Parametric Studies on Differential Shortening Of Vertical Members in High-Rise R.C Building

Vivek simha,

Post Graduate Student, Department Of Civil Engineering

The National Institute Of Engineering, Mysore, India

Dr. G. Sarangapani

Professor, Department Of Civil Engineering

The National Institute Of Engineering, Mysore, India

Abbreviations

ETABS - Extended three dimensional Analysis of Building Systems

RC – Reinforced Concrete

3D - Three Dimensional

OSA – One Step Analysis

CSA – Construction Stage Analysis

Notations

E – Modulus of Elasticity of material

I- Moment of Inertia of the structural element

Δ - Axial Displacement of the Member

L – Length of the Member

f_{ck}= Characteristic Cube Compressive Strength of Concrete

ABSTRACT

At present, there is a growing demand for residential units and office suites in India, resulting in the construction of large number of high rise buildings. By far, reinforced concrete is the most widely accepted and used material in high rise structures.In addition to the gravity loads, lateral loads due to earthquake and wind are other loads that should be considered in such high-rise buildings. These lateral loads cause horizontal displacement (lateral drift) of these buildings. To control this lateral drift, it is necessary to provide very large column sizes. However, providing such large column sizes leads to uneconomical sections. Therefore, the trend followed these days is to provide a central core, with shear wall. These shear walls, in addition to lateral loads also resist larger axial loads. Due to the fact that shear walls are of larger size in comparison to the column, they undergo less compression in comparison to column under axial loads. This leads to differential shortening between the two adjacent vertical members. The conventional analysis method for tall buildings consider all loads being applied in a single step (one step), but in practice self-weight and part of live load are released on the building gradually as the construction progresses and therefore construction stage analysis using software E-TABS needs to be carried out.

In the present work, a parametric study is done on differential shortening of vertical members in tall R.C buildings. The parameters considered are varying the columns sizes, increasing storey height and grade of concrete. Comparison of various parameters such as beam moments and differential shortening and effect of spans using one step analysis and construction stage analysis is studied

Keywords: Shear wall, differential shortening, one step analysis, construction stage analysis, E-TABS

1. Introduction

In modern tall buildings, vertical members such as shear walls and columns are subjected to differential shortening continuously during construction stage and installation time. In case of steel structures, the steel columns undergo only elastic shortening at the very instance of load application. Differential shortening can create a number of problems in any given structure. This could include sudden unexpected movement in the slab-column frame. In general, building structures are analyzed in a single step using linear static analysis (OSA) on the basic assumption that the building is fully loaded i.e. the whole structure is loaded at a single time. In reality, however, the structure is constructed storey wise. Dead load is applied storey wise and the finishing load is also imposed in stages as the structure is constructed in stages. The maximum shortening of a column occurs at the roof storey, reducing to zero at the base. The main purpose in computing anticipated column shortening is to compensate for the differential length changes during construction so as to ensure that the slabs will be horizontal in their finial position. The designer has a degree of control over his design assumptions and modulus of elasticity to control the effect of shortening.

2. Objective

The objective of this study is to see the effect of one step analysis and construction stage analysis on beam moments and differential shortening and compare structure with and without shear wall on differential shortening, to also develop an understanding on the effect of the following parameter on differential shortening - storey height, grade of concrete and column sizes.

3. Literature Review

M.HassanienSerror and A.Essam El-D [1]talk about the influence of floor levels and type of static system on differential shortening using construction sequence analysis. The structure is modelled and analysed in MIDAS/GEN. Study is done for 20 to 60- floor residential buildings, with 5x5m bay and column spacing of 4x4m. Two structural systems have been studied first one is shear wall structure and second one is outrigger structures. The storey height considered is 3m. The column reinforcement used in the study is 2% for a 40-storey building. Outrigger is placed at level 20 and for 60-storey at level 20 and 40. From the results obtained it was observed that for a shear wall structure, the maximum floor differential displacement occurs at a level around ⅔ of the building height, whereas for an outrigger structure, it occurs at about ½ to 4/5 heights. It was concluded that for a shear wall structure as the storey increases, or column steel ratio increases, or beam axial stiffness increases, the floor differential displacement increases. The behaviour of outrigger is unique as the storey height increase has very small effect on the column shortening. Using one step analysis the maximum floor differential displacement is overestimated by twofolds to threefolds. In order to capture the effect of differential column shortening, it is recommended to use construction sequence analysis for concrete structures. SnehalD.Poojara and Dr.Paresh V. Patel [2] investigated the influence of change in column size and lumping of different number of floors on axial column shortening. The lumping size of floor varies from one floor to five floor lump and the effective lumping size is found. The study is for 10, 20 and 30 storey buildings. It was observed that as the storey increases the differential shortening proportionally increases. To take the effect of sequential dead load into account, construction stage analysis has been carried out using ETABS.It is concluded that with increases in structure height the column shortening should not be disregarded. Accurate results are achieved by lumping two floors. Tianyi Yi and Xingdong Tong[3] talk about the effect of construction sequence in typical medium to high rise building. The effects of beam to column axial stiffness and increase in storey on differential shortening of column is studied. The storey height varies from 20-80 storeys with column spacing of 30ft. Two types of structures are used one with shear wall and other with outriggers. The outriggers are placed at level26 for a 40-story, level 20 and 40 for a 60-story and level 20, 40 and 60 for an 80-storey building. Two different columns are used – 1. Concrete with 2% reinforcement ratio and 2.Steel column. The strength of concrete varies between 10ksi to 5ksi and steel grade is A992G50. A comparison of four cases has been studied – 1. Storey level 2. Shear wall and outrigger structure 3. Reinforced column and steel column 4. End beam condition pinned and fixed. The structure is modelled and analysed in ETABS V.9 using construction sequence analysis. In the shear wall structure, for a 40-storey and above differential shortening between exterior column and shear wall causes noticeable floor unevenness. In horizontal members additional moments are developed, whereas column forces have no effect. In case of outrigger structures the effect of shortening can be ignored.

4. Background

During construction of a structure the loads such as dead load and part of live load are applied floor by floor. However, when the structure is modelled in software the dead load, live load and the superimposed loads are all applied together. To take into account the effect of sequential dead load and live load on shortening, construction stage analysis is carried out using software Extended Three Dimensional Analysis Of Building Systems (ETABS).

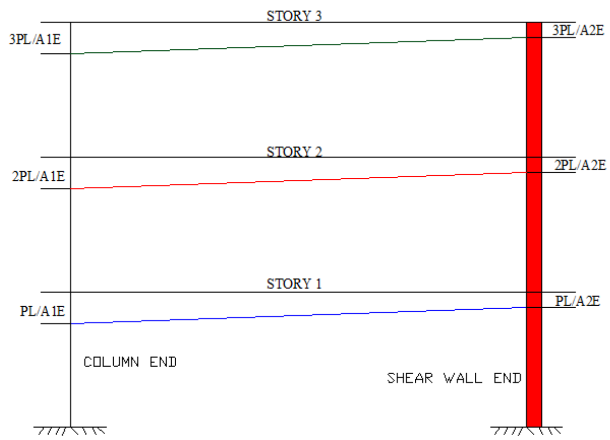


Figure 1: Construction of a three storey building using CSA

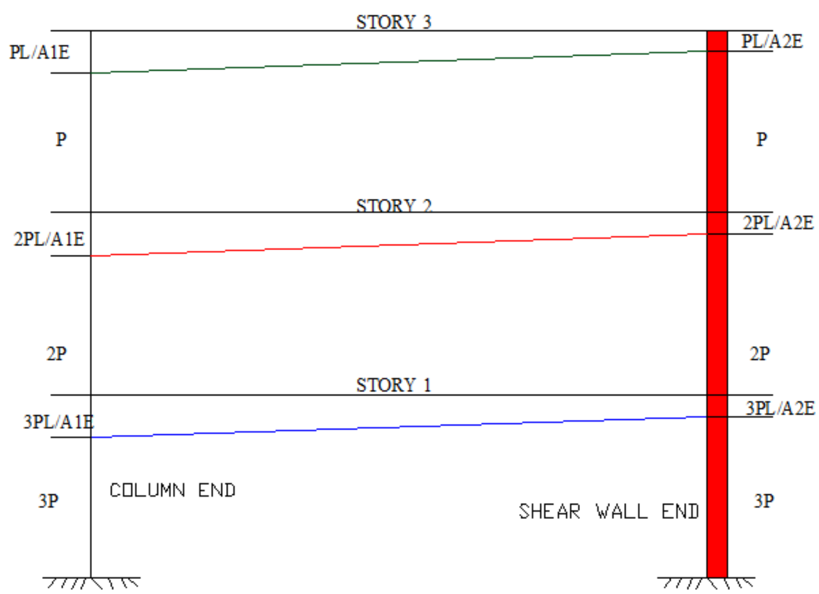


Figure 2: Construction of a three storey building using OSA

In CSA the total amount of shortening occurring is $\frac{3PL}{A1E}$ in total, where as in case of OSA the total shortening occurring is $\frac{6PL}{A1E}$ at the column end. When OSA is done it is assumed that the structure is loaded at once, hence the load on the storey one column is 3P, storey two columns is 2P and storey three column is P. The shortening occurring in storey one is $\frac{3PL}{A1E}$, in storey two is $\frac{2PL}{A1E}$ and in storey three is $\frac{PL}{A1E}$. The total shortening occurring in column is $\frac{3PL}{A1E}+\frac{2PL}{A1E}+\frac{PL}{A1E}=\frac{6PL}{A1E}$In CSA each floor is analyses at a time, the amount of shortening undergone in storey one and two is corrected when storey three is constructed. Therefore the shortening in storey three is cumulative of storey one, storey two and storey three.

5. Methodology of the work

The plan of the building investigated is such that it has core wall at centre and peripheral columns. The vertical members are connected by stiff beams. The shape of the structure is curved. Due to this curvature the length of the beams are not of equal length throughout, the effect of equal span and unequal span on differential shortening can be studied. Moment of inertia of a shear wall is higher than the moment of inertia of a column; therefore shear wall is a stiffer member than column. Hence the shortening happening in column is far greater than the shortening happening in shear wall. In this study an office building with 10, 20, 30 and 40 story is considered.Column number C10 and shear wall number W15 & W16, are the members investigated in the study.

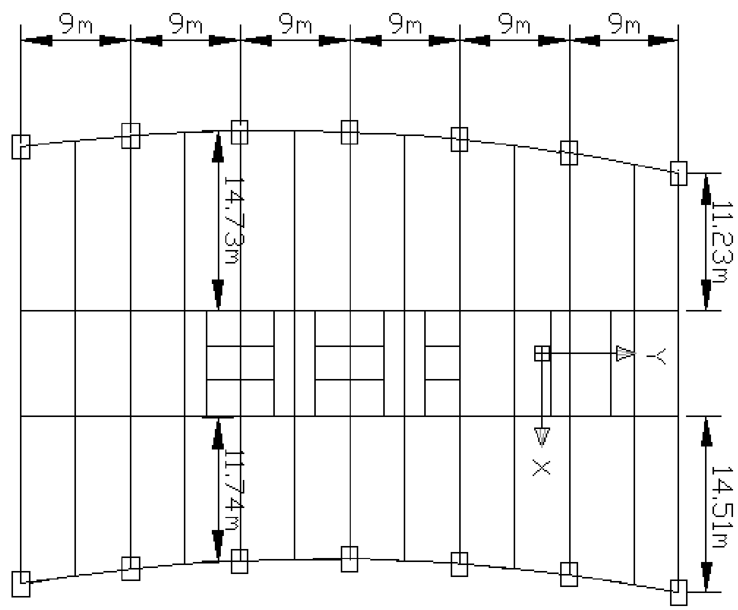


Figure 3: Plan of the structure

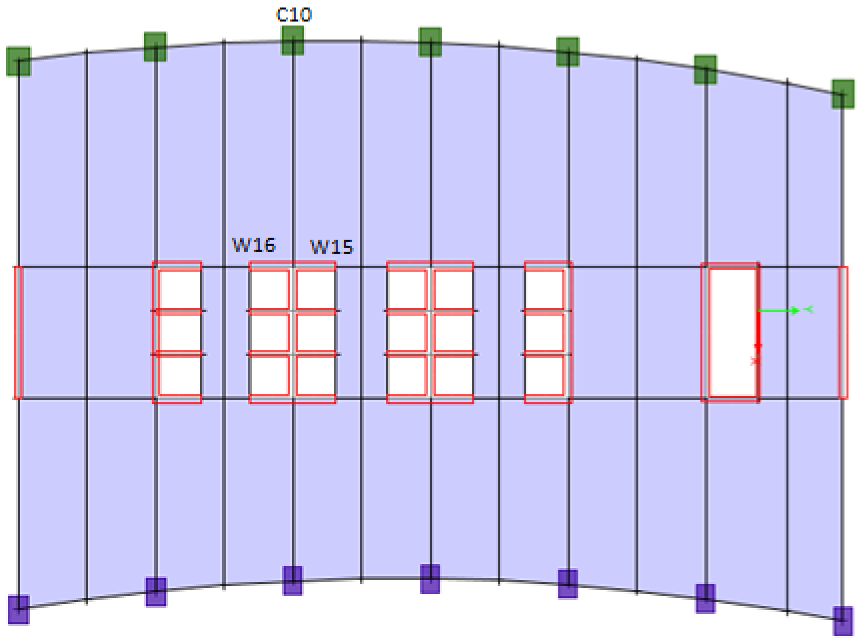


Figure 4: Layout of beam, column and shear wall

The column sizes are shown in table 1 and 2. As the structure is curved the frame span of either side of shear wall is different, hence the column sizes on either side is different. The column sizes are calculated using reinforcement ratios of 2%, 3% and 4%.

Table 1: Column dimension for longer frame span

STORY	REINFORCEMENT RATIO		
	2%	3%	4%
10 STOREY	900 x 800 mm	800 x 800 mm	800 x 700 mm
20 STOREY	1400 x 1000 mm	1200 x 1000 mm	1000 x 1000 mm
30 STOREY	1800 x 1200 mm	1600 x 1200 mm	1600 x 1000 mm
40 STOREY	1800 x 1600 mm	1800 x 1400 mm	1800 x 1200 mm

Table 2: Column dimension for shorter frame span

STORY	REINFORCEMENT RATIO		
	2%	3%	4%
10 STOREY	800 x 800 mm	800 x 700 mm	800 x 600 mm
20 STOREY	1400 x 900 mm	1200 x 900 mm	1000 x 900 mm
30 STOREY	1800 x 1100 mm	1600 x 1000 mm	1600 x 900 mm
40 STOREY	1800 x 1400 mm	1800 x 1200 mm	1800 x 1100 mm

In this study beam dimensions used is 900 x 600 mm and 200 x 600 mm. Shear wall thickness of 500 mm and 300 mm are used. The thickness of slab in all the models is taken as 150mm. M40, M50 and M60 grade of concrete is used.

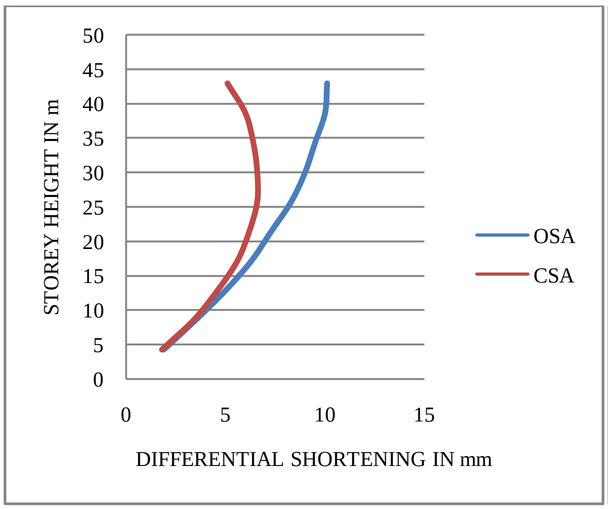
6. Research Cases

Study is done for 10, 20, 30 and 40-story buildings to investigate the effect of differential shortening of vertical members. The objective of the study is to compare beam moments, differential shortening between OSA and CSA. Also, to see the effect of storey, grade of concrete and column size on differential shortening.

7. RESULTS AND DISCUSSION

7.1 Comparisons between OSA and CSA

7.1.1 Differential Shortening



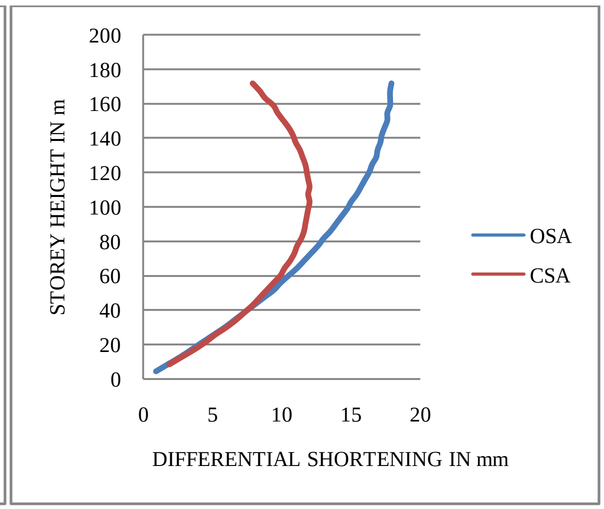


Figure 5:Variation in differential forshortening 10-storey

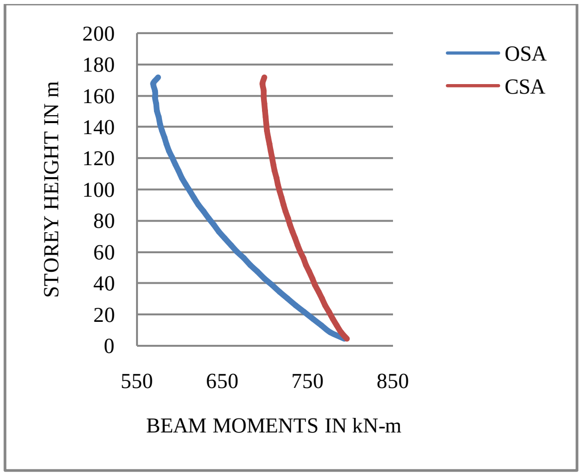
Figure 6: Variation in differential shortening for 40-storey

The differential shortening between vertical members are overestimated in OSA and in comparison to CSA. In 20-storey the maximum differential shortening is 17.2mm in OSA and in CSA 11.4mm was observed, similarly in 30-storey 18.2mm for OSA and 12.1mm for CSA. As the height of the structure increases differential shortening also increases.

By comparing the beam moments and differential shortening between OSA and CSA it can be clearly seen that CSA gives a realistic result in comparison to OSA. This variation is due to the method of analysis, in CSA the structure is analysed floor by floor.

7.1.2 Beam moments

In this study beam forces at column end and shear wall are investigated for 10, 20, 30 and 40-storey buildings.



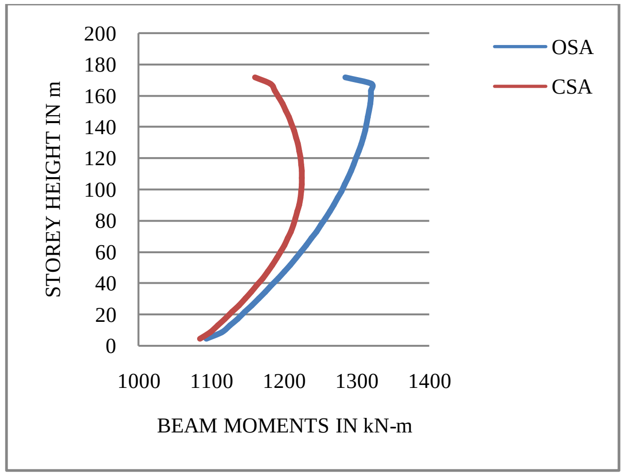


Figure7: OSA and CSA at Column End

Figure 8: OSA and CSA at Shear Wall End

The beam moments at column end in OSA is underestimated in comparison to CSA, whereas in case of shear wall end the beam moments are overestimated. Similar results were seen for 20-storey, in OSA at column end beam moment observed was 672.9kN-m and in CSA 780.2kN-m, in shear wall end 1291.44kN-m was obtained for OSA and 1183.5kN-m for CSA. Similar result was seen for 30-storey building.

7.1.3 Variation of frame span

In this study the effect of frame span on the two methods ofanalysis is observed.

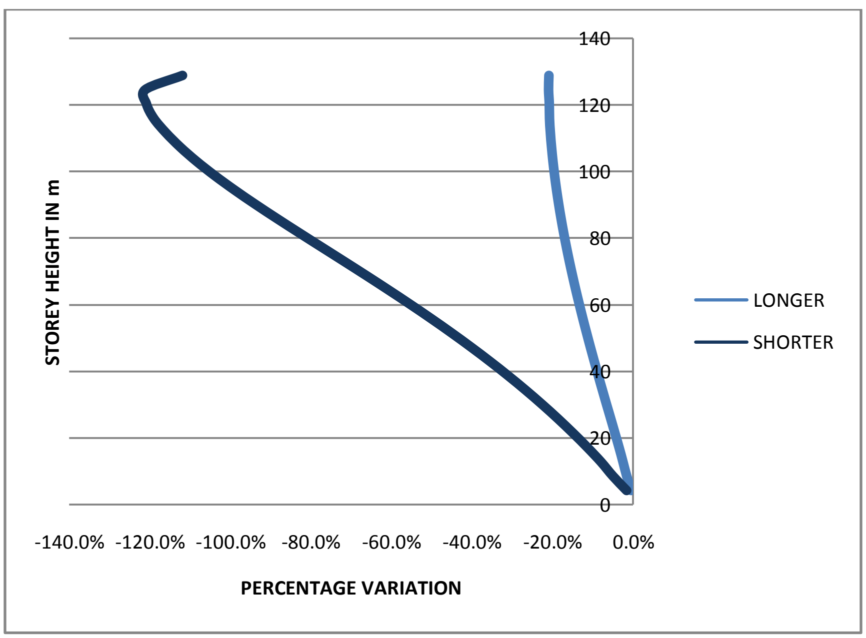


Figure9: Percentage variation between OSA and CSA for equal and unequal spans at column end

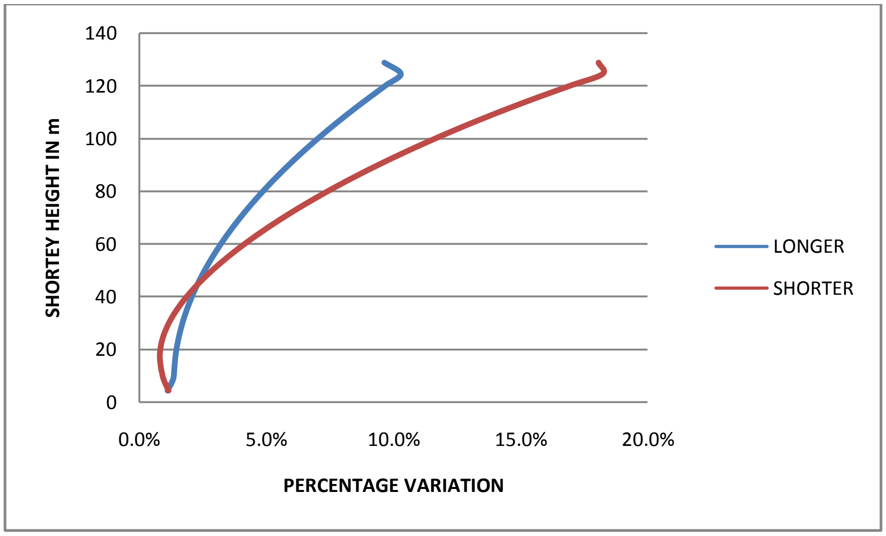


Figure10: Percentage variation between OSA and CSA for different spans at shear wall end

When the frame spans are shorter in the structure the variation between OSA and CSA in the beam moments in the column end shows a drastic difference in moments between the two analyses. In the shorter frame span the moments in OSA are underestimated nearly by 112%, where as in longer span the variation is just 21%, this variation in moments is due to the situation of sinking of supports.

$$\text{Moment} = 6EI\Delta/L^2$$

Where 'E' is the modulus of elasticity of concrete used, 'I' is the moment of inertia of the beam section, 'Δ' axial displacement and 'L' is the length of the beam. Even though the differential shortening remains almost same as there is a change in the length of the beams there is a large variation in the beam moments. The length of the frame in longer span is 14.55m and shorter span is 11.74m. Therefore with the increase in span the moment reduces, hence in shorter frame span the moments observed is more in comparison to longer frame span. With increase in height of the structure this effect will become more effective, hence during design this parameter should be carefully looked into.

7.2 Storey Height (Considering CSA)

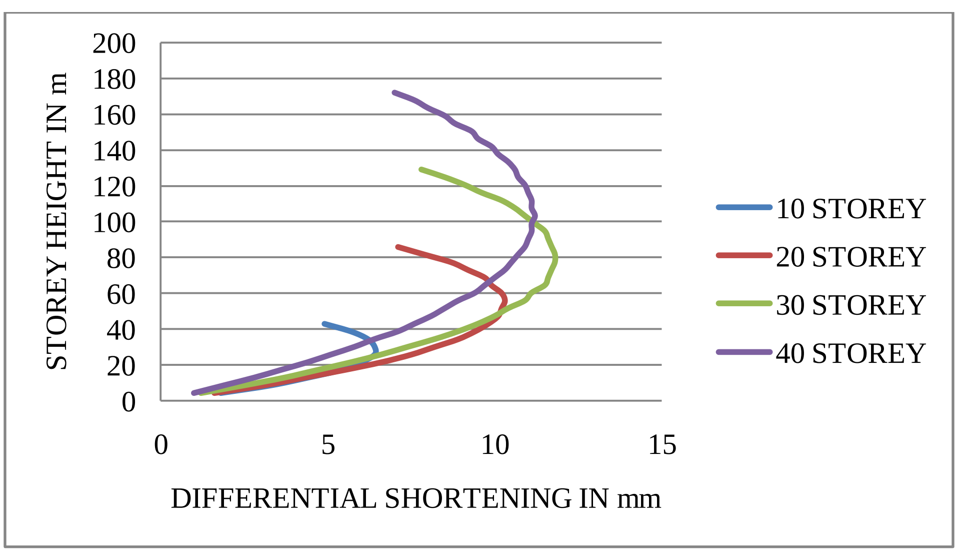


Figure11: Differential shortening at different storey height

In the above graph it can be clearly observed that as the storey height increases the differential shortening also increases. This is because as the dead load is more the axial deformation will also be more with increase in the height. The maximum differential shortening of the building varies from 1.8 to 6.6 mm in 10-story building, 1.7 to 11.4mm in 20-story building, 1.3 to 12.1 mm for 30-story building and 0.9 to 12mm for 40-story building. It can be seen that for 10-story building the differential shortening is very less compared to the rest of the story heights. It can be observed that the differential shortening for 30-story and 40-story is almost same.This is because the column sizes proportionally increases with the height of the structure.

7.3 Variations in Grade of Concrete(Considering CSA)

The Modulus of Elasticity is the only varying parameter with the variations in the grade of concrete. Modulus of elasticity for concrete is given by the expression

$E_c = 5000\sqrt{f_{ck}}$

E_c= Modulus of elasticity in N/mm^2

f_{ck}= Characteristic cube compressive strength of concrete in N/mm^2

Table 3: Modulus of elasticity for different grade of concrete

GRADE OF CONCRETE	M40	M50	M60
MODULOUS OF ELASTICITY IN MPa	31622.78	35355.34	38729.83

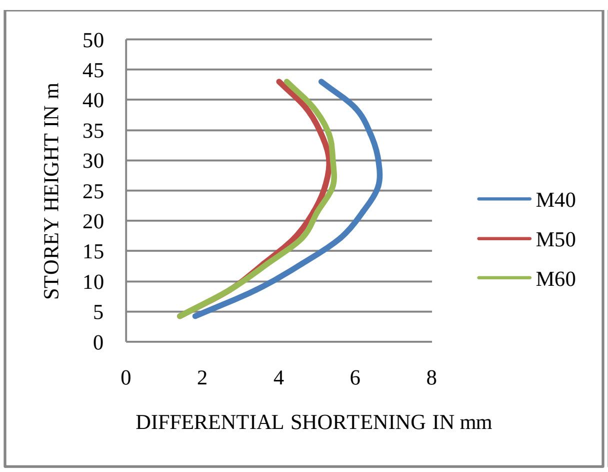


Figure 12: Differential shortening for storey-10

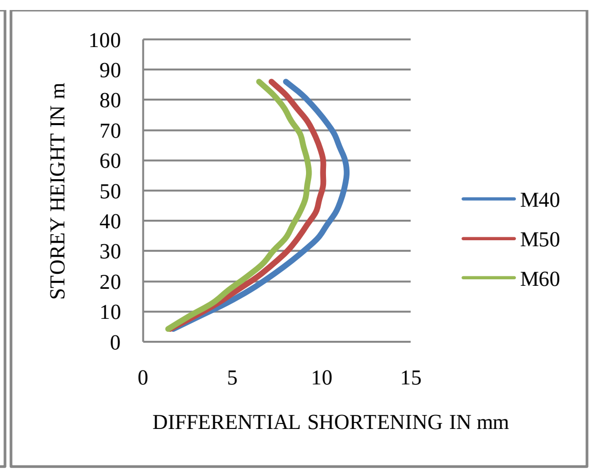
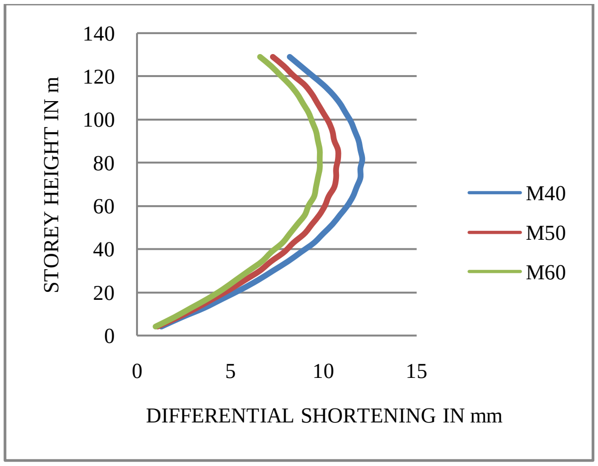


Figure 13: Differential shortening for 20 -storey



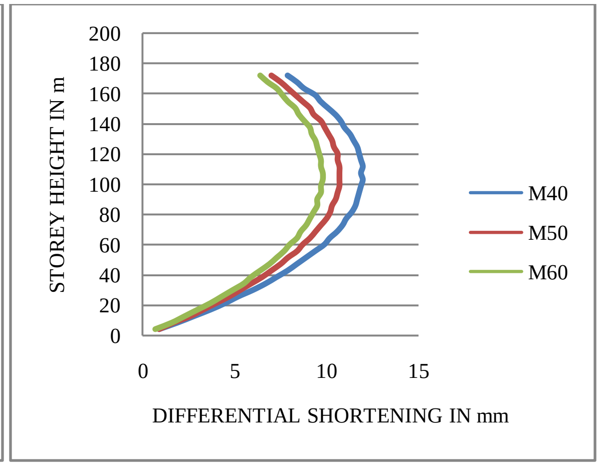


Figure14: Differentialshortening for 30-storey **Figure** 15: Differential shortening for 40- storey

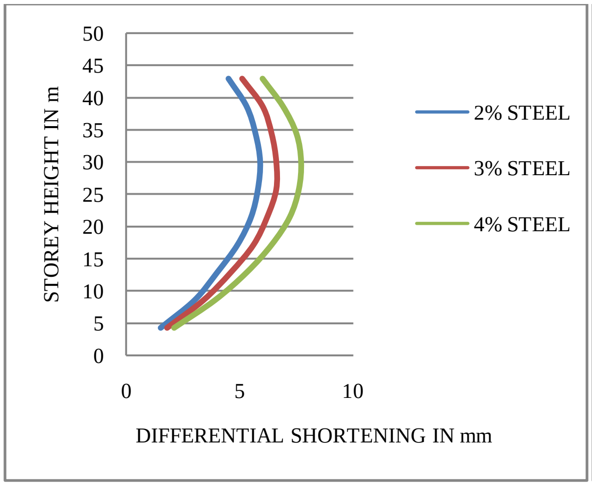
From the above graphs it can be observed that with change in grade of concrete there is significant difference in the differential shortening for 20, 30 and 40 story building. The maximum differential shortening for a 20-story building is 10.3mm for M40, 9.2mm for M50 and 8.4mm for M60. Similarly it is seen for 30-story building the maximum differential shortening for M40 was 11.8mm, for M50 it was 10.6mm and for M60 it was 9.7mm. For 40-story it was observed that for M40 the maximum differential shortening was 11.2mm, for M50 it was 10mm and for M60 it was 9.1mm respectively. From the above observations it is seen that there is a decrease in differential shortening when M60 is used compared to M40. The grade of concrete is increased from M40 to M50 and M50 to M60, the amount of differential shortening occurring decreases. This decrease in differential shortening ranges from 0.9 to 2.1mm. When the grade of concrete is increased, the variation in differential shortening is significant. These changes are significant enough to make any reduction in beam moments and column forces. Hence it can be said that by changing the grade of concrete the differential shortening has significant effect in this structure.

7.4Variation in Column Size(Considering CSA)

In this investigation the height of the building is varied from 10 to 40 story ranges in interval of 10-storey and assuming reinforcement ratios of 2%, 3% and 4% the size of the columns are calculated.

Table 4: Column areas for various reinforcement ratios

REINFORCEMENT RATIO	2%	3%	4%
COLUMN AREAS	AREA OF COLUMN IN mm^2	AREA OF COLUMN IN mm^2	AREA OF COLUMN IN mm^2
10 STORY	640000	560000	480000
20 STORY	1260000	1080000	900000
30 STORY	1980000	1600000	1440000
40 STORY	2520000	2160000	1980000



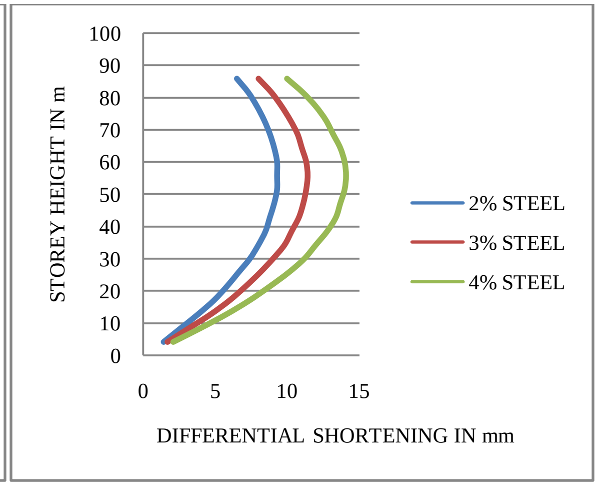
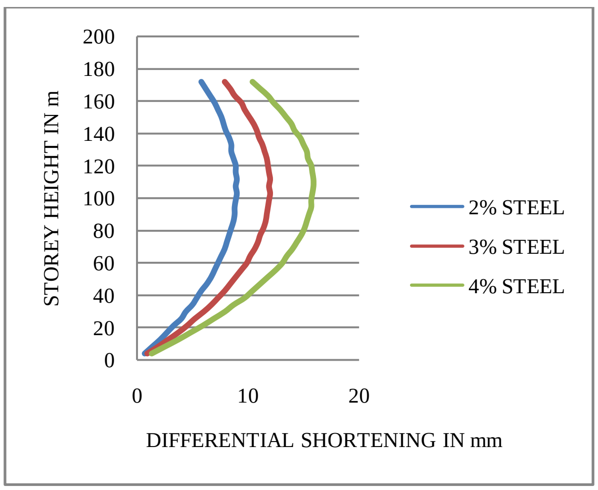


Figure 16: Differential shortening for 10-storey**Figure** 17: Differential shortening for

20-storey



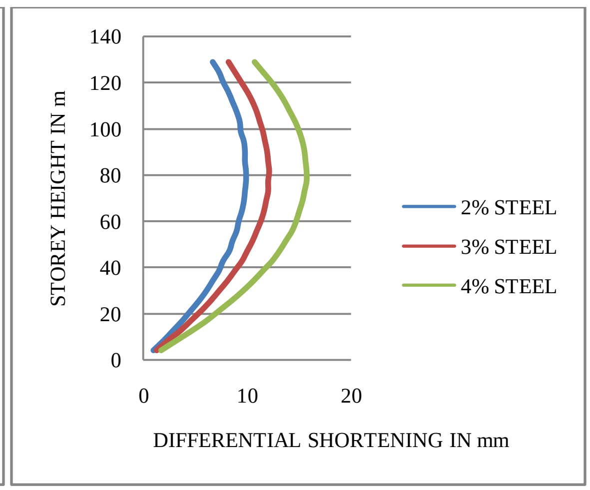


Figure 18: Differential shortening for 30-storey **Figure** 19: Differential shortening for 40-

storey

It can be clearly seen that as the column sizes reduce the effect of differential shortening is more. The maximum differential shortening for a reinforcement ratio of 2% is 5.9mm, for 3% is 6.6mm and for 4% is 7.7mm for 10-story. The maximum differential shortening for a 10-story building is observed in 7th story. In a 20-story building ,when reinforcement ratio of 2% is used the maximum differential shortening occurring was 9.3mm, when 3% reinforcement ratio was used it was 11.4mm maximum differential shortening and when 4% reinforcement ratio was used it was 14.1mm. For 30-story, the variation in maximum differential shortening between 2% reinforcement ratio and 4% reinforcement ratio is 5.8mm, in 4% reinforcement ratio ithas a maximum differential shortening of 15.7mm where as in 2% reinforcement ratio a maximum differential shortening of 9.9mm is observed. By using less steel and increasing the column size for a 30-story the maximum differential shortening can be reduced to as less as 40% in comparison to maximum shortening obtained using 4% reinforcement ratio. In a 40-story building the maximum differential shortening between 2%reinforcement ratio and 4% reinforcement ratio is 6.9mm. From the above numbers it is clear that smaller the column area higher will be the differential shortening. The variation is considerable and should be taken into account during the design phase. As we can see the behaviour of the structure is the same in all the three reinforcement ratios, it is only the differential shortening occurring that differs in each of the cases.

7.5 Conclusion

In this study the various aspects contributing to the differential shortening of vertical members under gravity loads have been examined. It is expected that the design forces will be different between the two analysis i.e. one step analysis and construction stage/sequential analysis. This effect is more dominating as the height of the building increases in shear walled structure.

Based on the results of the various studies carried out following are the conclusions drawn:

- When models with one step analysis and construction stage analysis were compared a large difference was seen in differential shortening of the vertical members. In one step analysis the differential shortening is higher when compared to construction stage analysis. This shows that analysis done using construction stage analysis gives more realistic values whereas the differential shortening is overestimated in one step analysis. This is due to fact that self-weights and some portion of the live loads is applied sequentially in construction stage analysis as it happens in actual construction.
- When the beam moments were compared for one step analysis and construction stage analysis, the beam moments at the column end were underestimated and at the shear wall end were overestimated for one step analysis when compared to construction stage analysis.
- In construction stage analysis, the differential shortening between the two vertical members increase with increase in height of structure.
- Longer and shorter frame spans were considered. The percentage variation for beam moments between one step analysis and construction stage analysis was eight times higher for shorter frame span in comparison to longer frame span. This is due to fact that the differential shortening results in sinking of supports situation. As we know that the additional moments due to sinking of supports is proportional to $1/L^2$, larger the span the effect will be less and smaller the span the effect is larger.
- When M40, M50 and M60 grade of concrete are used, the differential shortening value decreases with increase in grade of concrete. Hence, change in grade of concrete has a significant effect on differential shortening in construction stage analysis. This is due to increase in modulus of elasticity. The differential shortening is inversely proportional to ‘E’, as ‘E’ increases the differential shortening decreases.
- When the column sizes are varied in construction stage analysis, it shows that larger the column size lesser will be the differential shortening. There is an increase in differential shortening by 1.5 times where smaller column size is used in comparison to larger column size. Hence, with decrease in column size the differential shortening increases.
- As the height of structure increases above 43m, the effect of differential shortening should not be disregarded.
- Axial and differential shortening in a building is maximum at the mid height of the building.
- To improve the analysis accuracy in tall buildings it is necessary to use construction stage analysis.

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