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Effects of Differential Axial Shortening in Highrise Structures

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Abstract: This research explores the challenge of differential axial shortening (DAS) in high-rise buildings, a phenomenon that can disrupt vertical alignment and serviceability if not properly addressed. The study examines how DAS is influenced by three key factors: material choice, lateral load resisting systems (LLRS), and construction sequence analysis. To capture realistic behavior, structural models were developed with reinforced concrete (RCC) columns, composite concrete-filled steel tube (CFT) columns, and shear walls, and tested under three scenarios—Dead Static, Linear Static, and Nonlinear Construction Sequence (NCS)—all in line with IS 16700:2023 serviceability requirements. The findings highlight that materials account for about 40% of DAS variation. RCC members showed the greatest long-term shortening due to creep and shrinkage, while composite columns consistently performed better, achieving up to 76% reduction when paired with shear walls. The structural system contributed around 25%, with Tube-in-Tube systems balancing core and perimeter, Bundled Tubes showing localized differences, and Outrigger systems redistributing forces most effectively—though at the cost of higher axial demands in perimeter columns. Construction sequence effects contributed about 20%, with staged analysis improving prediction accuracy by roughly 35% compared to static models. Broader system-level consequences (≈10%) included load redistribution and secondary stresses in slabs and beams, while practical strategies (≈5%) such as preset elevations, outrigger stiffness tuning, and material mixing proved effective in reducing DAS impacts. In summary, the study demonstrates that composite columns, especially when combined with shear walls and staged construction, provide superior control of DAS. By quantifying the contributions—materials (40%), LLRS (25%), construction sequence (20%), system consequences (10%), and mitigation strategies (5%)—this work offers clear, actionable guidance for structural engineers aiming to improve vertical alignment, serviceability, and long-term performance in tall buildings.

Key words: DAS, Construction sequence, LLRS, Tall building

I. INTRODUCTION

A. General

Concrete is commonly used as a primary construction material for tall building construction. Load bearing components such as columns and walls in concrete buildings are subjected to instantaneous and long-term axial shortening caused by the time dependent effects of "shrinkage", "creep" and "elastic" deformations. Reinforcing steel content, variable concrete modulus, volume to surface area ratio of the elements and environmental conditions govern axial shortening. The impact of differential axial shortening among columns and core shear walls escalate with increasing building height. Differential axial shortening of gravity loaded elements in geometrically complex and irregular buildings result in permanent distortion and deflection of the structural frame which have a significant impact on building envelopes, building services, secondary systems and the life time serviceability and performance of a building. Existing numerical methods commonly used in design to quantify axial shortening are mainly based on elastic analytical techniques and therefore unable to capture the complexity of non-linear time dependent effect. Ambient measurements of axial shortening using vibrating wire, external mechanical strain, and electronic strain gauges are methods that are available to verify pre-estimated values from the design stage. Installing these gauges permanently embedded in or on the surface of concrete components for continuous measurements during and after construction with adequate protection is uneconomical, inconvenient and unreliable. Therefore, such methods are rarely if ever used in actual practice of building construction.

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 vary 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.

B. Differential Axial Shortening

Differential axial shortening refers to the unequal vertical deformation (shortening) of structural vertical elements (e.g., columns, core walls, and shear walls) in high-rise buildings due to sustained loads such as gravity loads, live loads, and shrinkage, creep, and temperature effects. This phenomenon leads to non-uniform settlement or displacement of floors across the plan or height of the building.

Key Causes:

- Variation in Cross-Section or Material Stiffness: Columns and walls with different dimensions or materials (e.g., RC vs. steel) shorten at different rates under load.
- Load Distribution Differences: Columns near the center/core typically carry more load compared to those on the perimeter.
- Concrete Creep and Shrinkage: Time-dependent deformations in concrete, especially significant in tall buildings over time.
- Construction Sequence: Early loaded columns begin to shorten before later ones, leading to imbalance.
- Temperature Effects: Expansion or contraction can further induce differential shortening.

C. 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.

Axial shortening (AS) of these composite columns due to time dependent phenomena of basic creep, shrinkage and elastic deformations is an inherent challenge in high rise buildings. The magnitudes of this deformation in each member may differ due to the differences in load tributary areas, the loading history and the geometric and material properties. As a consequence, the differential axial shortening between these members occurs. Unfavorable effects of Differential Axial Shortening (DAS) in buildings constructed with concrete were first observed in 1960s, in tall reinforced concrete buildings of more than 30 storeys (Fintel et al. 1987). More recently in a 45 storey RC building in Chicago, Illinois William D. Bast et al. (2003) measured 4 inches of axial shortening of the core wall at the 45th floor as marked by the gap created between the condenser riser pipe and the top of the metal pipe support.

The adverse effects of this DAS in a high-rise building include sloping of floor plates, cracking in beams and slabs due to the excess stresses induced, buckling of elevator guide rails and pipes, damage to partitions and the façade of buildings or column cladding and thus reducing the functionality of the structure. Figure 3.3 shows the impact of DAS on a shear wall. As indicated in this figure, Stiff horizontal structural systems such as belt and outrigger systems are subjected to high stresses (Fintel et al. 1987). Usually, these adverse effects are directly proportional to the height due to the fact that axial shortening is cumulative over the building height.

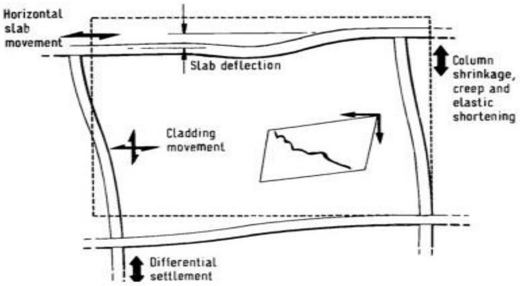

Fig 1 Failure of wall panel due to differential axial shortening (Fintel et al. 1987)

D. 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 stress from concrete to reinforcing bars. Time dependent creep coefficient for a constant compressive stress applied at time t0 according to CEB-FIP Model Code (1990) is shown in Fig.2

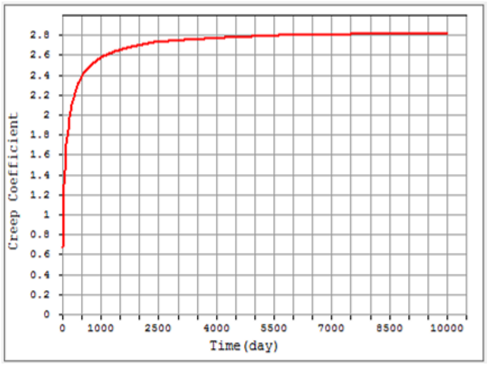

Fig 2 Time Dependent Creep function based on CEB- FIP model code

E. 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 shrink age shortening of columns. Time dependent shrinkage strain according to CEB-FIP Model Code (1990) is shown in Fig.3

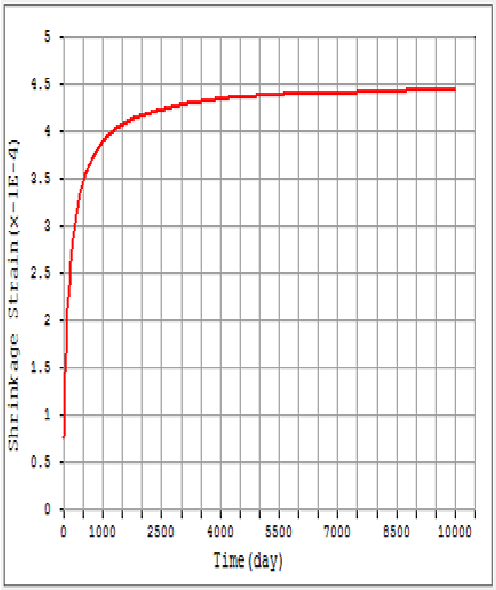

Fig 3 Times Dependent Shrinkage function based on CEB- FIP model code

The virtual outrigger concept's primary idea is to transport moment from the core to trusses or walls that are not directly connected to it by use of floor diaphragms, which are normally quite stiff and powerful in their own plane. The horizontal couples in columns or other structural elements outside the core are subsequently transformed into vertical couples by the trusses or walls. Virtual outriggers can be effectively implemented with belt trusses and basement walls Fig 4 Tall building with belt trusses as Outriggers.

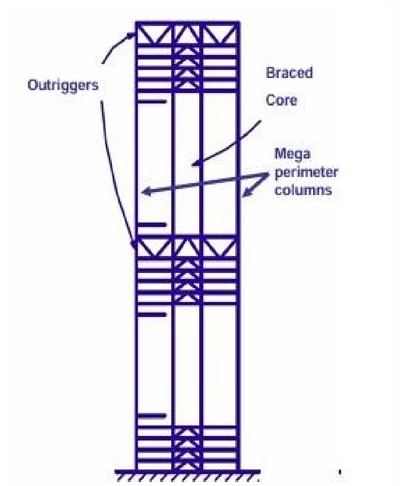

Fig 4 Tall building with belt trusses as Outriggers.

1.1.1 Behavior of Outriggers

Consider the building seen in Fig. 3.1, which is strengthened by a story-high outrigger at the top, to comprehend the behavior of an outrigger system. The arrangement is sometimes called a cap or hat truss system since the outrigger is located at the top. The cap truss's tie- down action creates a restoring pair at the top of the building, which causes a point of contra flexure in the deflection curve. This reversal in curvature causes the building to drift, lowering the core's bending moment.

The stretching and shortening of the windward and leeward columns restrict rotation at the top of the core, which can be thought of as a single-redundant cantilever. Tensile and compressive forces combine to form a restoring pair that counteracts the core's rotation. Thus, it is possible to think of the cap truss as a restraining spring that is situated at the cantilever's top. The restoring couple resulting from a unit rotation of the core at the top can be used to characterize its rotational stiffness.

Under the assumption that the cap truss is infinitely rigid, the rotation of the core multiplied by the columns' individual distances from the core center determines the axial elongation and shortening of the columns. The axial deformation of the columns is equal to θ *d/2, where θ represents the rotation of the core, if the comparable column is d/2 from the core's center. The comparable columns' axial deformation equals 1 × d/2 = d/2 units since the equivalent spring stiffness is determined for the core's unit rotation, or θ = 1.

The associated axial load is determined by Where P is the columns' axial load A is the area between the columns.

E stands for elastic modulus.

D is the separation between the outside columns;

L is the building's height.

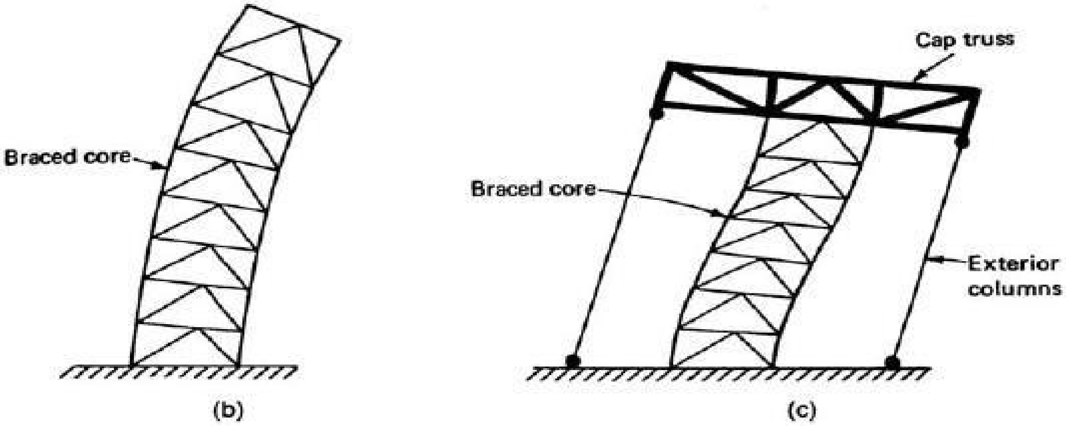

Fig 5 Building plan with cap truss
(b) Cantilever bending of core; (c) tie-down action of cap truss.

Combination of steel and concrete provides an excellent composite action and hence use of this action to design structural components is well established. Among these, the concrete filled tube (CFT) columns have gained popularity in present high rise building construction around the globe, due to their many advantages such as the strength increase of concrete caused by the confinement effect and the steel by preventing local buckling, the ability of the steel shell/skin to be used as form work for the column construction, the superior durability in fire conditions, excellent seismic resistance (Hajjar 2000) and the improved aesthetics enabling more slender sections Figure 1.9 Buildings with CFT columns

Fig 6 Buildings with CFT columns (a) Taipei 101 Tower, Taiwan (b) Guangzhou New TV Tower (GNTVT), China (c) Latitude Sydney building, and Australia)

II. LITERATURE SURVEY

SeongHun Kim & Hyo-Gyoung Kwak (2024) Studied comparisons between reinforced concrete (RC) and concrete-filled tube (CFT) columns in high-rise buildings highlight how differential axial shortening can influence structural performance, particularly under varying dead load portions. The research emphasizes that time-dependent concrete deformations, such as creep and shrinkage, are the most critical factors affecting shortening, while construction sequence and floor-level adjustments play a lesser role. Parametric analyses further reveal that axial shortening is negligible in buildings below 20 stories and remains limited even in taller structures, allowing designers to simplify preliminary design considerations. Importantly, when the dead load portion is less than 30% of the ultimate axial resistance, the differential axial shortening effect can be safely excluded, offering a practical guideline in the absence of codified standards. This proposed relationship provides engineers with a useful tool for determining initial column sections during early design stages, streamlining the process while maintaining serviceability and structural reliability.

Ahmed Elansary et.al., (2023) studied the impact of different structural systems on reinforced concrete (RC) buildings and highlighted the limitations of ordinary analysis (OA) in estimating differential shortenings (DS) between vertical elements, which can lead to structural and architectural issues. To address this, they applied staged analysis with time-dependent effects (SAT), which better reflects the sequential nature of construction. Their investigation covered eight RC buildings ranging from 35 to 175 m in height, designed with rigid frames (RF), shear walls (SW), wall frames (WF), and tube-in-tube (TT) systems, and assessed three mitigation strategies: enlarging all vertical sections, proportioning internal columns, and introducing outriggers. The findings showed that increasing cross sections was ineffective, while iterative proportioning of internal columns consistently provided optimal solutions across all systems; outriggers offered partial improvement in WF and TT structures. This work underscores the importance of SAT in capturing realistic construction behavior and provides practical guidance for mitigating DS discrepancies in tall RC buildings.

Elansary et.al., (2021) researched about the Staged construction analysis of reinforced concrete buildings with different lateral load resisting systems. Lateral load resisting systems (LLRS) in reinforced concrete (RC) buildings should be adequately determined to control their response under lateral and gravity loads. Practitioners used to select the LLRS using one-step analysis (OSA) by assuming both the lateral and gravity loads are applied at one stage to a complete building. Instead, staged- construction analysis (SCA) should be adopted because RC buildings are constructed in different stages and the gravity loads act sequentially. In this research, a nonlinear finite element model for SCA of RC buildings is developed and validated using a robust commercial software. The developed model is extended to account for time dependent effects (SCAT) such as shrinkage, creep, and strength gain.

The model is utilized to analyze eight RC buildings with different heights and LLRS. Design parameters for the studied buildings are proportioned to satisfy both the working and ultimate state design criteria. Differential displacements and straining actions in horizontal elements as well as shortenings in vertical elements are estimated using SCAT and then compared to their counterparts obtained from OSA. SCAT yielded shortening and differential displacements larger than those obtained from OSA by a percentage that reached 143%, 153%, 116%, and 154% for buildings with rigid frame, shear wall, wall-frame, and tube in tube LLRS, respectively. Increase in straining actions obtained from SCAT ranged between 26% and 554% more than those obtained from OSA. Decrease in straining actions obtained from SCAT ranged between 26% and 71% less than those obtained from OSA.

III. METHODOLOGY

The Effect of column shortening is a major consideration in the design and construction of tall buildings, especially in concrete and composite structural systems. The method presented in the PCA report by the fintel and Ghosh is the most widely used for the analysis of column shortening, but results can be very different depending on the time function of shrinkage suggested by ACI, CEB-FIB and PCA. Axial shortening is the most neglected phenomenon by the structural engineers. IS 16700-2023 recommends to do construction sequence analysis for the building more than 150m tall. Fig 7

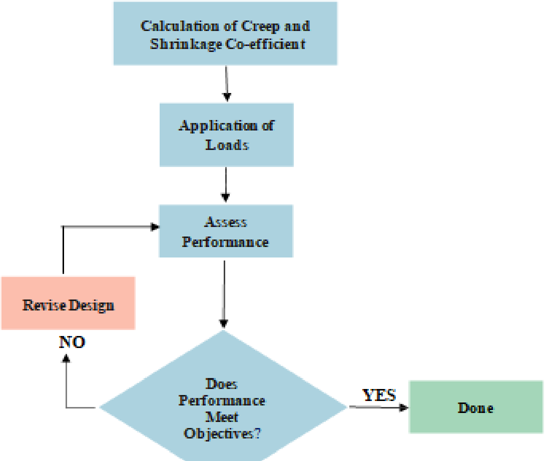

Fig 7 Flow chart

A. *Method to Calculate Axial Shortening in High Rise Buildings*

The magnitude of time dependent deformations varies in vertical structural components due to many factors. These differentials lead to numerous serviceability problems such as tilting of floor plates, distortion of non-structural elements such as claddings and facades and other services such as lift guide rails and plumbing systems. One good example is the tallest high rise in the world the Burj Khalifa tower in UAE (Baker et al. 2007). According to Moragaspitiya et al. (2010) this tower had to be closed soon after opening due to the failure of lift operation which may be a result of adverse effects of DAS. In addition to the serviceability, DAS can also alter the load paths in the structure which may induce excessive stresses on some vertical elements and horizontal elements such as the outriggers.In recent applications, design engineers have adopted creep, shrinkage and elastic models included in code-based methods such as ACI, AS 3600, CEB and GL2000 (ACI committee 209-2008; AS3600-2001; CEB-FIP,1990; Gardner,2004). GL2000 method has been developed more recently and creep, shrinkage and elastic models included in this method has become increasingly popular compared to the other methods because of its accuracy (Gardner, 2004). Goel, Kumar& Paul (2007) conducted a comprehensive study to investigate the most accurate methods among ACI-209R- 82, the B3, the CEB FIP (1990) and GL2000.

B. *Case Description*

Following are the case studies on Theoretical Buildings (TB1) done in order to understand the axial shortening of the building: -

Case No.	Description
TB1	30 Storey RCC Tube in Tube Frame Building
TB2	40 Storey RCC Tube in Tube Frame Building

TB3	50 Storey RCC Tube in Tube Frame Building
TB4	30 Storey Composite Tube in Tube Frame Building
TB5	40 Storey Composite Tube in Tube Frame Building
TB6	50 Storey Composite Tube in Tube Frame Building
TB7	30 Storey RCC Bundled Tube Building
TB8	40 Storey RCC Bundled Tube Building
TB9	50 Storey RCC Bundled Tube Building
TB10	30 Storey Composite Bundled Tube Building
TB11	40 Storey Composite Bundled Tube Building
TB12	50 Storey Composite Bundled Tube Building
TB13	30 Storey RCC Outrigger Building
TB14	40 Storey RCC Outrigger Building
TB15	50 Storey RCC Outrigger Building
TB16	30 Storey Composite Outrigger Building
TB17	40 Storey Composite Outrigger Building
TB18	50 Storey Composite Outrigger Building

C. *Modelling*

In this study, a high rise building 30,40,50 storey with columns and shear walls, tube-in- tube, outriggers have been modeled. The building dimensions are 20mx24m and overall characteristics have been carefully selected to represent a realistic scenario where differential axial shortening is studied. The models are designed for seismic zone IV region, indicating a high seismic risk. Additionally, the structure is subjected to wind speed of 44m/s.The modelling and analysis have been done using ETABS software. The building geometric plans are given below. A total 18 different structural models have been generated to investigate the impact of differential axial shortening on tall building performance. Each model was designed with central core, whose location is symmetric to assess the influence of lateral stiffness, drift and energy dissipation.

Table 1 General Specifications

Number of stories	G+30, G+40, G+50
Plan dimension of a single tower in X direction	20m
Plan dimension of a single tower in Y direction	24m
Single story height	3m
Slab Thickness	200mm
Shear Wall Thickness	300mm-600mm
Column Size	800x800 mm
Beam size	200x600 mm

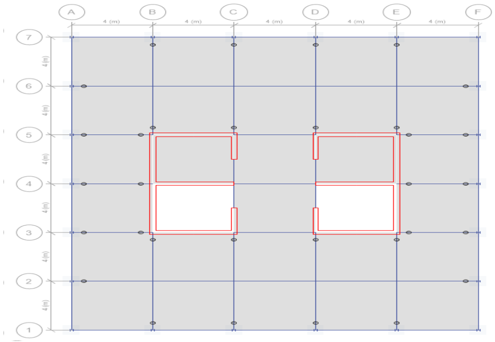

Fig 8- Plan view of Moment Resistant Tower Models

Time Dependent Properties for Concrete Parameter Calculation

The earthquake analysis is done by Non-Linear static method. Their input parametersare given below Non-Linear analysis

Table 2 Static analysis parameters

Code	ACI 209R-2008
Relative Humidity	50%
Shrinkage Start Age	21 Days
Curing Type	Moist Cure
Importance factor	1.2
Soil Type	Medium Stiff

IV. RESULTS AND DISCUSSION

To understand the Axial Shortening of this structure, the parameters Vertical Displacement of the column member will be studied. Serviceability results like Displacement, Base Shear and time period are also given to validate the performance of the structure, incorporated from Linear Dynamic analysis using CSI ETABS.

Table 3 Description of building data

	Drift (mm)					
Case No.	EQX	EQY	SPECX	SPECY	WX	WY
TB1	106	88	66	47	54	31
TB2	211	183	126	97	122	72
TB3	372	329	247	185	228	138
TB4	77	69	49	39	39	24
TB5	153	141	95	79	89	56
TB6	372	329	247	185	228	137
TB7	99	84	65	46	39	22
TB8	195	169	124	96	84	49
TB9	337	294	232	172	151	90
TB10	99	81	57	43	38	22
TB11	202	173	128	100	83	48
TB12	338	294	233	172	151	90
TB13	71	84	45	44	35	29
TB14	140	179	85	92	78	70
TB15	246	326	144	176	145	135
TB16	56	67	20	23	28	23
TB17	111	141	67	77	63	55
TB18	198	255	110	136	117	106

4.1 Axial Shortening Results for RCC Tube in Tube 50m Tall Building (TB3)

Storey	Linear Dead	Combo As per ASCE 37-14	NL Construction sequence
50	20.6	19.7	4.8
49	20.4	19.5	4.7
48	20.4	19.5	6.9
47	20.4	19.4	6.7
46	20.3	19.4	6.7
45	20.2	19.3	8.6
44	20.0	19.2	8.3
43	19.9	19.1	8.2
42	19.7	18.9	9.9
41	19.6	18.8	9.6
40	19.3	18.6	9.4
39	19.1	18.4	10.9
38	18.9	18.3	10.6
37	18.7	18.1	10.3
36	18.5	17.9	11.6
35	18.2	17.7	11.3
34	17.9	17.4	11.0
33	17.7	17.2	12.1
32	17.3	17.0	11.7
31	17.0	16.7	11.4
30	16.7	18.5	12.2
29	16.4	18.2	11.8
28	16.0	18.0	11.5
27	15.7	17.7	12.3
26	15.4	17.4	11.8
25	15.0	17.0	11.5
24	14.6	16.7	12.0
23	14.2	16.3	11.6
22	13.8	15.9	11.1
21	13.4	15.6	11.5
20	12.9	15.1	11.0

19	12.5	14.7	10.6
18	12.1	14.3	10.9
17	11.7	13.9	10.4
16	11.3	13.5	10.0
15	10.8	13.1	10.1
14	10.3	12.6	9.6
13	9.9	12.2	9.1
12	9.4	11.7	9.0
11	8.9	11.2	8.5
10	8.4	10.6	7.9
9	7.9	10.2	7.8
8	7.4	9.7	7.2
7	6.9	9.2	6.7
6	6.4	8.6	6.4
5	5.9	8.1	5.9
4	5.4	7.6	5.3
3	4.8	7.0	4.9
2	4.3	6.4	4.3
1	3.7	5.8	3.7
BASE	0.0	0.0	0.0

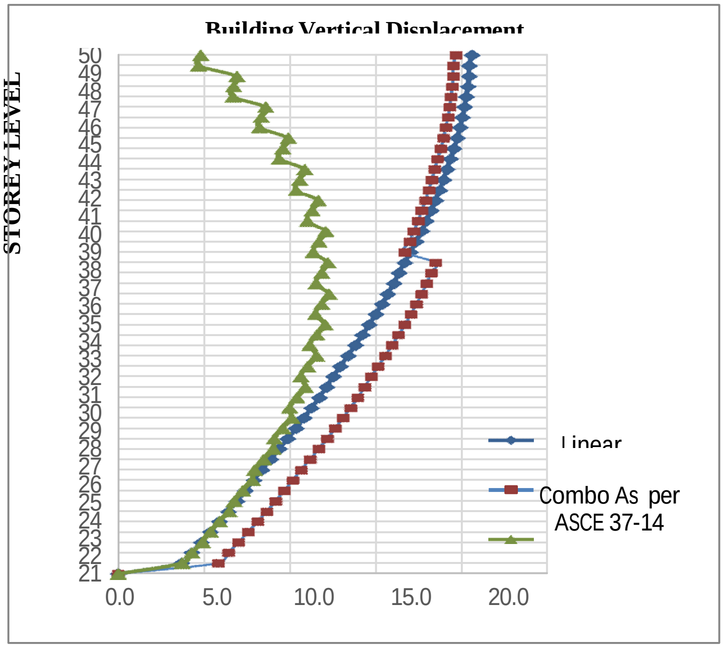

Fig 9 Vertical Displacement (DAS) results of Tower TB3

V. CONCLUSION

1) In high-rise buildings, vertical elements with RC shows up to 50% more differential axial shortening in linear static case compared to composite.
2) Among LLRS configurations, in bundled tube buildings, differential axial shortening drops by 31–53% compared to tube-in tube, with RC and Composite performing almost identically when the grade of concrete is increasing, differing only by 10–20%, while Outrigger buildings provides enhanced control of shortening with up to 70-76% by redistributing axial forces.
3) Incorporating non-linear construction sequence analysis (NCS) significantly reduces differential axial shortening with reductions ranging from 10-76% across tube-in-tube, bundled tube and outriggers.
4) Stage-by-stage construction and outrigger installation timing strongly influence differential axial shortening patterns. “All-at-once” analysis underestimates differential axial shortening, while construction sequence analysis reveals realistic redistribution and peak differentials. Sequence-aware modeling improves prediction accuracy and highlights critical stages where deferential axial shortening can be mitigated.
5) It is concluded that composite consistently perform better than RC, composite with non-linear construction sequence analysis provides the most reliable control of differential axial shortening.

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