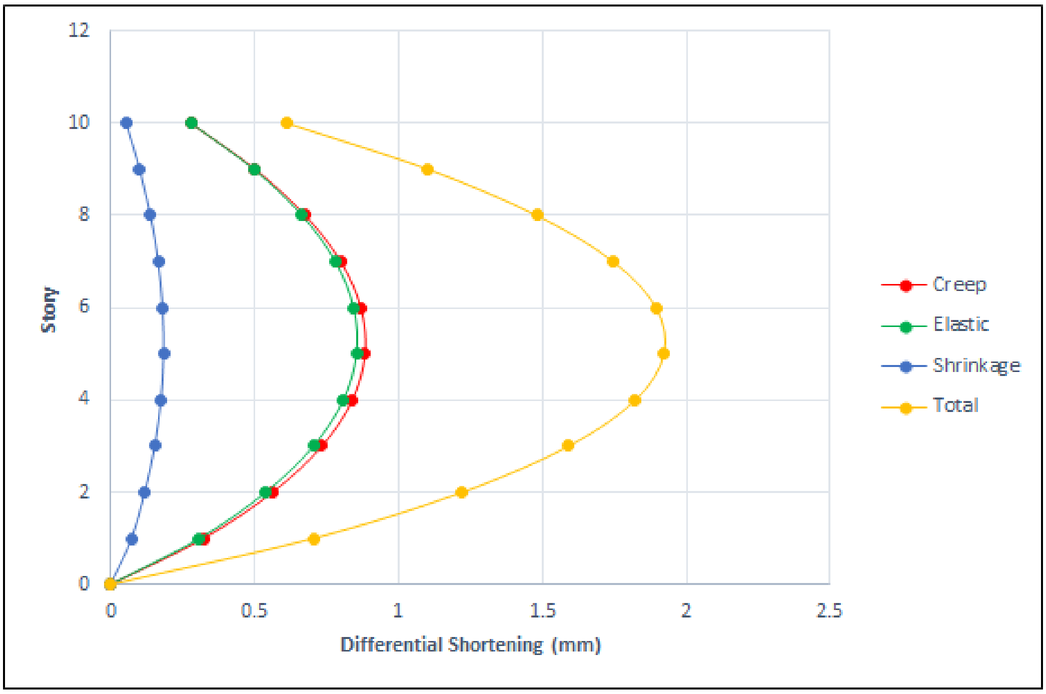


Figure 5.12: Differential Shortening in 10 Storied Building with 28dpf Construction Rate

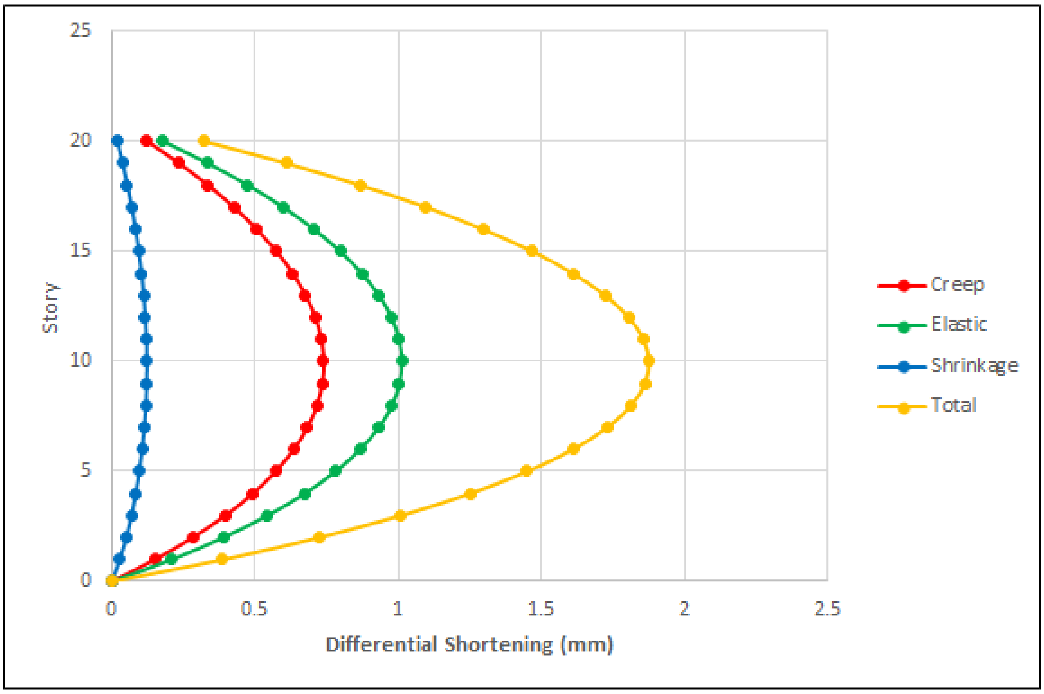


Figure 5.13: Differential Shortening in 20 Storied Building with 7dpf Construction Rate

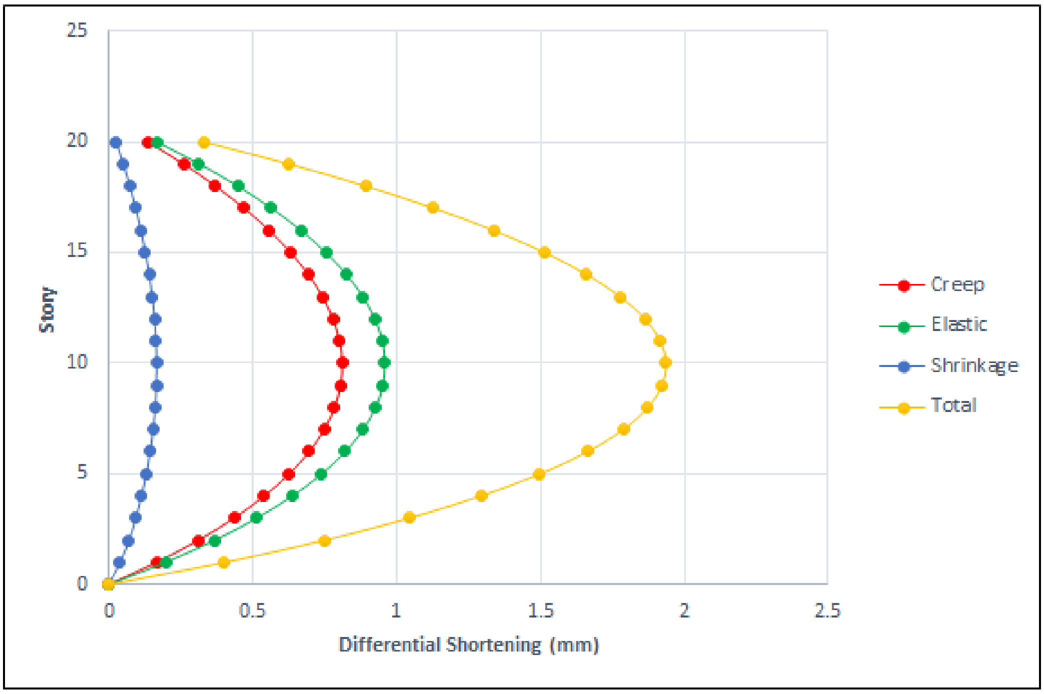


Figure 5.14: Differential Shortening in 20 Storied Building with 28dpf Construction Rate

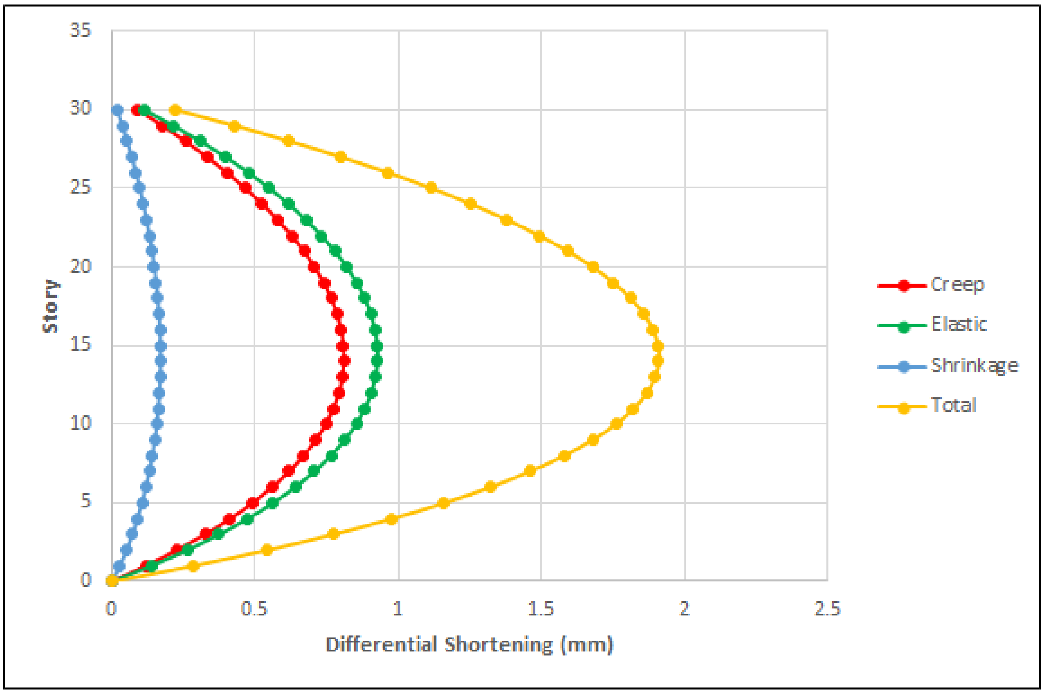


Figure 5.15: Differential Shortening in 30 Storied Building with 7dpf Construction Rate

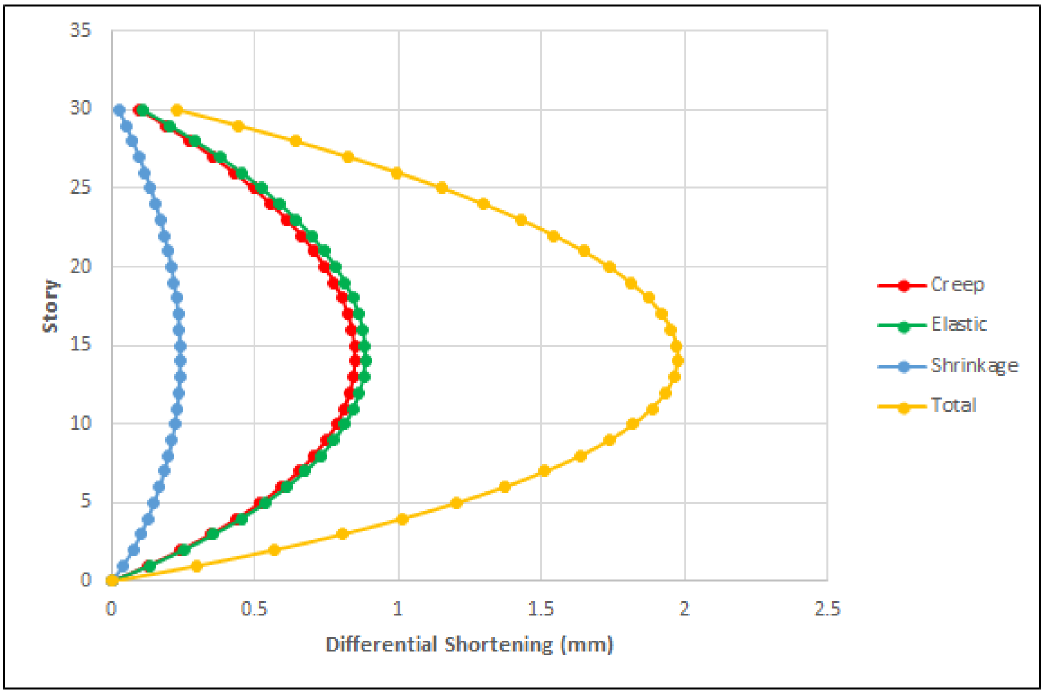


Figure 5.16: Differential Shortening in 30 Storied Building with 28dpf Construction Rate

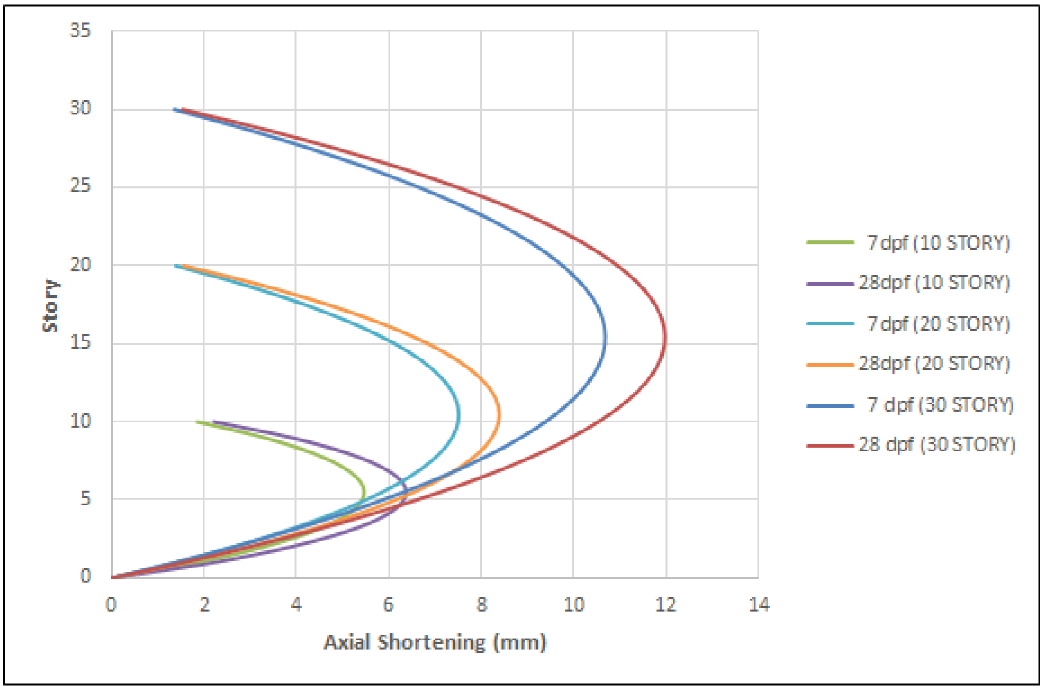


Figure 5.17: Effect of Construction Rate on Column Axial Shortening

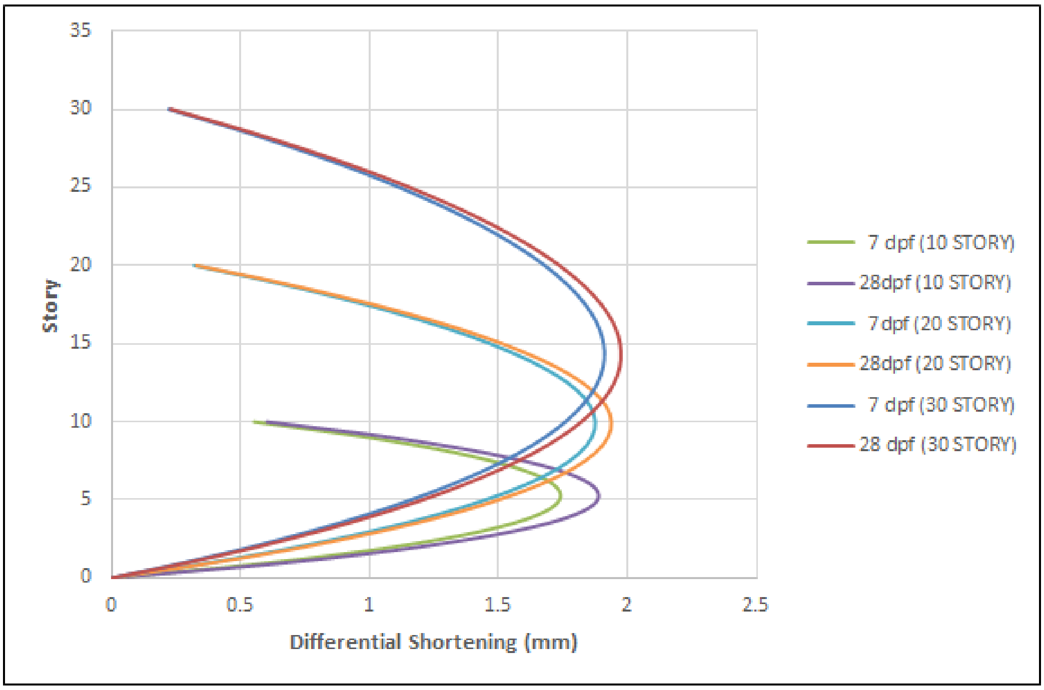


Figure 5.18: Effect of Construction Rate on Column Differential Shortening

5.4.2 Beam End Moments

Effect of construction rate on gravity load induced end moment (unfactored) for the beam between exterior columns and first interior columns marked with circle in Fig.5.1 in rigid frame buildings is showed in Fig.5.19, 5.20 and 5.21. Maximum beam end bending moment (left and right end) is presented considering one step analysis (OSA) and construction stage analysis with 7dpf and 28dpf construction rate. Negative values of beam end moment indicates hogging moment at the ends of beam.

Analysis results for bending moments in beams show that by decreasing the construction rate from 7dpf to 28dpf, beam end moment increases by 15%. Construction stage analysis results in medium to high-rise buildings (i.e. in this study 20 & 30 storied building) for beam end moments show higher values up to mid height stories and lower values near the top stories. Though the effect of construction stage on beam end moments increases with number of stories, the effect of change in construction rate on beam end moments decreases due to more number of load increments.

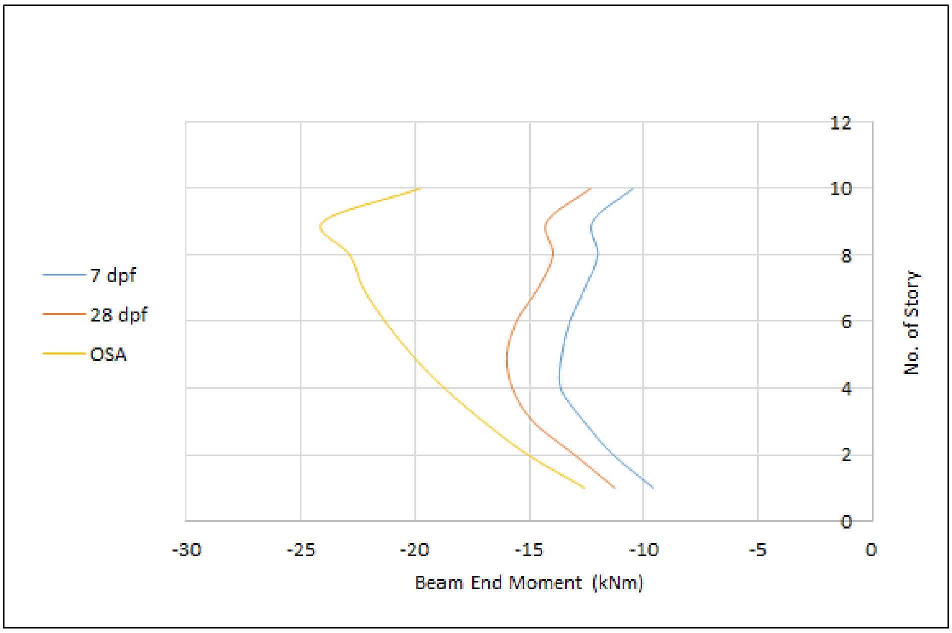


Figure 5.19: Effect of construction rate on gravity load induced beam end moments in 10 storied building

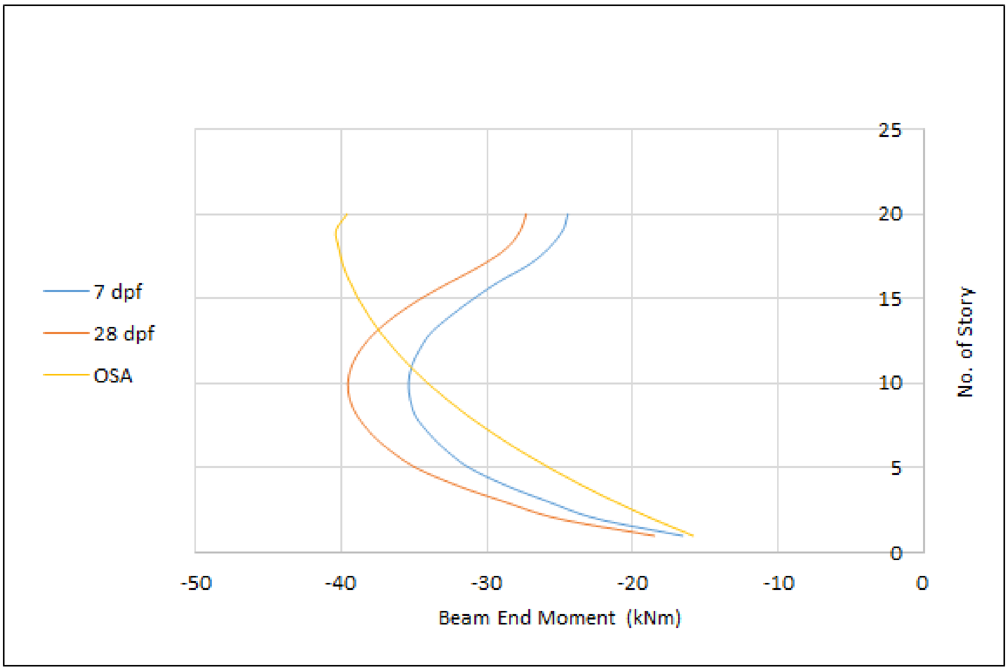


Figure 5.20: Effect of construction rate on gravity load induced beam end moments in 20 storied building

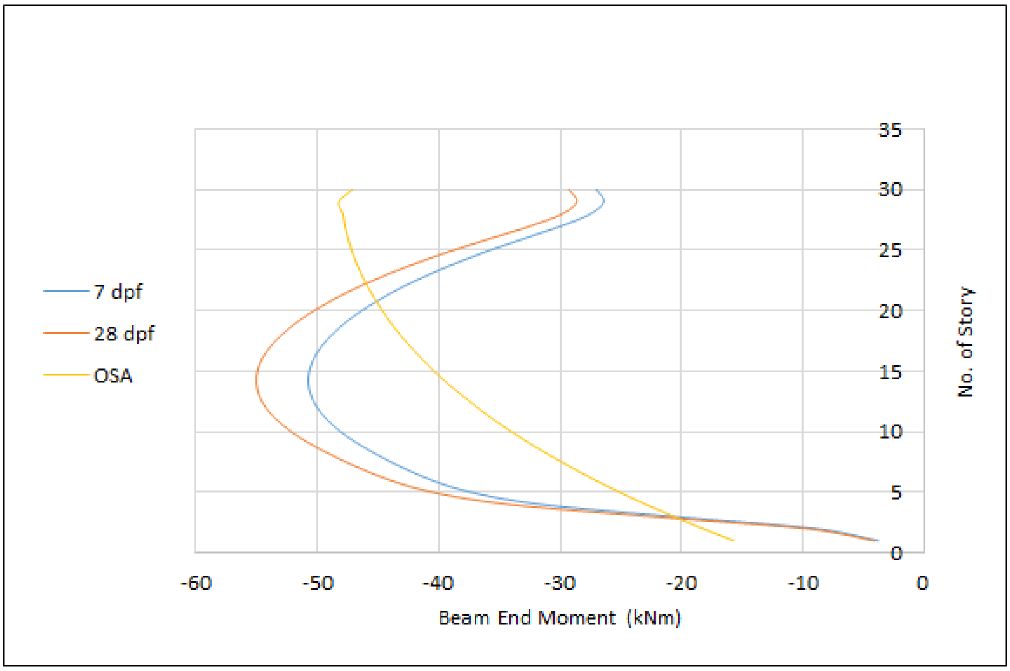


Figure 5.21: Effect of construction rate on gravity load induced beam end moments in 30 storied building

5.5 Effect of Relative Humidity

Effect of Relative Humidity on column shortening is presented in this section. Relative humidity releases the stress induced due to sustained loading and volumetric strains in concrete. Thus, relative humidity of ambient environment affects the creep and shrinkage induced shortening and has no impact on elastic strains. Relative humidity of ambient environment is classified in MIDAS Gen at the time of defining time dependent material properties i.e. creep & shrinkage.

5.5.1 Axial and Differential Shortening

Wall-Frame buildings of 40 & 60 Story are considered to study the effect of relative humidity on building structures. Environmental conditions like relative humidity of the ambient environment affects the column shortening significantly and its effect and alters its action depending on the type of exposure to the climate. As the wall-frame building involves large construction sequence of the structural elements due to time lag between the construction of columns, shear walls and partition walls, exposure to the climate affects more in wall-frame buildings and hence the variation of relative humidity is considered to be the effective parameter in the column shortening effects in wall-frame buildings. For the present study, three different relative humidity i.e. 50%, 70% and 90% and constant construction rate of 7dpf are considered.

Axial shortening of central columns with Square Mark, as shown in Fig.5.2 and 5.3 are presented, while differential axial shortening of columns with Circular Mark, as shown in Fig.5.2 and 5.3 are presented. Fig. 5.22 to 5.24, 5.26 to 5.28 and Fig. 5.30 to 5.32, 5.34 to 5.36 shows the effect of relative humidity on elastic, creep and shrinkage induced axial as well as differential shortening in 40 and 60 storied wall-frame buildings respectively. Fig.5.25, 5.29, 5.33 and 5.37 show the effect of relative humidity on maximum values of creep, shrinkage, elastic and total shortening. Fig. 5.38 and 5.39 show the effect of relative humidity on total axial and differential shortening of columns in 40 and 60 storied wall-frame buildings.

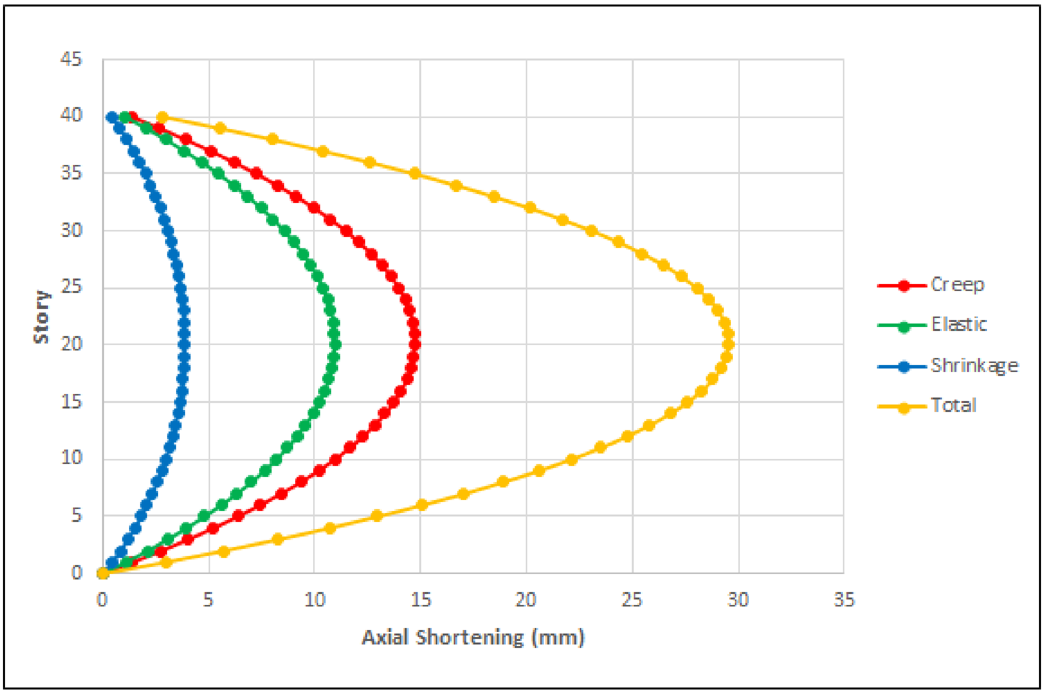


Figure 5.22: Axial Shortening in 40 Storied Building : RH 50%

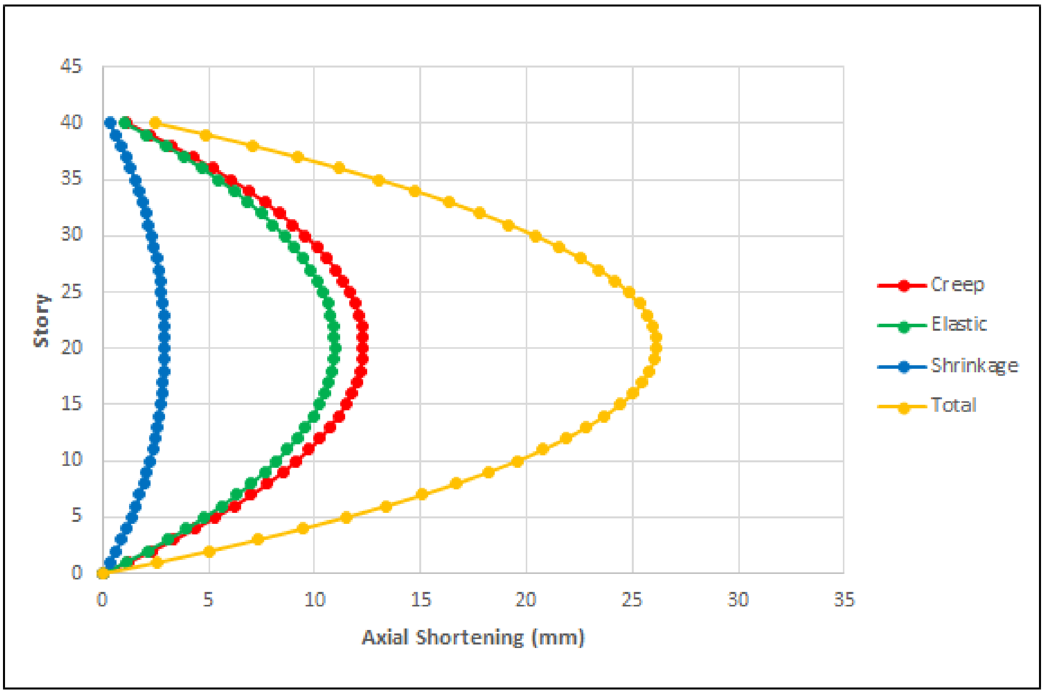


Figure 5.23: Axial Shortening in 40 Storied Building : RH 70%

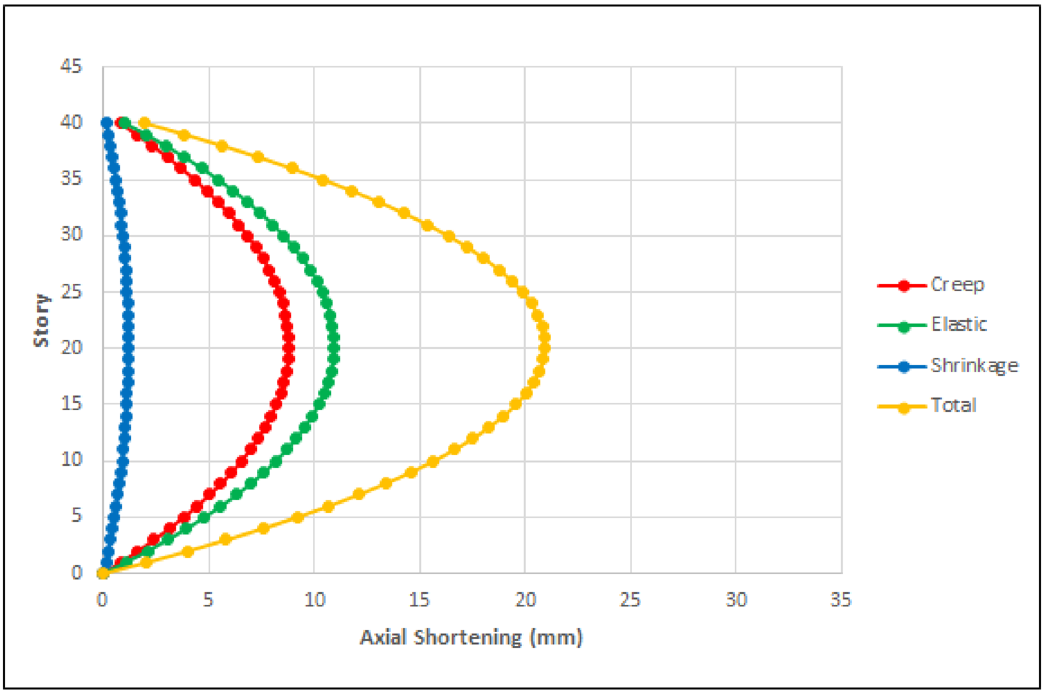


Figure 5.24: Axial Shortening in 40 Storied Building : RH 90%

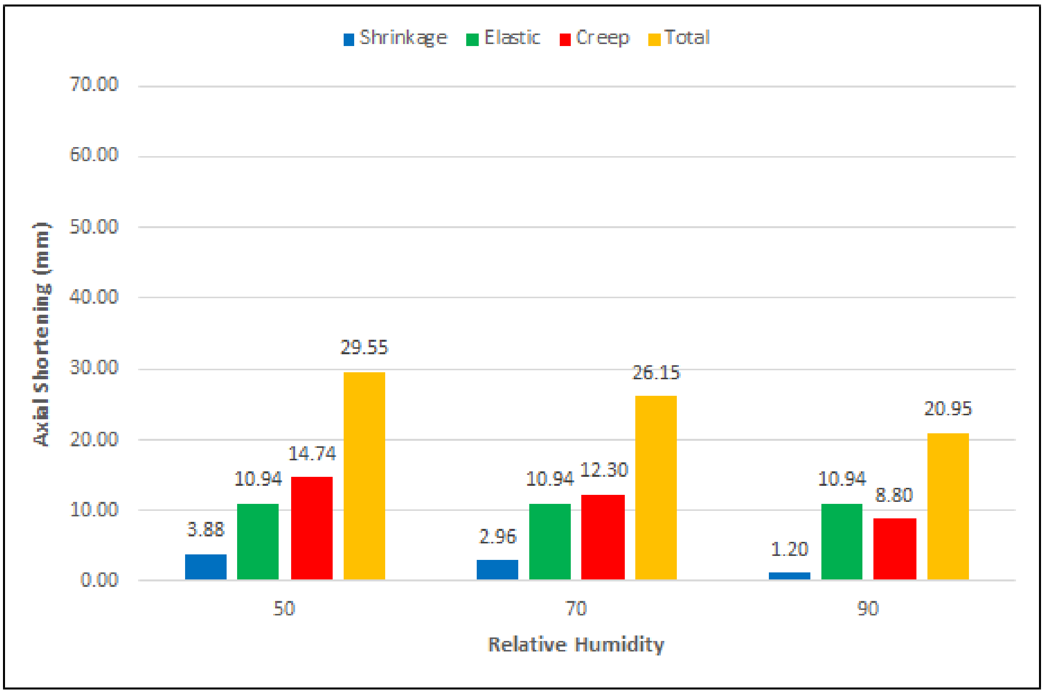


Figure 5.25: Effect of Relative Humidity on Axial Shortening in 40 Storied Building

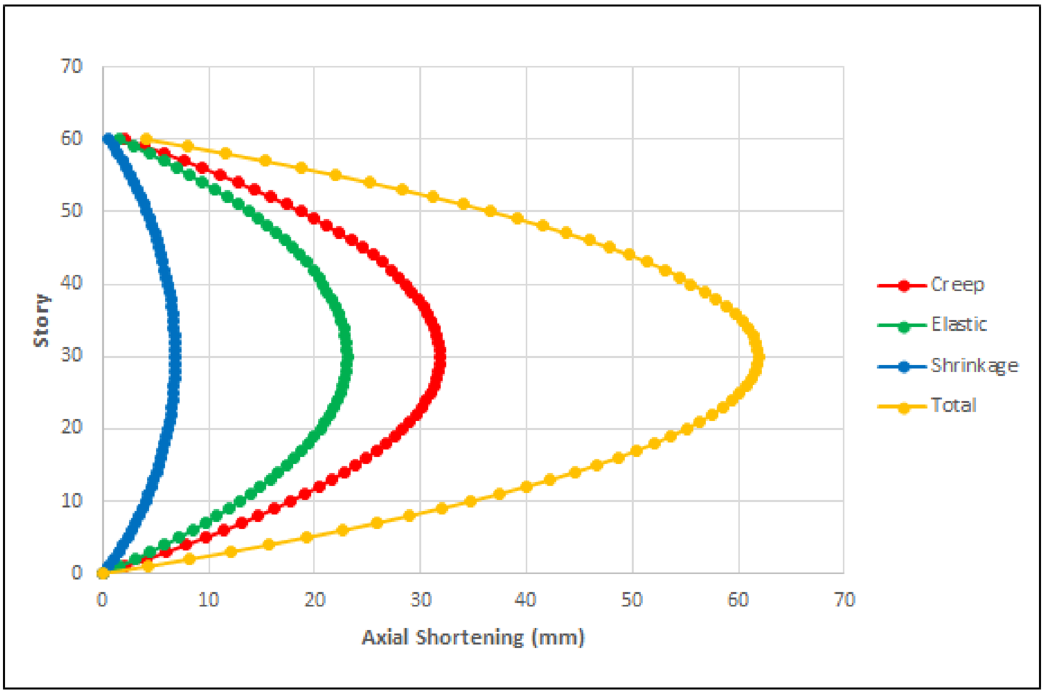


Figure 5.26: Axial Shortening in 60 Storied Building : RH 50%

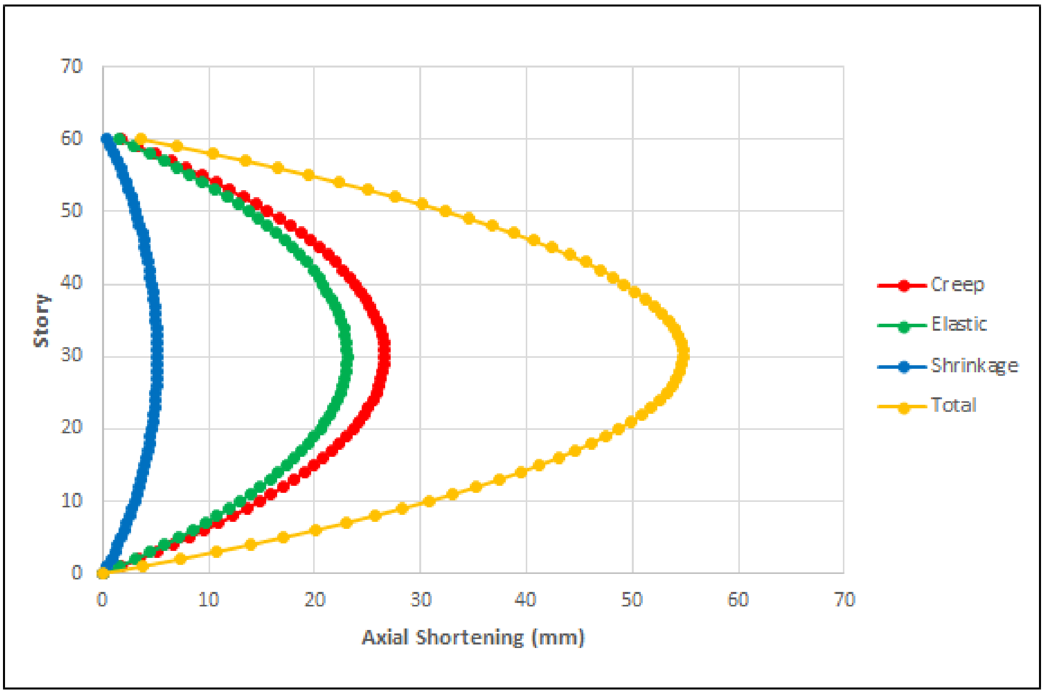


Figure 5.27: Axial Shortening in 60 Storied Building : RH 70%

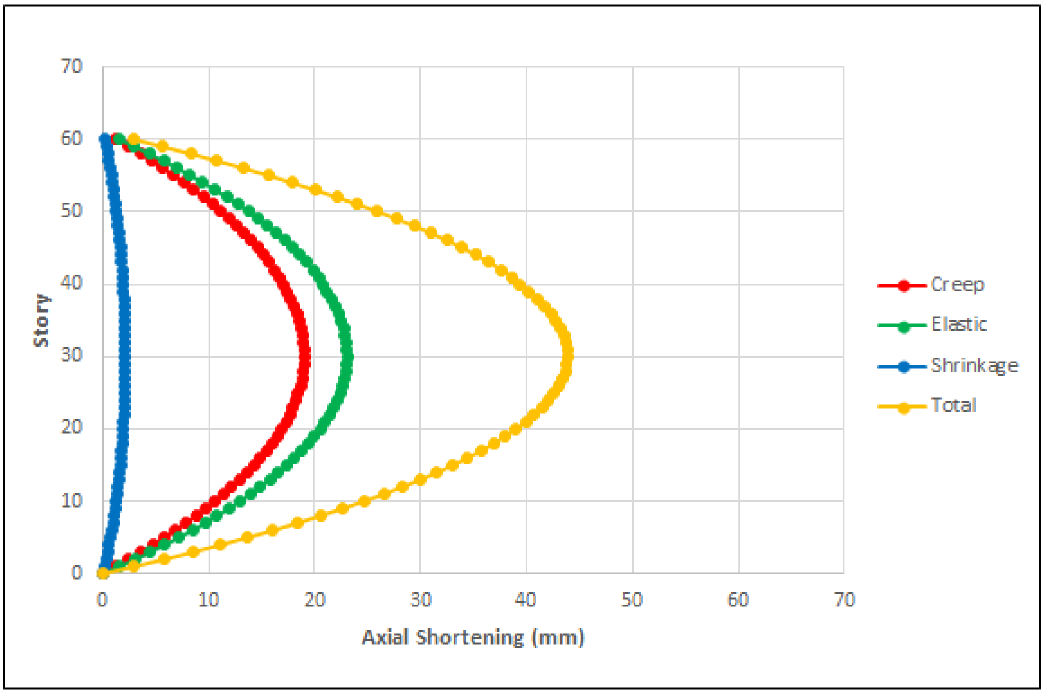


Figure 5.28: Axial Shortening in 60 Storied Building : RH 90%

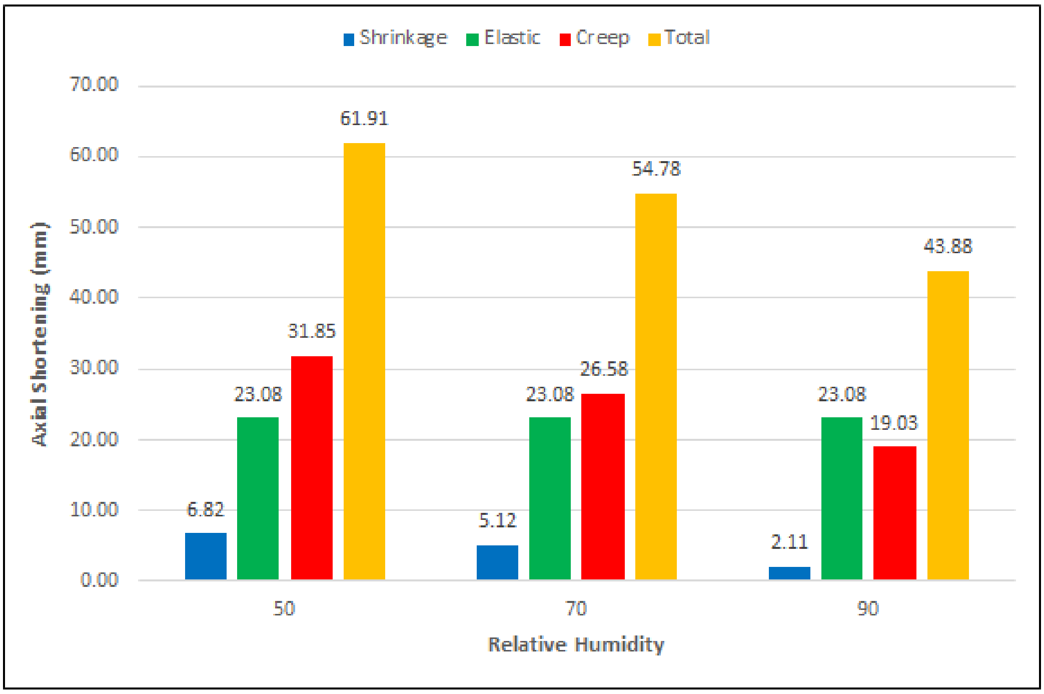


Figure 5.29: Effect of Relative Humidity on Axial Shortening in 60 Storied Building

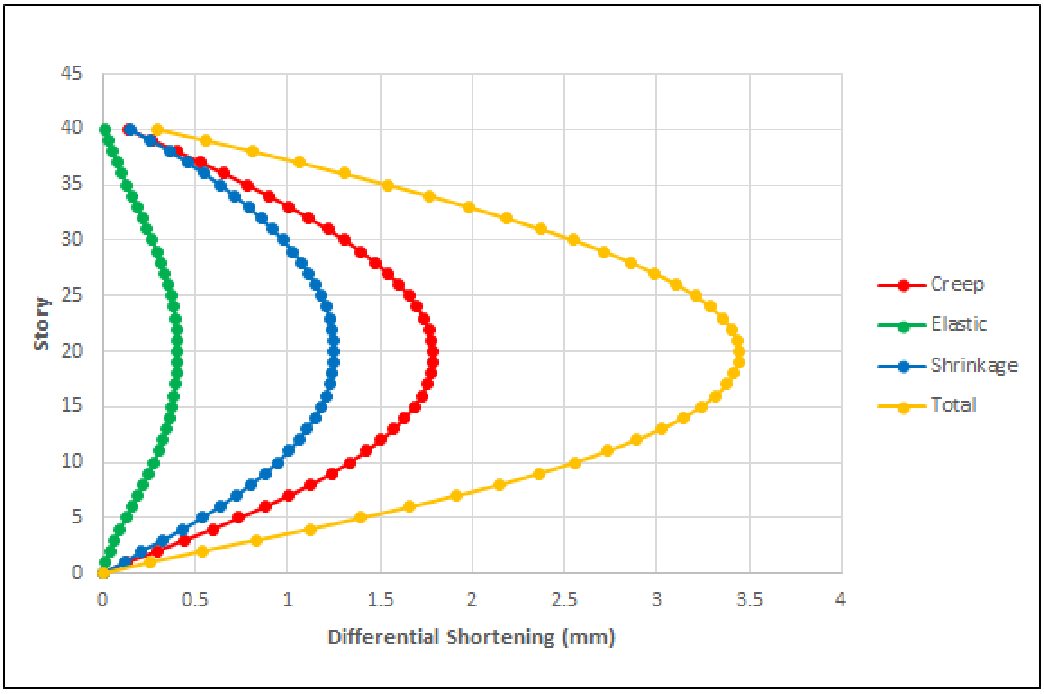


Figure 5.30: Differential Shortening in 40 Storied Building : RH 50%

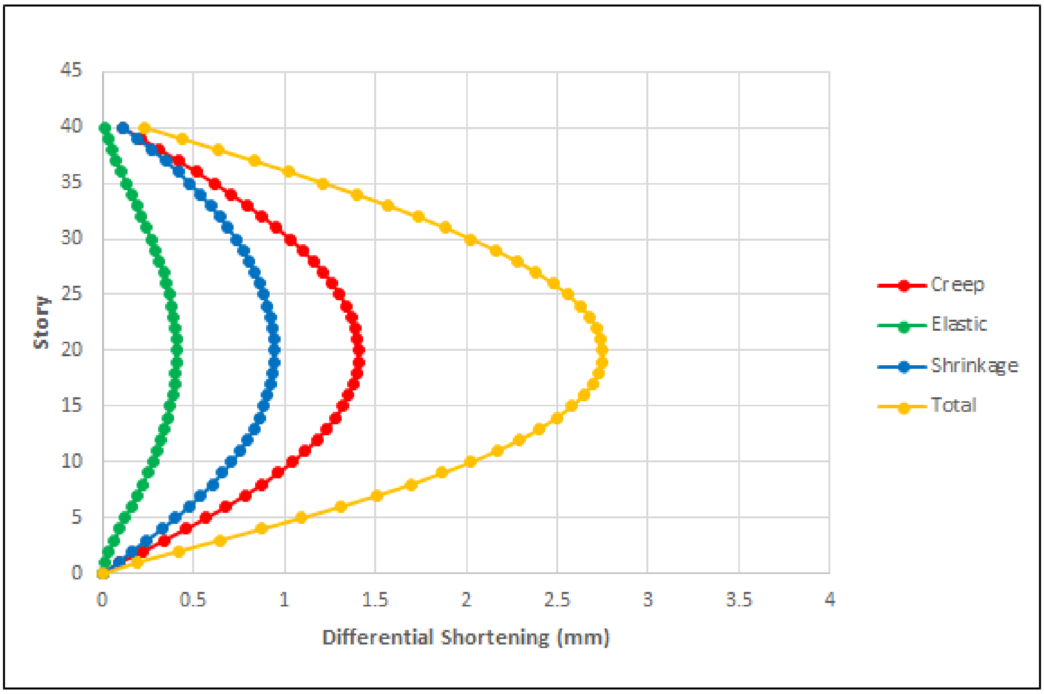


Figure 5.31: Differential Shortening in 40 Storied Building : RH 70%

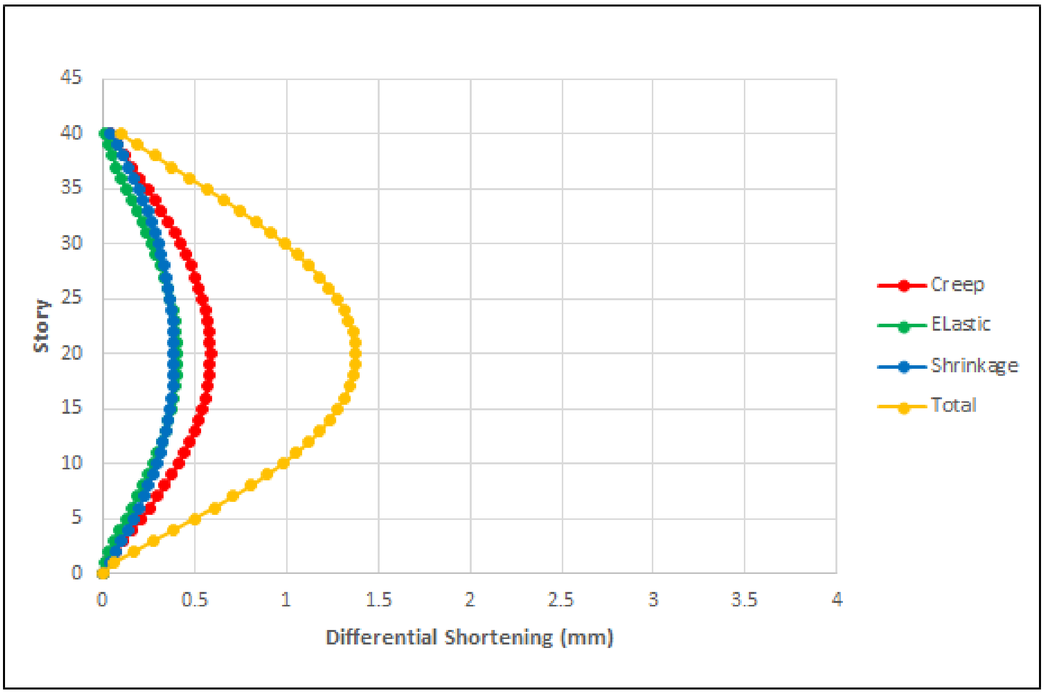


Figure 5.32: Differential Shortening in 40 Storied Building : RH 90%

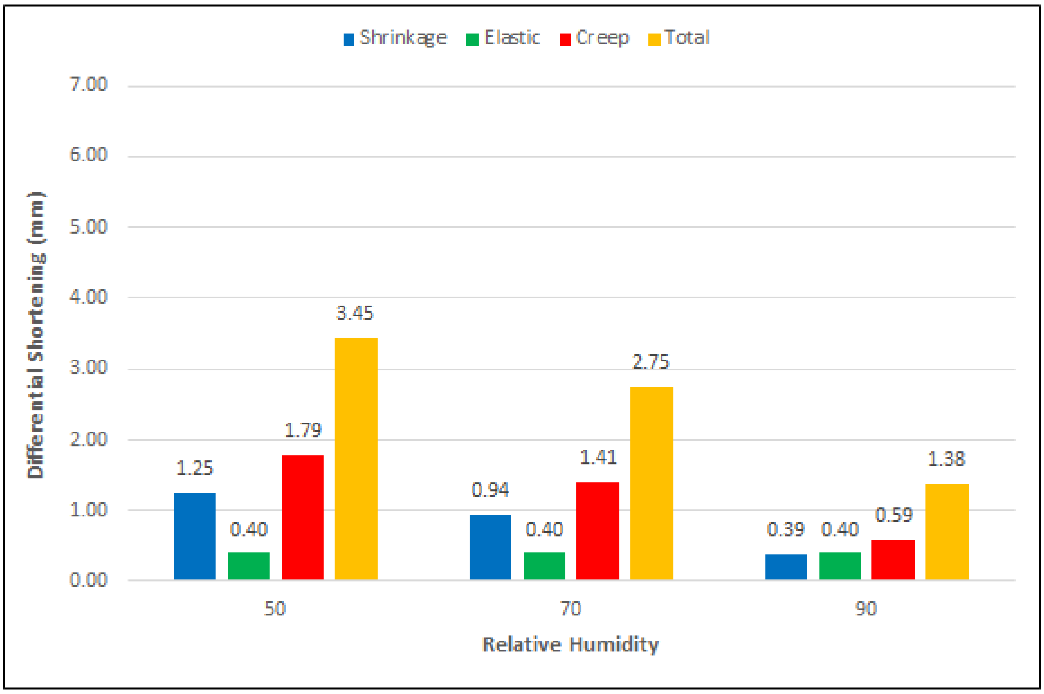


Figure 5.33: Effect of Relative Humidity on Differential Shortening in 40 Storied Building

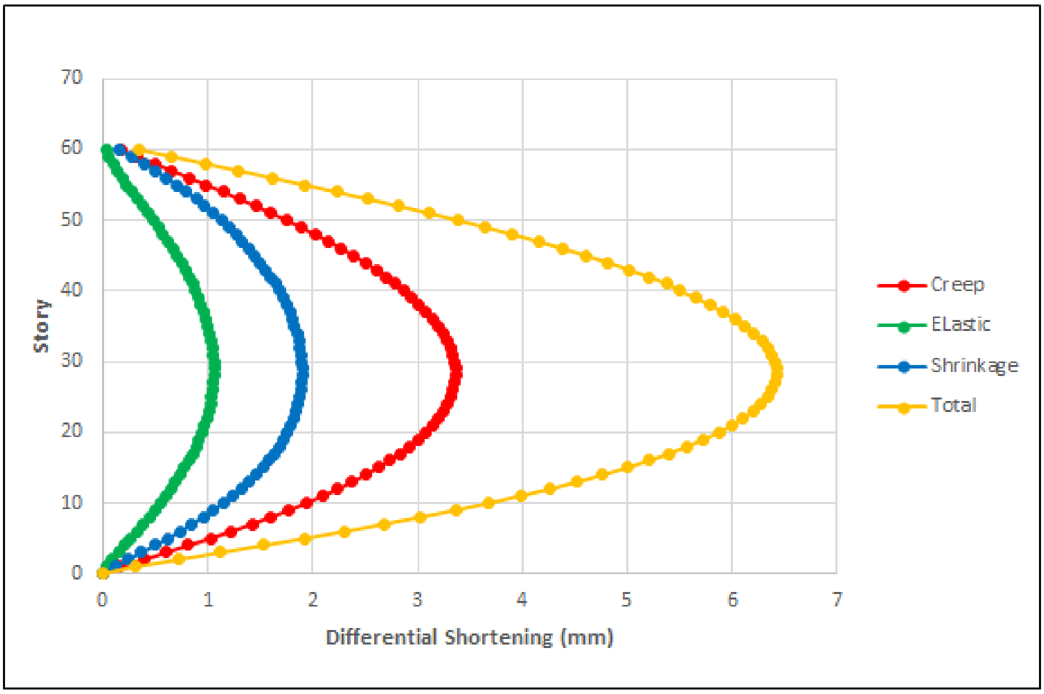


Figure 5.34: Axial Shortening in 60 Storied Building : RH 50%

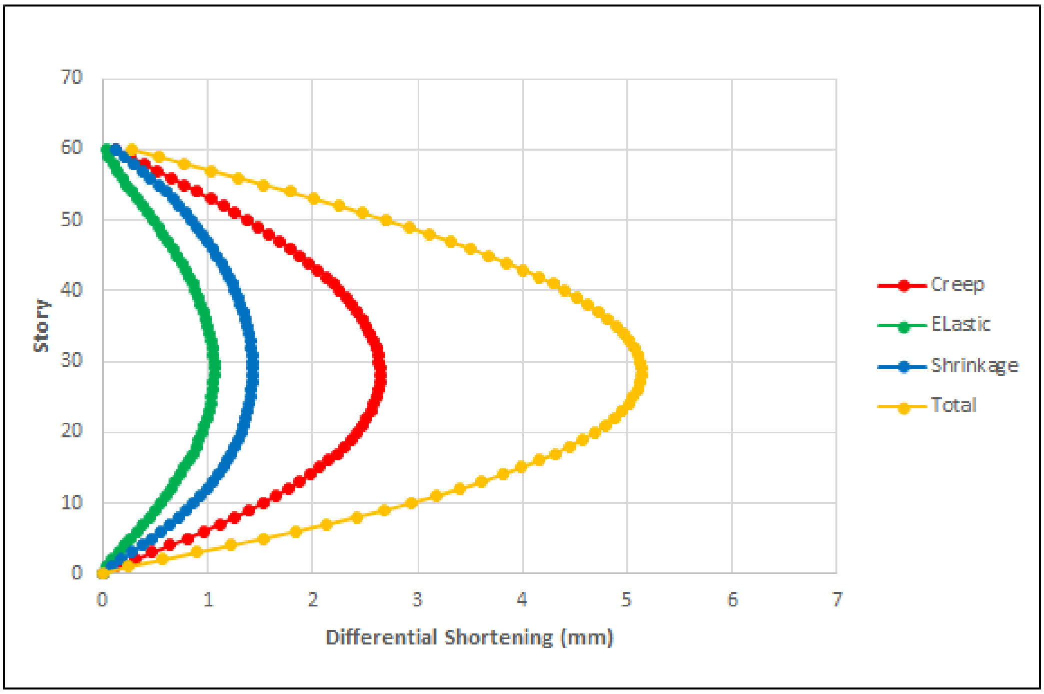


Figure 5.35: Axial Shortening in 60 Storied Building : RH 70%

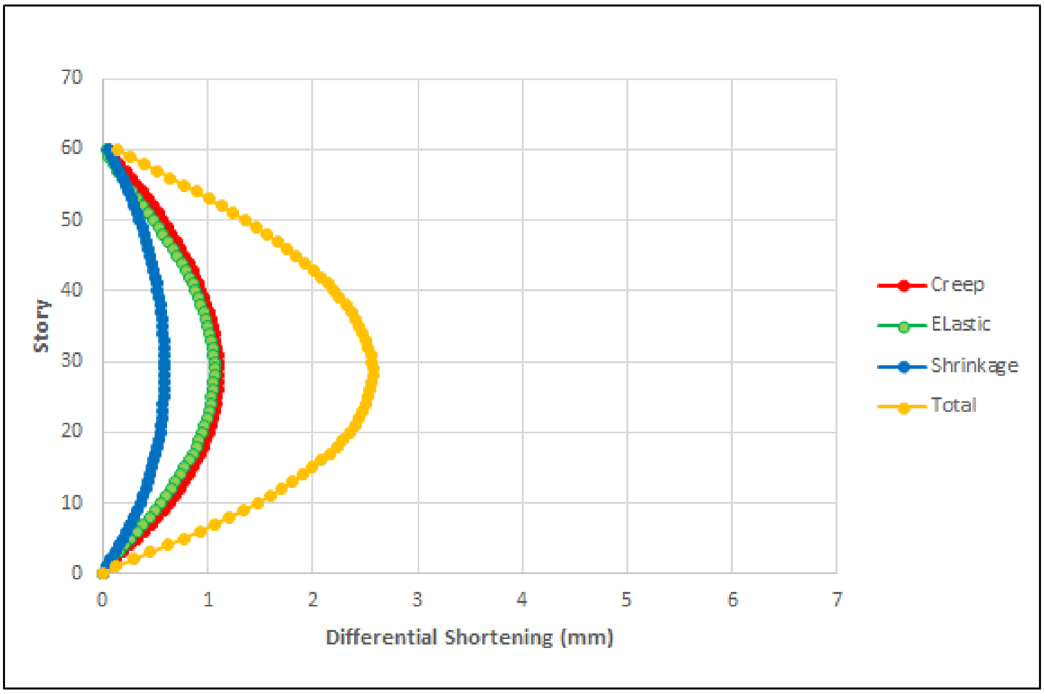


Figure 5.36: Axial Shortening in 60 Storied Building : RH 90%

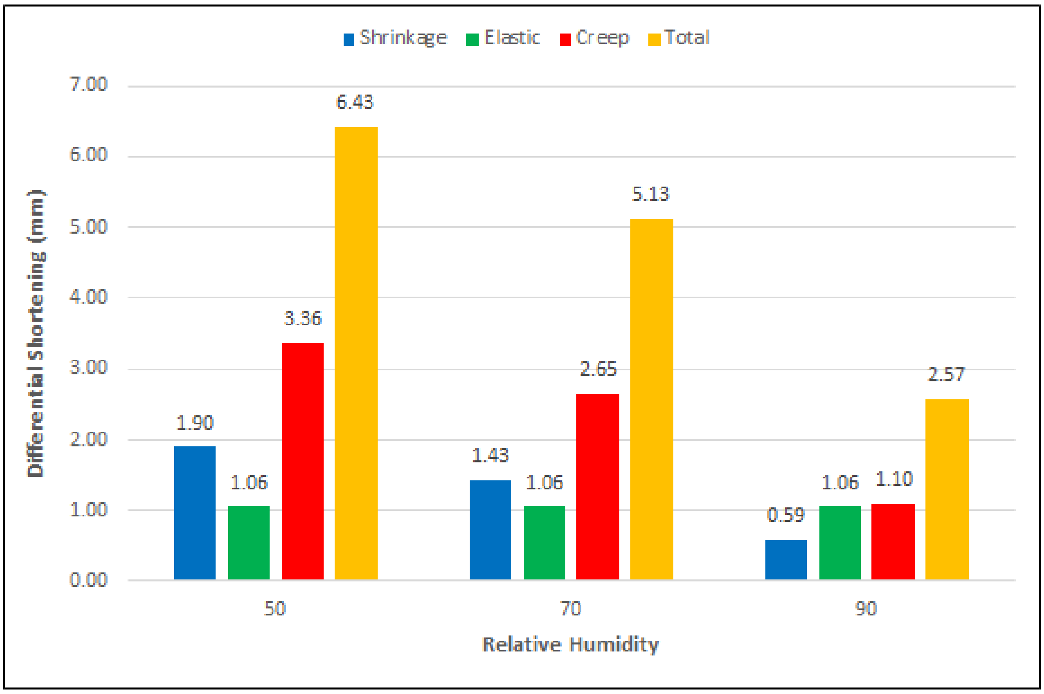


Figure 5.37: Effect of Relative Humidity on Differential Shortening in 60 Storied Building

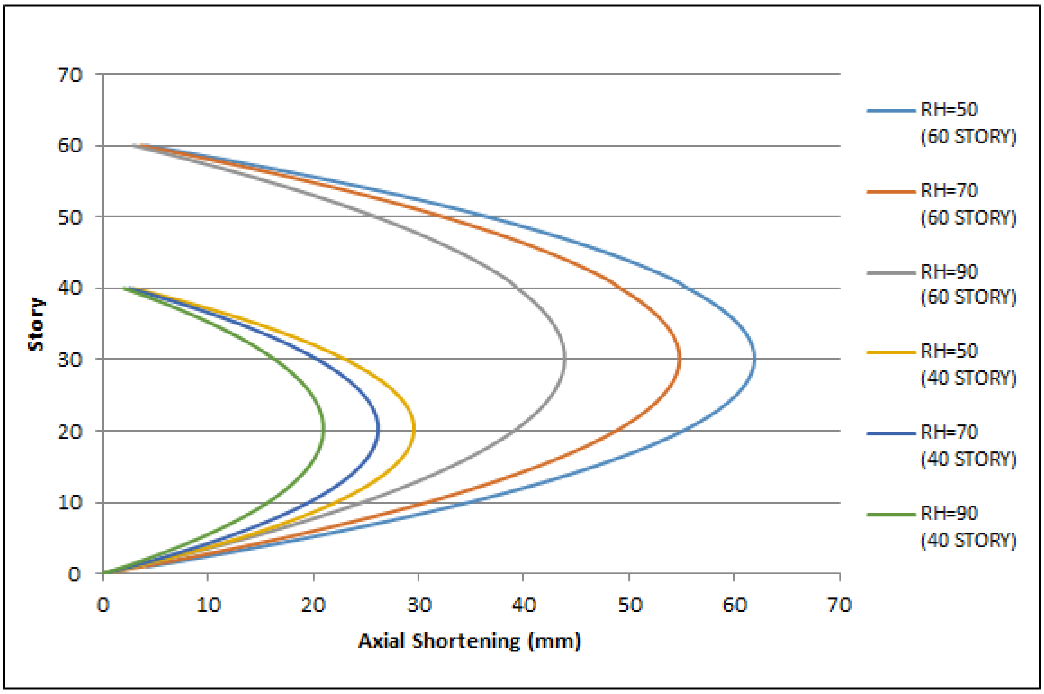


Figure 5.38: Effect of Relative Humidity on Column Axial Shortening in Wall-Frame Buildings

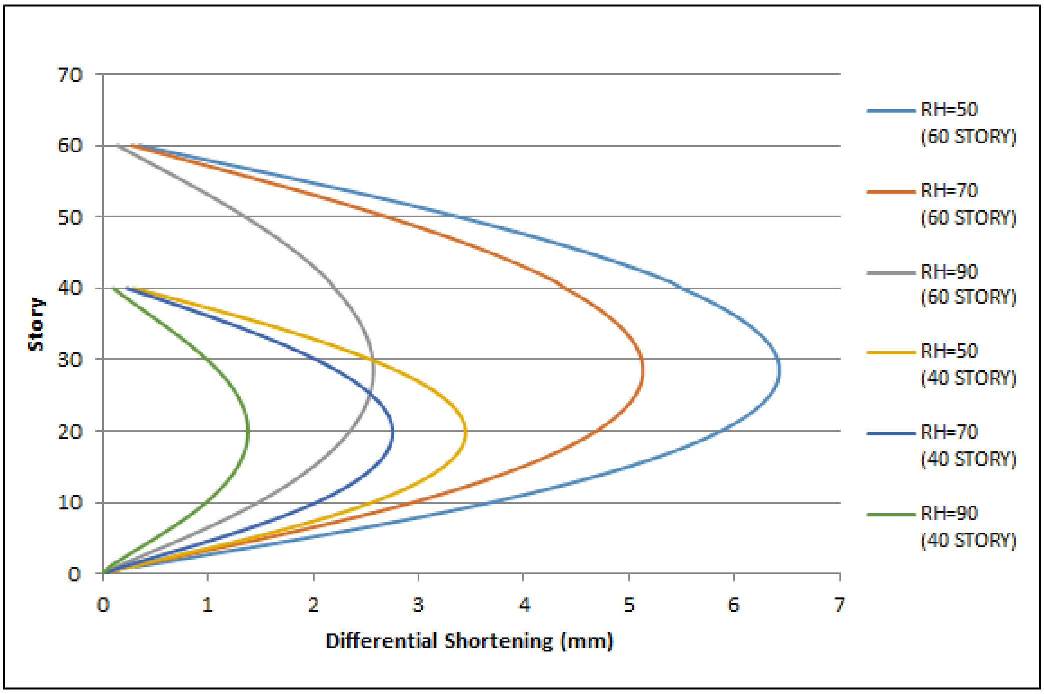


Figure 5.39: Effect of Relative Humidity on Column Differential Shortening in Wall Frame Buildings

Analysis results for axial shortening in 40 and 60 storied wall-frame buildings show that due to increase in relative humidity from 50% to 70% and 90%, creep induced axial shortening of column reduced by 17% and 40%, where as shrinkage induced axial shortening of column reduced by 24% and 70% respectively. Axial shortening of column due to elastic shortening remained unchanged. So total resultant axial shortening reduced by 12% and 30% with increase in relative humidity from 50% to 70% and 90% respectively. The variation in the axial shortening is more near the mid height stories compared to upper and lower stories. For low to medium relative humidity i.e. RH=50% and RH=70%, creep induced shortening is governing , where as for very high relative humidity i.e. RH=90%, elastic shortening is governing. Shrinkage induced shortening is the lowest in all the cases of relative humidity i.e. RH=50%, RH=70% and RH=90%.

Analysis results for differential shortening in 40 and 60 storied wall-frame buildings show that due to increase in relative humidity from 50% to 70% and 90%, creep induced differential shortening of column reduced by 22% and 67%, where as shrinkage induced axial shortening of column reduced by 25% and 70% respectively. Axial shortening of column due to elastic shortening remained unchanged. So total resultant axial shortening is reduced by 20% and 60% with increase in relative humidity from 50% to 70% and 90% respectively. The variation in the differential shortening is more near the mid height stories compared to upper and lower stories. Creep induced shortening is governing in all the cases of relative humidity i.e. RH=50%, RH=70% and RH=90%. Elastic shortening is the lowest in all the cases of relative humidity i.e. RH=50%, RH=70% and RH=90%.

5.5.2 Beam End Moments and Design of Elements

With increase in Relative Humidity from 50% to 70% and 90%, Creep and Shrinkage induced axial as well as differential shortening **decreases** due to reversal and relaxation of stresses, but resultant beam end moments in beam **increases** due to increased total absolute strains in beams. Elastic shortening of column is not affected by the change in relative humidity. Fig. 5.40 and 5.41 show the effect of change in relative humidity on gravity load induced beam end moment(unfactored) for the beam between the exterior columns and first interior columns marked with circle in Fig.5.2 and 5.3 in 40 and 60 storied wall-frame buildings respectively. Maximum beam end moment is obtained considering one step analysis (OSA) and construction stage analysis with ambient relative humidity considered as 50%, 70% and 90%. Negative values of the beam end moment indicates hogging moment at the ends of beam.

Fig, 5.42, 5.44 and 5.43, 5.45 show the effect of relative humidity on design of structural elements i.e. Beams and Columns in 40 and 60 storied wall-frame buildings respectively. Beams considered to study the effect of construction stage & relative humidity on design of beams are the those connected in between the exterior columns and first interior columns marked with Circle in Fig.5.2 and 5.3. Columns considered to study the effect of construction stage & relative humidity on design of columns are the central columns marked with Square in Fig.5.2 and 5.3.

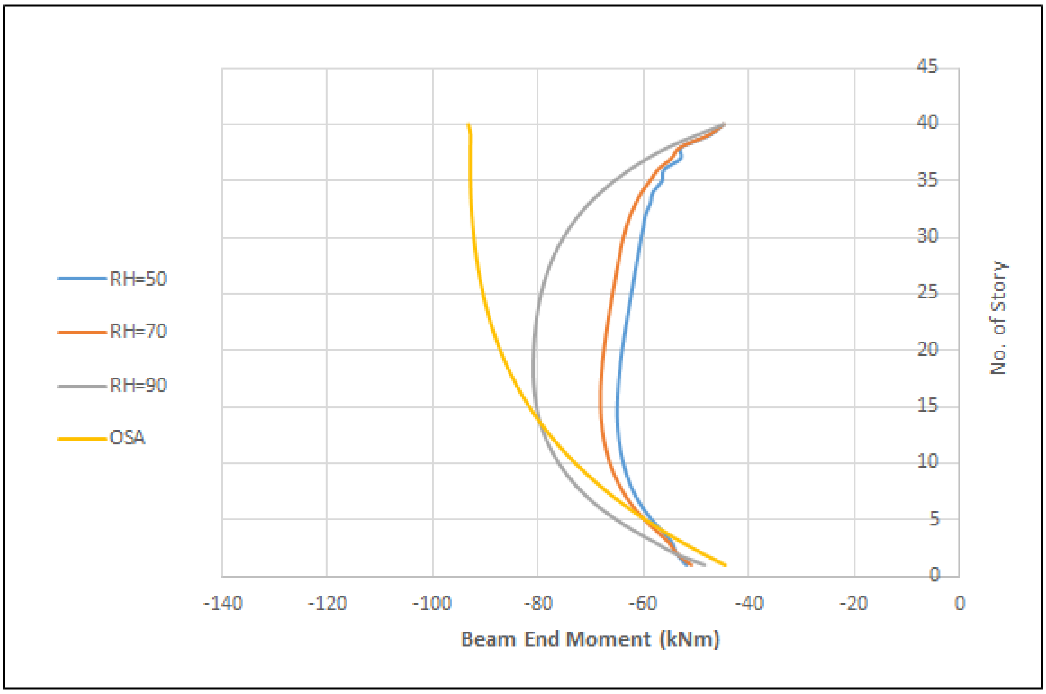


Figure 5.40: Effect of Relative humidity on gravity load induced beam end moments in 40 storied building

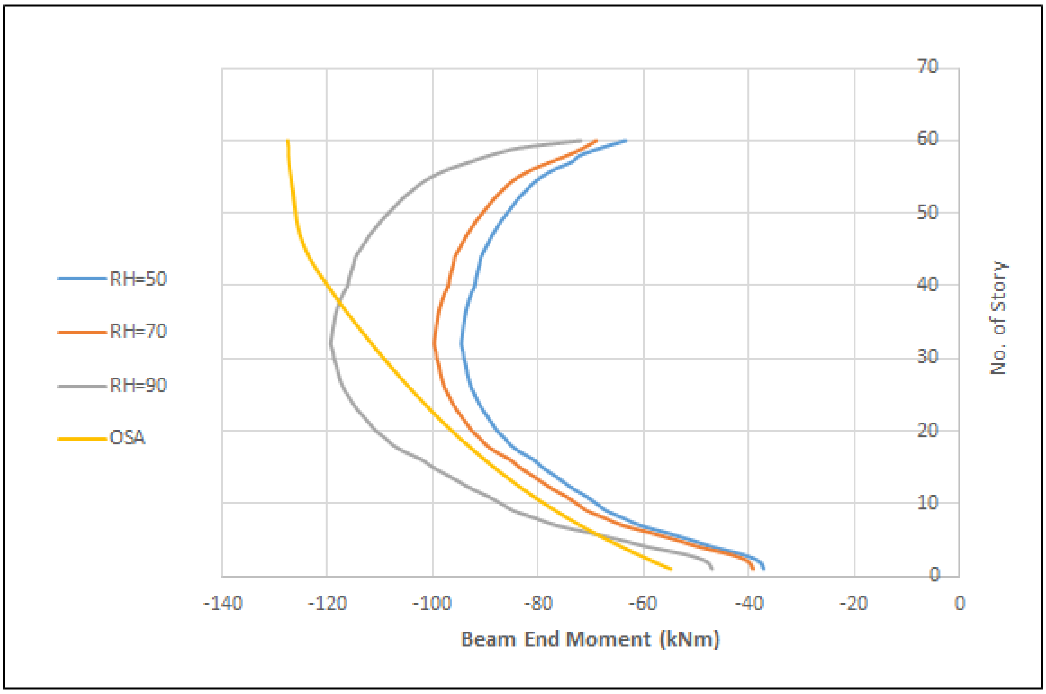


Figure 5.41: Effect of Relative humidity on gravity load induced beam end moments in 60 storied building

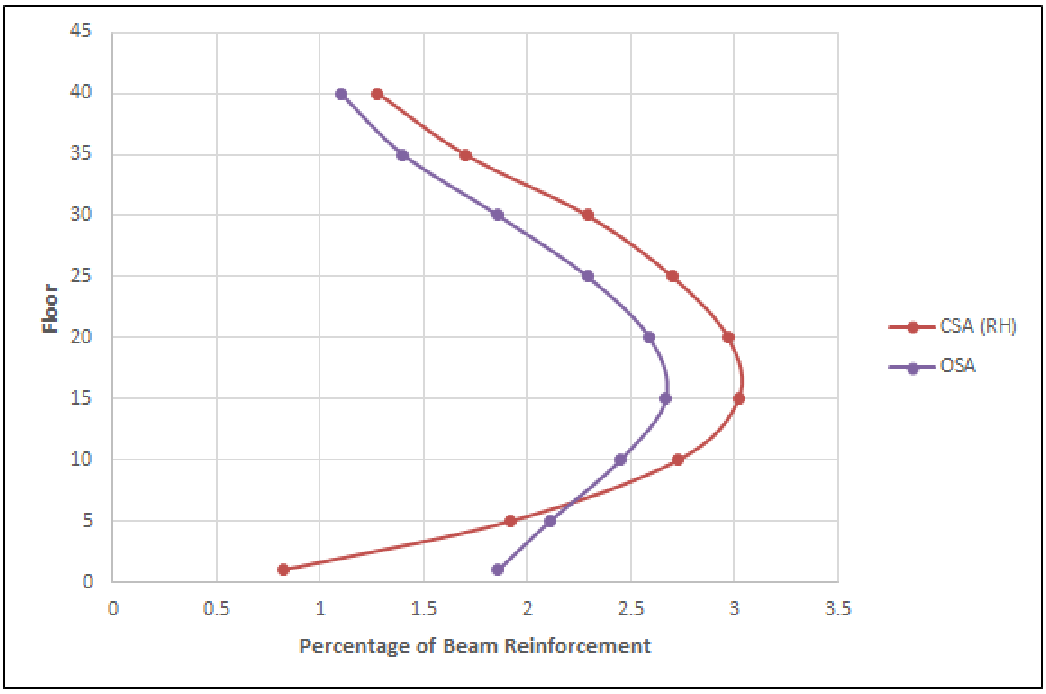


Figure 5.42: Effect of Relative humidity on design of beam in 40 storied building

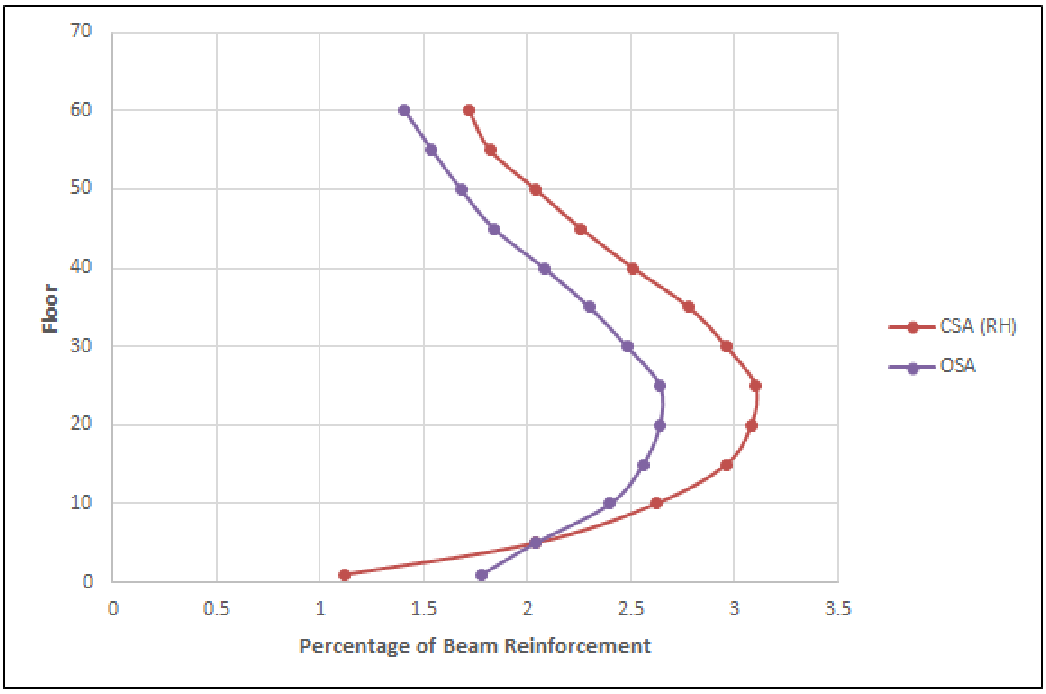


Figure 5.43: Effect of Relative humidity on design of beam in 60 storied building

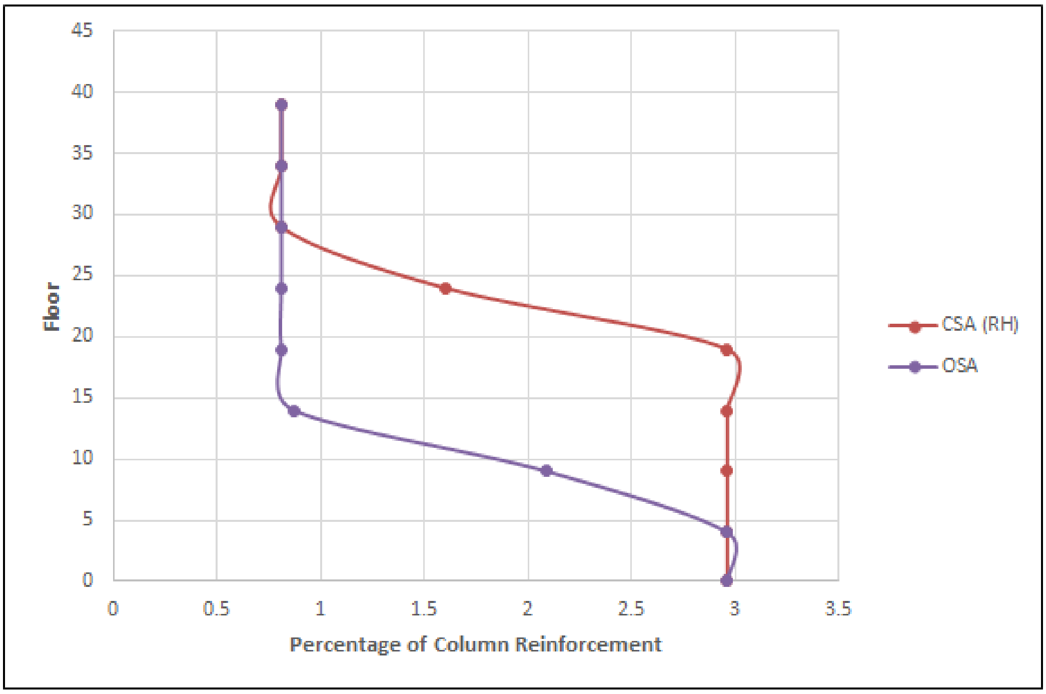


Figure 5.44: Effect of Relative humidity on design of column in 40 storied building

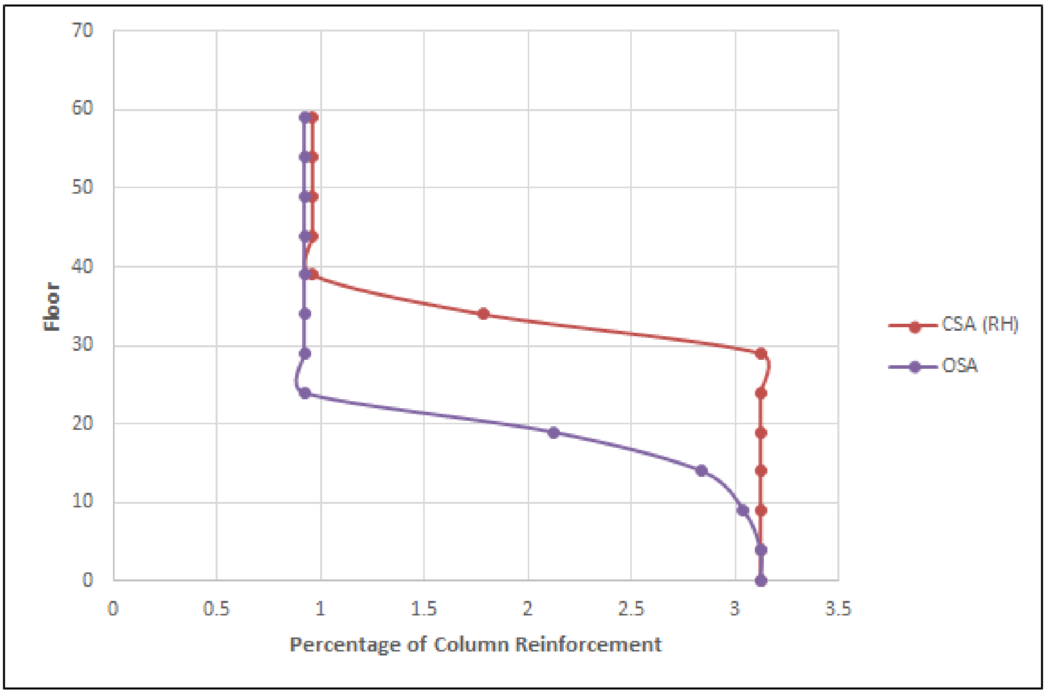


Figure 5.45: Effect of Relative humidity on design of column in 60 storied building

From Fig.5.40 and 5.41 it is observed that due to increase in relative humidity from 50% to 70% and 90%, the beam end moment **increases** by 5% and 25% respectively. The beams near the mid height stories show more change in beam end moment compared to upper and lower stories due to relative humidity and construction stage effect.

In this study, as the design is governed by the lateral load combinations, there is no change observed in the required amount of main reinforcement in beams and columns due to change in relative humidity. Hence the Fig.5.42 to 5.45 shows only the effect of construction stage on design of elements i.e. beams and columns. Results shown with the legend CSA (RH) indicate the required amount of reinforcement in beams and columns obtained through construction stage analysis irrespective of the change in relative humidity.

Due to the construction stage effects, main reinforcement in beams is increased by 15% whereas the reinforcement in columns is increased by 200% near the mid height stories in 40 and 60 storied wall-frame buildings. Main reinforcement in beams obtained by sequential analysis shows lower values in bottom stories compared those obtained by one step analysis. The maximum reinforcement in columns is observed to be same in both the cases of sequential analysis and one step analysis.

5.6 Results and Discussion

Table 5.3, 5.4 and 5.5 shows the Effect of Construction Rate considered in Sequential Analysis on Gravity load induced Beam End Moments in 10, 20 & 30 Storied Rigid Frame Buildings. Table 5.6 and 5.7 shows the Effect of Relative Humidity considered in Sequence Analysis on Gravity load induced Beam End Moments and Design of Elements in 40 and 60 storied Wall-Frame Buildings respectively.

Table 5.3: Effect of Construction Rate on Beam End Moments in 10 Story Building

	OSA	7 dpf	28 dpf
Beam End Moment (kNm)	24.02	13.63	15.98
% Change	–	-43.25	-33.47

Table 5.4: Effect of Construction Rate on Beam End Moments in 20 Story Building

	OSA	7 dpf	28 dpf
Beam End Moment (kNm)	40.37	35.4	39.55
% Change	–	-12.31	-2.03

Table 5.5: Effect of Construction Rate on Beam End Moments in 30 Story Building

	OSA	7 dpf	28 dpf
Beam End Moment (kNm)	48.21	50.72	55.01
% Change	–	+5.21	+14.1

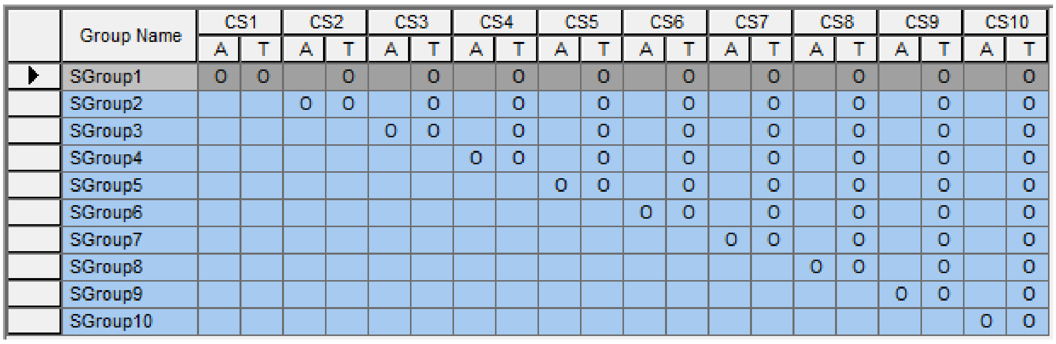
Table 5.6: Effect of Relative Humidity on Beam End Moment and Design of Elements in 40 Storied Wall-Frame Building

	OSA	RH = 50%	RH = 70%	RH = 90%
Beam End Moment (kNm)	93.26	64.99	68.2	80.99
% Change	–	-30.31	-26.87	-13.16
Steel Reinf. (Beam)	2.67	3.02	3.02	3.02
% Change	–	+13.11	+13.11	+13.11
Max. Steel Reinf. (Column)	2.96	2.96	2.96	2.96
% Change	–	0	0	0

Table 5.7: Effect of Relative Humidity on Beam End Moment and Design of Elements in 60 Storied Wall-Frame Building

	OSA	RH = 50%	RH = 70%	RH = 90%
Beam End Moment (kNm)	127.57	94.58	99.75	119.40
% Change	-	-25.86	-21.81	-6.4
Steel Reinf. (Beam)	2.64	3.1	3.1	3.1
% Change	-	+17.42	+17.42	+17.42
Max. Steel Reinf. (Column)	3.12	3.12	3.12	3.12
% Change	-	0	0	0

Fig.5.46 shows the Activation of Structure Group which represents the Schematic Construction Sequence of the Building Models. Each Structure Group, once activated, remains active throughout the life of the structure. Load Groups are of similar nature to structure groups and acts from floor to floor.



Group Name	CS1		CS2		CS3		CS4		CS5		CS6		CS7		CS8		CS9		CS10	
	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
SGroup1	O	O		O		O		O		O		O		O		O		O		O
SGroup2			O	O		O		O		O		O		O		O		O		O
SGroup3					O	O		O		O		O		O		O		O		O
SGroup4							O	O		O		O		O		O		O		O
SGroup5									O	O		O		O		O		O		O
SGroup6											O	O		O		O		O		O
SGroup7													O	O		O		O		O
SGroup8															O	O		O		O
SGroup9																	O	O		O
SGroup10																			O	O

Figure 5.46: Structure Group Activation of Construction Stage

In the Fig.5.46 "CS" indicates **Construction Stage** and "SGroup" indicates **Structure Group**. "A" and "T" in the Fig.5.46 represents the term **Activate** and **Transfer** which indicates activation of structure group and transfer of action of one structure group to another.

Gravity load induced bending moment diagram obtained in MIDAS Gen is shown in the Fig.5.47 and the deflected shape of the building after completion of construction under sequential gravity load is shown in the Fig.5.48.

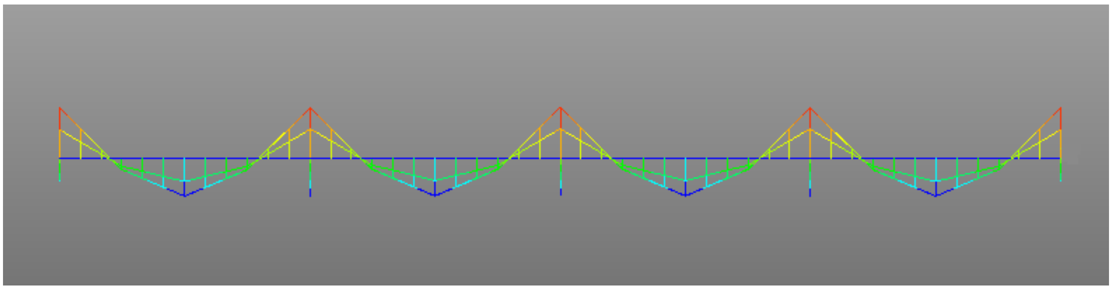


Figure 5.47: Beam End Moment Diagram to Sequential Sequential load

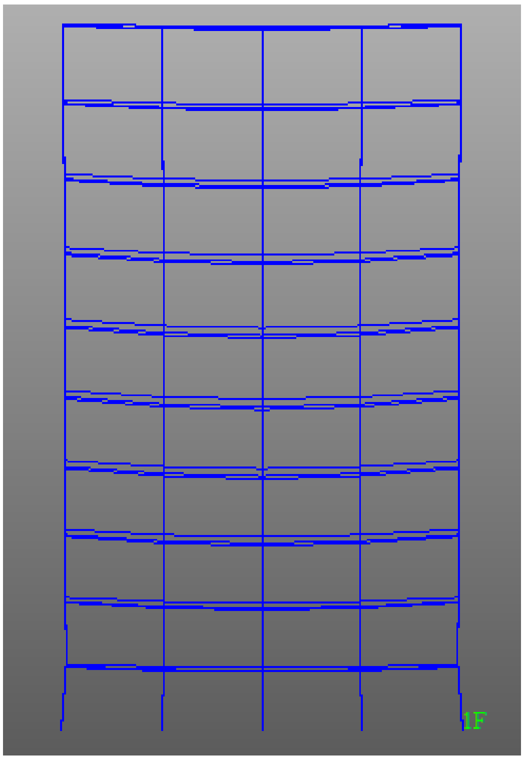


Figure 5.48: Deflected Shape of Building due to Sequential Load

From the above results and study, following observations are made:

- Autogenous shrinkage induced shortening should be considered in the evaluation of column shortening effect for the high-rise building structures, exposed to very low relative humidity of the ambient environment.
- Maximum axial shortening occurs in the central columns of the buildings and maximum differential shortening is observed between the exterior and first interior column located on the shorter span of the building in case of rigid frame buildings and exterior column on the shorter span and central core wall in wall-frame buildings.
- Construction Stage Analysis does not have much impact on low-rise buildings but affects the design of medium to high-rise buildings by increasing the steel reinforcement in the beams.
- Reduced construction rate increases the time dependent column shortening and beam end moments. If the construction rate is lower, the structural elements are supposed to be exposed to the ambient environment for more time duration and which eventually releases the stress due to creep and shrinkage strains.
- Time dependent creep strain plays major role in the column shortening effects in high-rise buildings due to incremental and sustained loadings.
- Increased relative humidity of ambient environment reduces the time dependent column shortening but increases the gravity load induced beam end moments.
- As in the high-rise buildings, the design is governed by the lateral load combinations, the effect of relative humidity on the design of beams and columns are not observed.

5.7 Summary

In this chapter, Effect of construction rate and relative humidity on beam end moments and design of elements such as beams and columns is studied. The increased construction rate could reduce the column shortening and resultant beam end moments. Relatively higher humidity reduced the column shortening values but increased the resultant beam end moments and showed no impact on design of structural elements. Due to construction sequence analysis considering creep, shrinkage and elastic shortening, the main reinforcement in beams and columns is increased in mid-height stories.

Chapter 6

Summary and Conclusion

6.1 Summary

Introduction of column shortening effect, implementation of construction stage analysis and column shortening due to secondary effects like creep, shrinkage and elastic shortening are presented in this report. Effect of construction stage analysis and column shortening on behavior of high-rise buildings is studied. Literature review of the relevant research articles is carried out which includes parameters associated with column shortening, effects of column shortening on behavior of medium to high-rise buildings and analytical and experimental procedures of column shortening prediction.

ETABS and MIDAS Gen software are used for carrying out nonlinear construction stage analysis and for estimating the column shortening effect. Modeling of construction stage and secondary effects like creep, shrinkage and elastic shortening in buildings models using ETABS and MIDAS Gen software are explained in detail.

Construction sequence analysis of low, medium and high rise building is carried out considering the elastic shortening effect of columns and lumping of varying number of floors using ETABS software. For this purpose, rigid frame buildings with 10, 20 and 30 story height and 27m $\times$ 18m plan dimensions are considered. Lumping of varying number of floors is considered for the parametric study and its effect on building structures is studied. Effect of column cross section and floor lumping on column shortening and differential column shortening are presented.

Analytical study to estimate the realistic time dependent response of building structure to the material nonlinearities such as creep, shrinkage and elastic strains of concrete is carried out by performing construction stage analysis using MIDAS Gen software. Time dependent material properties, construction rate of the building and relative humidity of the environment are considered for study. Rigid frame buildings with 10, 20 and 30 story height and 27m $\times$ 18m plan dimensions and wall-frame buildings with 40 and 60 story height and 45.5m $\times$ 29.5m plan dimensions are considered for the analytical investigation. Material nonlinearities are modeled in software, for analysis of buildings, by calculating the time dependent strains in concrete as per the model specified in "CEB - FIP Model Code (1990)".

Effects of creep, shrinkage and elastic shortening on bending moments in beams and design of the structural elements of medium to high-rise buildings are studied and results are discussed.

6.2 Conclusion

Based on the present analytical study, following concluding remarks are derived.

- Elastic shortening analysis of buildings:
  - Larger cross-section of columns are suitable in order to reduce the resultant differential shortening of columns.
  - Lumping of floor is an effective method to include the construction stage effect in the analysis and design of medium to high-rise buildings.
  - Lumping of less number of floors increases the accuracy of analysis results whereas lumping of more number of floors reduces the time required for

the iterative analysis.

  - Amount of error present in the column shortening prediction decreases with the increasing height of the building.
  - Two floor lumping (2F) is found to be an effective lumping size which gives the accuracy of the results as high as 95% and reduces the time required to complete the iterative analysis.
  - Construction sequence analysis has minor impact on the resultant axial dead loads on columns.

- Inelastic shortening analysis of buildings:
  - Maximum axial shortening occurs in the central columns of the buildings and maximum differential shortening is observed between the exterior and first interior column located on the shorter span of the building in case of rigid frame buildings and exterior column on the shorter span and central core wall in wall-frame buildings.
  - With decrease in the construction rate from 7 days per floor to 28 days per floor, creep and shrinkage induced shortening increases whereas elastic shortening reduces.
  - The effect of change in construction rate on column shortening reduces with the height of building.
  - With decrease in the construction rate from 7 days per floor to 28 days per floor, about 15% increase in gravity load induced beam end moments is observed in the high-rise buildings.
  - With increase in the relative humidity from 50% to 70% and 90%, about 15% and 40% reduction is observed in creep induced axial shortening whereas about 25% and 70% reduction is observed in shrinkage induced axial shortening.
  - With increase in the relative humidity from 50% to 70% and 90%, about 25% and 70% reduction is observed in creep as well as shrinkage induced

differential shortening.

- Effect of relative humidity can be neglected in elastic as well as differential elastic shortening of columns.
- With increase in relative humidity from 50% to 70% and 90%, about 5% and 25% increment is observed in the beam end moments.
- Due to construction stage effects, about 15% increase in the main reinforcement in beams and about 200% increase in the reinforcement in columns is observed in mid-height stories of the high-rise buildings.
- The allowance for column shortening of around 10 to 15 mm should be kept in buildings up to 30 story height and around 20 to 25 mm and 40 to 50 mm should be kept in buildings with 30 to 40 and 40 to 60 story height.
- Differential shortening of around 4 to 5 mm can be expected in adjacent columns and core of the high-rise buildings

6.3 Future Scope of Work

The present work can be extended in future to include following aspects:

- Column shortening effect in outrigger structures and in other structural systems used for high-rise buildings.
- Column shortening effect on foundation design and construction of high-rise buildings.
- Column shortening effect on geometrically complex buildings
- Effect of stress transfer from concrete to steel due to time dependent material response.
- Effect of type of cement used in concrete
- Lateral load induce column shortening in high-rise buildings.

Appendix A

Calculation of Material Properties

Time dependent Creep Coefficient, Shrinkage Strain, Strength Function and Modulus of Elasticity of Concrete are calculated as per the provisions of CEB (1993), CEB-FIP Model Code 1990 using excel spreadsheet, of which the input parameters and output values are shown in **A.1** and **A.2** respectively.

A.1 INPUT PARAMETERS:

⇒ **Strength**

s	0.25
$\mathbf{t}_1$	1

⇒ **Elasticity of Concrete**

Aggregate	Basalt	
α_E	1.2	
$\mathbf{E}_{co}$	21500	N/mm^2
$\mathbf{E}_{ci}$	36239.47	N/mm^2

⇒ **Creep Coefficient**

RH	70	%
$\mathbf{RH}_0$	100	%
$\mathbf{h}_0$	100	mm
$\mathbf{h}_b$	176.47	mm
$\mathbf{h}_c$	500	mm
h	100	mm
$\mathbf{t}_1$	1	days
$\mathbf{f}_{cmo}$	10	N/mm^2
$\mathbf{f}_{ck(cube)}$	25	N/mm^2
$\mathbf{f}_{ck(cyl)}$	20	N/mm^2
$\mathbf{f}_{cm}$	28	N/mm^2
$\mathbf{t}_0$	10	days
Φ_{RH}	1.65	
ß$(\mathbf{f}_{cm})$	3.17	
ß$(\mathbf{t}_0)$	0.59	
Φ_0	3.11	
ß$_H$	406.50	(<=1500)

⇒ **Shrinkage Strain**

$\mathbf{t}_S$	3	days
ß$_{sc}$	5	
ß$_{sRH}$	0.6570	
ß$_{RH}$	-1.0184	
$\varepsilon_s(f_{cm})$	0.0005	
ε_{cso}	-0.0005	

A.2 OUTPUT VALUES:

⇒ Development of Strength and Elasticity with Time

time (days)	**Strength**	**Elasticity**	
t	**ß$_{cc}$(t) f$_{cm}$**	**ß$_{E}$(t) E$_{ci}$**	
1	1.86	21195.03	N/mm^2
2	3.72	25725.36	N/mm^2
3	5.58	28030.53	N/mm^2
4	7.44	29501.80	N/mm^2
5	9.30	30549.94	N/mm^2
6	11.16	31347.45	N/mm^2
7	13.02	31981.64	N/mm^2
8	14.89	32502.16	N/mm^2
9	16.75	32939.73	N/mm^2
10	18.61	33314.50	N/mm^2
11	20.47	33640.33	N/mm^2
12	22.33	33927.13	N/mm^2
13	24.19	34182.20	N/mm^2
14	26.05	34411.04	N/mm^2
15	27.91	34617.91	N/mm^2
16	29.77	34806.13	N/mm^2
17	31.63	34978.39	N/mm^2
18	33.49	35136.82	N/mm^2
19	35.35	35283.22	N/mm^2
20	37.21	35419.03	N/mm^2
21	39.07	35545.49	N/mm^2
22	40.94	35663.63	N/mm^2
23	42.80	35774.34	N/mm^2
24	44.66	35878.37	N/mm^2
25	46.52	35976.36	N/mm^2
26	48.38	36068.89	N/mm^2
27	50.24	36156.45	N/mm^2
28	52.10	36239.47	N/mm^2

⇒ **Variation of Creep and Shrinkage with Time**

time (days)	**Creep Coefficient**	**Shrinkage Strain**
t	Φ_0 **ß**$_c$**(t-t**$_0$**)**	ε_{cso}**ß**$_s$**(t-t**$_s$**)**
13.34	0.7337	-0.000081
17.78	0.9425	-0.000096
23.71	1.1124	-0.000113
31.62	1.2681	-0.000132
42.17	1.4183	-0.000152
56.23	1.5664	-0.000174
74.99	1.7139	-0.000198
100	1.8607	-0.000223
133.35	2.0057	-0.000249
177.83	2.1473	-0.000276
237.14	2.2830	-0.000303
316.23	2.4106	-0.000329
421.7	2.5275	-0.000353
562.34	2.6322	-0.000375
749.89	2.7235	-0.000395
1000	2.8013	-0.000412
1333.52	2.8661	-0.000426
1778.28	2.9189	-0.000437
2371.37	2.9613	-0.000447
3162.28	2.9949	-0.000454
4216.97	3.0211	-0.000460
5623.41	3.0414	-0.000464
7498.94	3.0570	-0.000468
10000	3.0689	-0.000470

Appendix B

List of Papers Published/Communicated

List of Papers Published and Presented

- Snehal D. Poojara and Dr. Paresh V. Patel (2014), "Axial Deformation of Columns in Multi-Story R.C. Buildings," *Proceedings of the International Conference on ACECIM'14*, SRM UNIVERSITY, Chennai, Vol. 1, pp. 678-685
- Snehal D. Poojara and Dr. Paresh V. Patel (2014), "Study of Column Shortening on Behavior of Multi-Story R.C. Buildings," *Proceedings of the* 5^{th} *National Conference on NCEVT'14*, PIET, Vadodara, Vol. 5, pp. 83-87
- Snehal D. Poojara and Dr. Paresh V. Patel (2014), "Axial Deformation of Columns in Multi-Story R.C. Buildings," *International Journal of Civil Engineering & Technology (IJCIET)*, IAEME, Chennai, Vol. 5, Issue 3, pp. 294-300

List of Papers Communicated

- Snehal D. Poojara and Dr. Paresh V. Patel (2014), "Differential Shortening of Vertical Elements in Tall Reinforced Concrete Buildings," *International Conference on Sustainable Civil Infrastructure-2014*, IIT Hyderabad & ASCE India Section, Hyderabad (Abstract Accepted)

Appendix C

List of Useful Websites

a. www.ctbuh.org

b. www.concrete.org

c. www.fib-international.org

d. ascelibrary.org

e. www.sciencedirect.com

f. www.icjonline.com

g. www.icevirtuallibrary.com

h. www.nrcresearchpress.com/page/cjce

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j. www.csiamerica.com

k. en.midasuser.com

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