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Original Article

Addressing Differential Axial Deformation Effect and Sway in 3D Building Frame Analysis

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ABSTRACT

The Differential Axial Deformation Effect (DADE) is a significant consideration in the 3D analysis of building frames, where elements like columns and walls experience compression forces leading to differential shortening. Traditional design methods often overlook DADE, yet the existing building stock seems serviceable despite this omission. However, modern 3D analysis inherently introduces DADE, prompting designers to seek methods to approximate traditional design forces while utilizing advanced analysis techniques. The aim is to achieve design forces close to those historically used, ensuring structural integrity without disregarding DADE entirely. The methods outlined in this report demonstrate how to reconcile 3D analysis results with traditional design principles while also addressing concerns about sway deflections and the need for a conservative approach. While there's a debate about the economic viability of designing for a wider envelope of design conditions, the report illustrates that the additional reinforcement needed is typically minimal. Notably, the DADE phenomenon is universal across Finite Element Method (FEM) analysis software, and the strategies discussed here can be applied across different platforms. The notion that staged construction analysis effortlessly resolves DADE issues is debunked. Staged construction analysis is complex, doesn't fully eliminate DADE, and can yield unreliable results if not used carefully. In summary, this report offers practical insights into navigating DADE in 3D structural analysis, emphasizing the importance of balancing modern techniques with traditional design considerations.

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INTRODUCTION

As a building's height increases, the shortening of its supports becomes a critical consideration for construction engineers, especially in tall structures with a rapid development pace. Research indicates that differential shortening between neighbouring members is most pronounced at mid-levels closer to the top of the structure, with the amount increasing with building height. This necessitates additional reinforcement to support increased moments resulting from differential shortening [1], [2], [3].

Traditionally, multi-storey concrete frames have been analysed and designed using idealized methods, where lateral loads are typically resisted by a subset of members, and gravity forces are the primary consideration for the remaining structure. This traditional approach, known as sub-frame analysis, simplifies the complex problem of structural design, but may not fully capture real-world behaviour [4].

With advancements in technology, buildings are increasingly modelled and analysed in three dimensions, leading to differences in load distribution, sway effects, and elastic shortening of compression members. However, while 3D analysis aims to largely eliminate the Differential Axial Deformation Effect (DADE), it does not remove natural sway effects, which can lead to disparities in comparisons [5].

It's important to recognize that both traditional sub-frame analysis and modern 3D analysis involve simplifications and assumptions, and neither produces scientifically precise conclusions. Instead, the goal is to encourage engineers to critically assess the comparisons between different analytical approaches and consider the implications for design and construction.

MATERIALS AND METHODS

In the design of a building, various structural elements were carefully considered to ensure stability, safety, and compliance with building codes and regulations. The structure's dimensions and materials were crucial factors in this process. The storey height of the building was defined by a 1.2 m distance from the foundation (Fdn) to the ground floor (G/F), with subsequent storeys rising 3 m each to the roof. A consistent thickness of 250 mm characterized all walls in the building.

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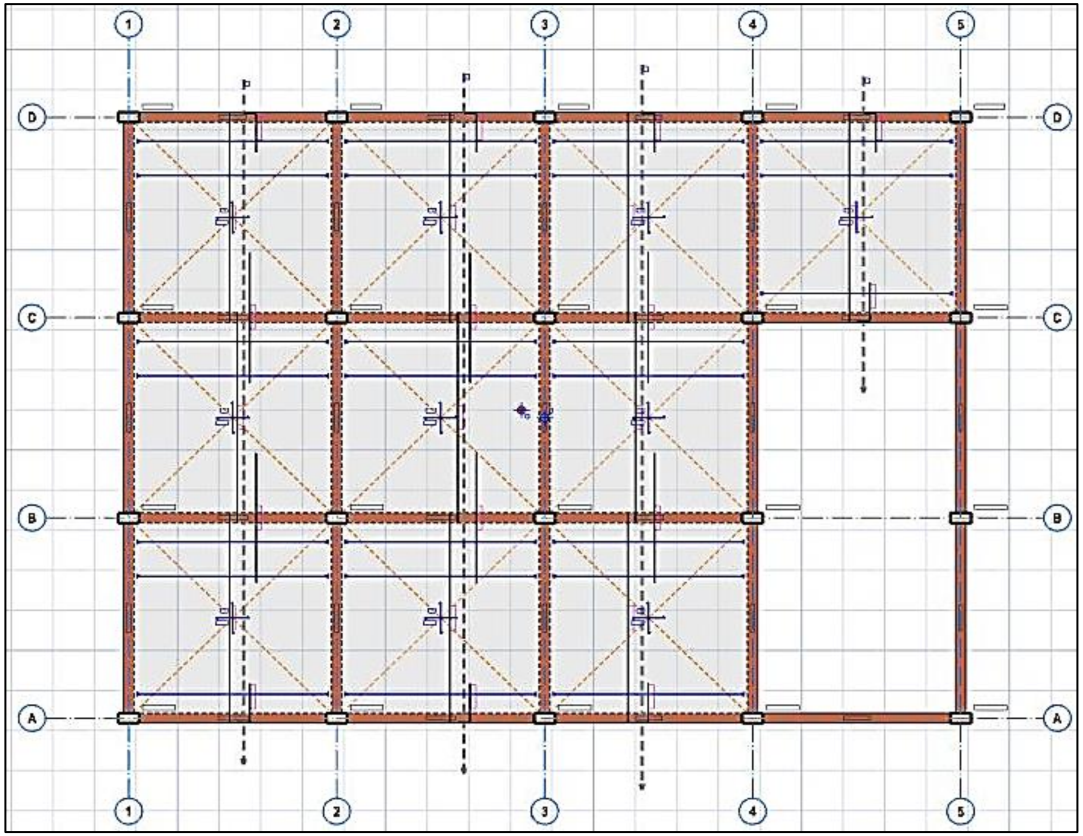
Figure 1: Example model of a 10-storey building

a



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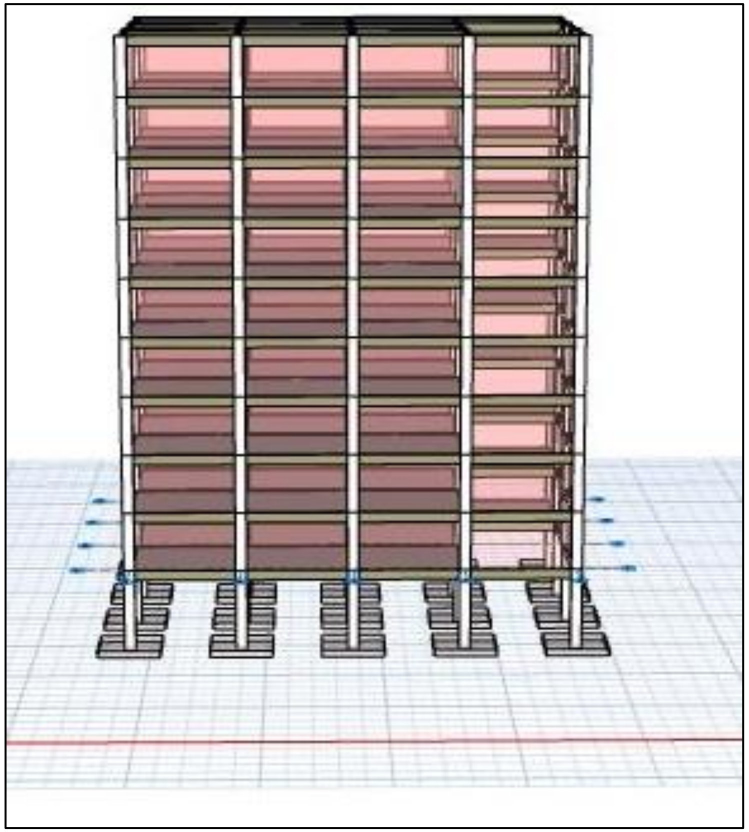

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Columns played a vital role in supporting the building's weight, with dimensions of 500 x 250 mm, extending from the foundation to the 10th floor. Horizontally supporting the structure, beams had dimensions of 250 x 500 mm.

Slabs, providing the floors of each storey, were 120 mm thick with a concrete cover of 25 mm. They had to bear a service dead load of 2.5 kN/mm^2 and a live load of 1.6 kN/mm^2.

Figure 2: Materials; and Column applications quantity take off storeys

a

Materials (Default)

	Material	Reinforcement Steel Grades
Columns:	C25/30	Grade 410 (Type 2)
Walls:	C25/30	Grade 410 (Type 2)
	Longitudinal Web Steel:	Grade 410 (Type 2)
	Horizontal Web Steel:	Grade 410 (Type 2)
Beams:	C25/30	Grade 410 (Type 2)
Slabs:	C25/30	Grade 410 (Type 2)
Ribbed Slabs:	C25/30	Grade 410 (Type 2)
Foundations:	C28/35	Grade 410 (Type 2)
Links:		Grade 410 (Type 2)

Unit Weight of Member: **24.000** kN/m3 (Column, Default)
Unit Weight of Blocks: **4.500** kN/m3
Coeff. of Thermal Expansion **0.00005** 1/*C

Edit Materials

b

COLUMN APPLICATIONS QUANTITY TAKE OFF STOREYS: (10)					
SIZE	UNIT WEIGHT (Kg/m)			Length (m)	T. WEIGHT (kg)
Y8	0.395			926.4	366.0
Y13	1.043			496.0	517.4
				T. WEIGHT (kg)	883.4
BM	SIZE	QTY	Length (mm)	TOTAL	FORM
1	13	160	3100	496.00	160 2900
2	8	772	1200	926.40	200 310 310 100 200

The concrete used in construction adhered to grades C25/30 and C28/35, ensuring structural integrity and durability. Wind load calculations, based on a mass of 248.8 tons, were automatically generated using BS8110-1997.

In designing the foundation, consideration was given to ensure it supported the entire structure and transfer loads to the underlying soil. The allowable stress of soil was 200 kN/m^2, with a soil subgrade coefficient of 50,000 kN/m^3.

Detailed calculations and considerations were undertaken to meet regulatory requirements and ensure the longevity of the structure. By analysing these parameters, appropriate dimensions for each component can be determined, ensuring the building's stability and safety under various loading conditions.

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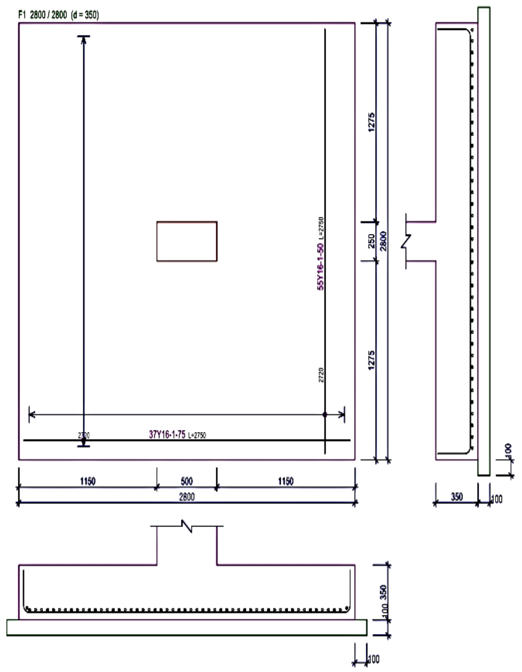
Figure 3: Form plans quantity take off, and Pad footing quantity take off

a

FORM PLANS QUANTITY TAKE OFF - STOREYS: 10					
SIZE	UNIT WEIGHT (Kg/m)			Length (m)	T. WEIGHT (kg)
Y8	0.395			1,809.6	714.9
				T. WEIGHT (kg)	714.9
BM	SIZE	QTY	Length (mm)	TOTAL	FORM
1	8	210	5200	1092.00	5200
2	8	192	1300	249.60	300 / 980
3	8	144	3250	468.00	3250

b



PAD FOOTINGS QUANTITY TAKE OFF					
SIZE	UNIT WEIGHT (Kg/m)			Length (m)	T. WEIGHT (kg)
Y16	1.580			5,060.0	7,996.0
				T. WEIGHT (kg)	7,996.0
BM	SIZE	QTY	Length (mm)	TOTAL	FORM
1	16	1840	2750	5060.00	270 / 2720 / 270

Codes		
BS8110-1997,BS6399,BS 5950		
Soil Parameters		
Soil Bearing Capacity (kN/m2)	200.00	
Subgrade Reaction (kN/m3)	50000.000	
Material Properties (Default)		
	Material	Rebar Grade
Columns	C25/30	Grade 410 (Type 2)
Walls	C25/30	Grade 410 (Type 2)
	Long. Web Rebar	Grade 410 (Type 2)
	Lat. Web Rebar	Grade 410 (Type 2)
Beams	C25/30	Grade 410 (Type 2)
Slabs	C25/30	Grade 410 (Type 2)
Ribs	C25/30	Grade 410 (Type 2)
Footings	C28/35	Grade 410 (Type 2)
Links	-	Grade 410 (Type 2)

Traditional Analysis Results

As previously stated, a 'conventional' design would historically have been based on the findings of a succession of discrete 2D subframe analyses as shown in *Figure 4a*.

Sub-frame evaluations are performed from top to bottom on each floor, assuming fixed supports. Deflection compatibility among sub-models is neglected. Column and wall forces are calculated by adding the axial loads determined in each of the individual evaluations. Alternatively, in many circumstances, the axial loads are calculated by assuming a supported floor area at each level.

FEM software allows for the creation and analysis of both 2D and 3D subframe models as needed, as shown in *Figure 4*. To replicate the results of subframe analysis in both directions, the top storey is isolated and studied as a single-floor model.

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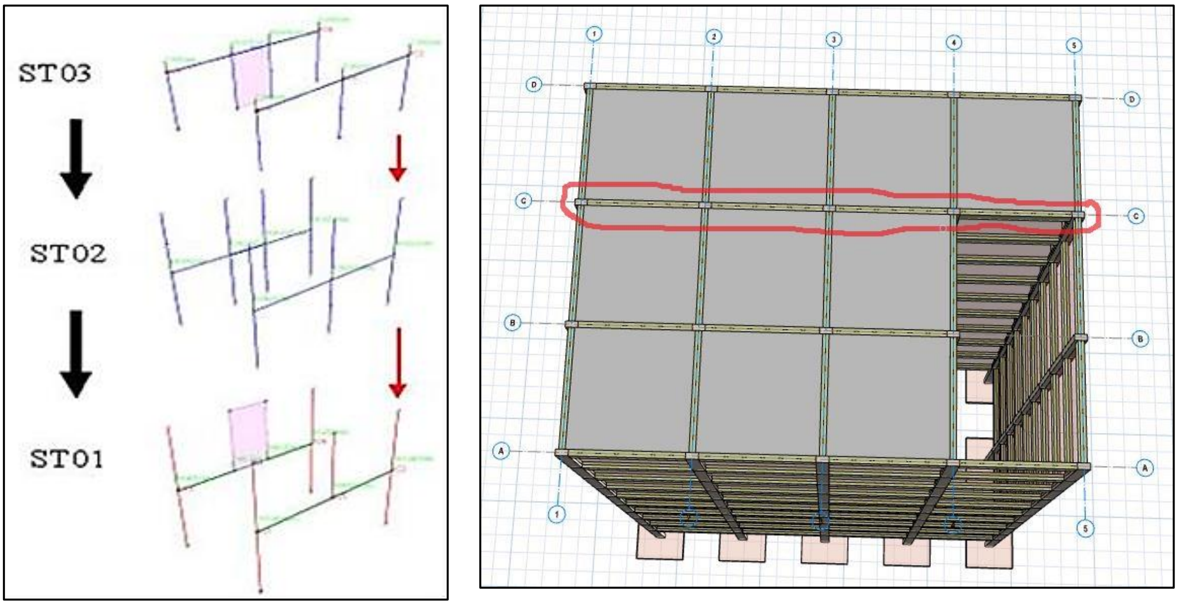
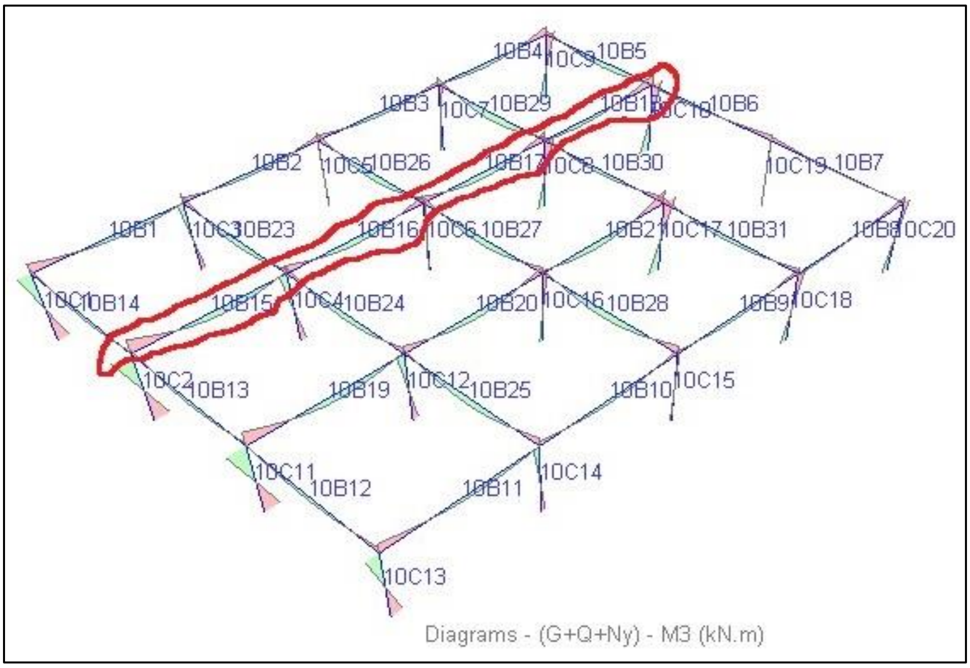
Figure 4: 2D subframe models; and 3D subframe models

a **b**



The analysis results for the main moment (10B15, 10B16, 10B17, 10B18) for this 3D subframe in the dead load situation are presented in *Figure 5*in the "Analytical" view (mid-pier wall idealization has been utilized).

Figure 5: Analysis results for the main moment



To make comparisons with various methodologies, the bending moment diagram for the highlighted beams can be shown in detail using the beam analysis results diagram (*Figure 6*).

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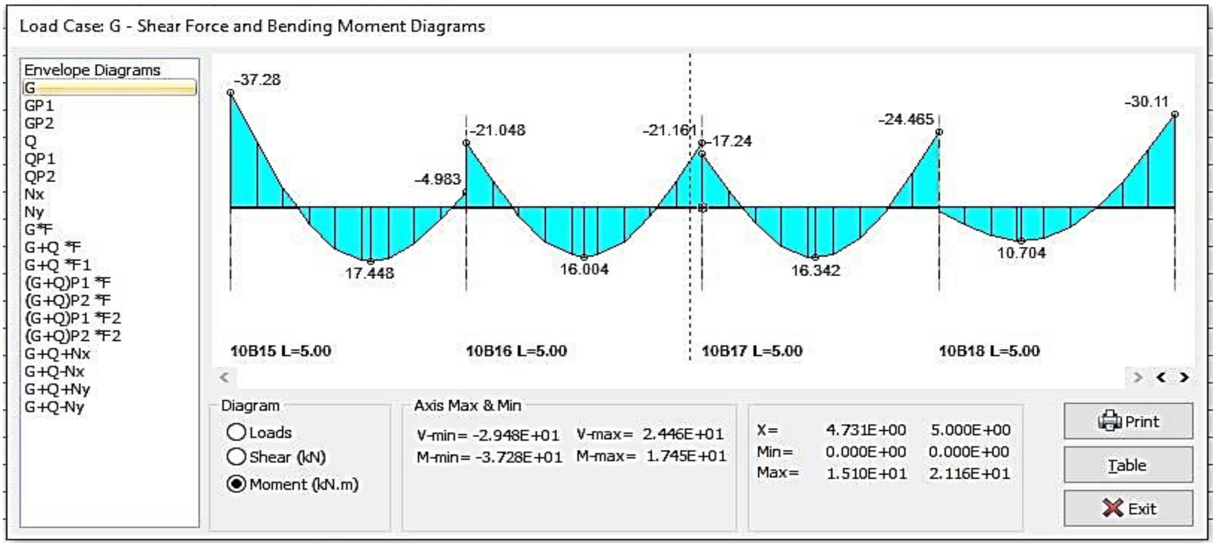
Figure 6: Beam analysis results diagram



We will use this as our "baseline" solution to compare different alternatives. Again, it is critical to notice the comments made in the opening discussion concerning the assumptions underlying the above result. It is a target baseline; it should not be interpreted as an entirely correct outcome.

Emulating the Traditional Approach in FEM

We will employ two basic analysis methods (*Figure 7*):

We used Protastructure software to do Sub-Floor study, often known as FE Chasedown study.

Building Analysis = Analysis of a complete 3D model.

The "FE Chasedown" analysis, which uses a sub-frame technique, is expected to closely align with the "baseline" solution.

The FEM software's 'building analysis' does not use sub-frames, instead treating the entire structure as a single 3D frame, with columns and walls set only at the foundation level.

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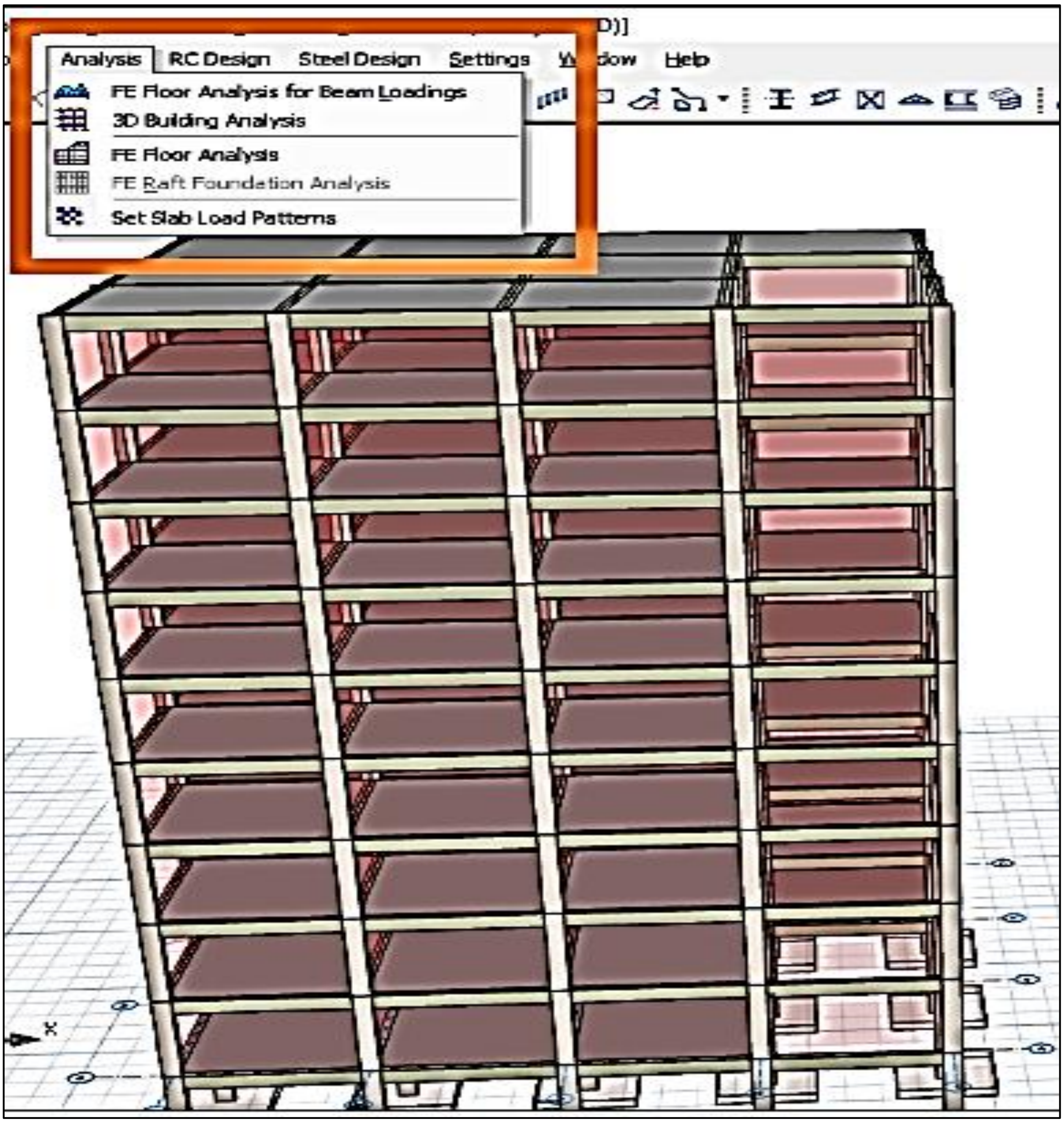
Figure 7: Performing analysis



Sub-Floor Analysis (FE Chasedown)

Choosing the option to execute a 'FE Chasedown analysis' initiates a batch process in which a separate analysis of each floor is performed one after the other, beginning at the top of the building and progressing to the lowest level. In each study, the calculated reactions from the level above are used as load input for the current floor.

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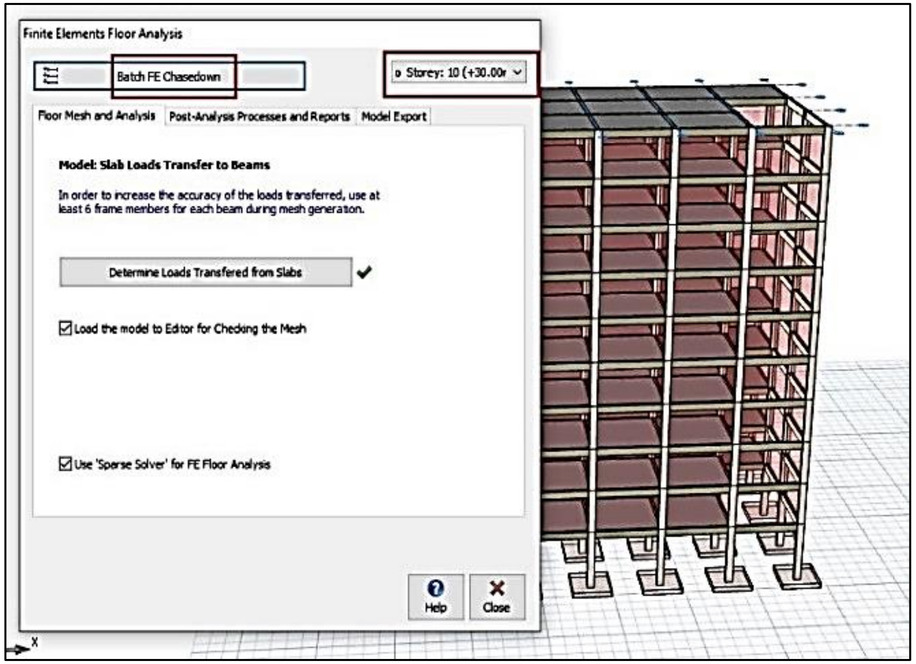
Figure 8: Batch FE Chasedown; and Shear (kN) diagram for Storey 10 analysed using FE Floor Analysis

a



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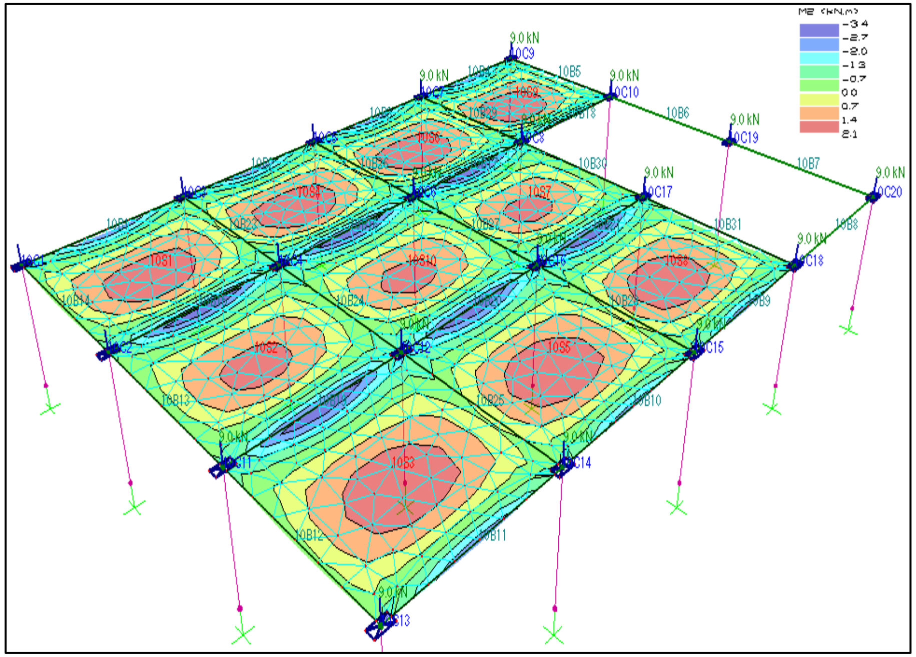

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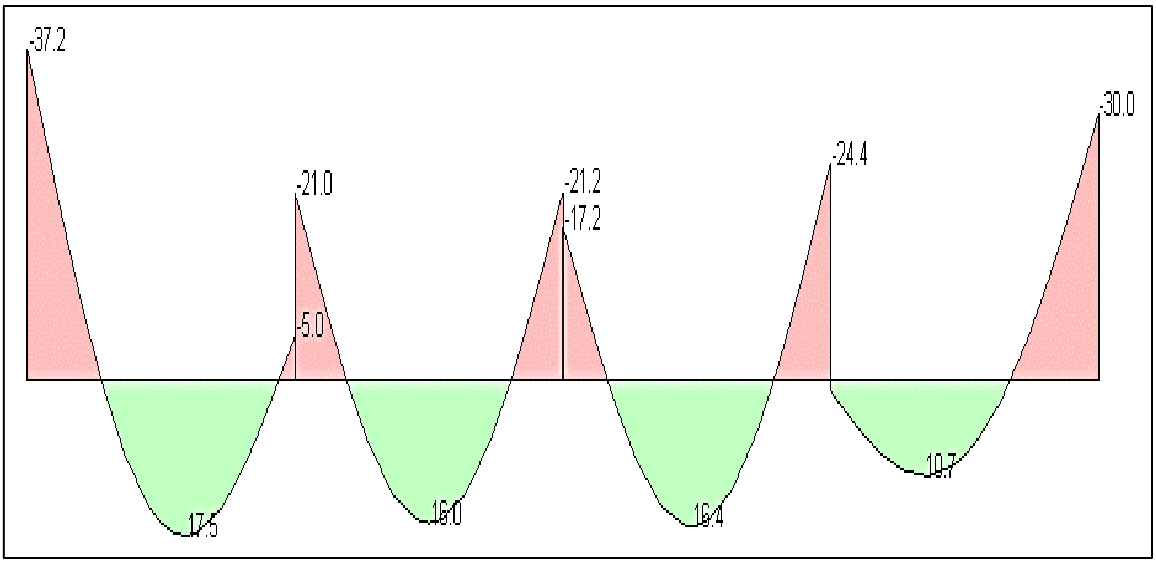
When this is run, the bending moment diagram for the comparison frame at the top storey is shown in *Figure 9*. This appears to be fairly consistent with the preceding baseline analysis results as shown in *Figure 9b*. Although the findings are not completely comparable, the discrepancies are often minor and are most likely due to internal variances in how FE beam and wall parts are expected to join.

Figure 9: The bending moment diagram for the comparison frame at the top storey; and Shear force and bending moment diagrams

a



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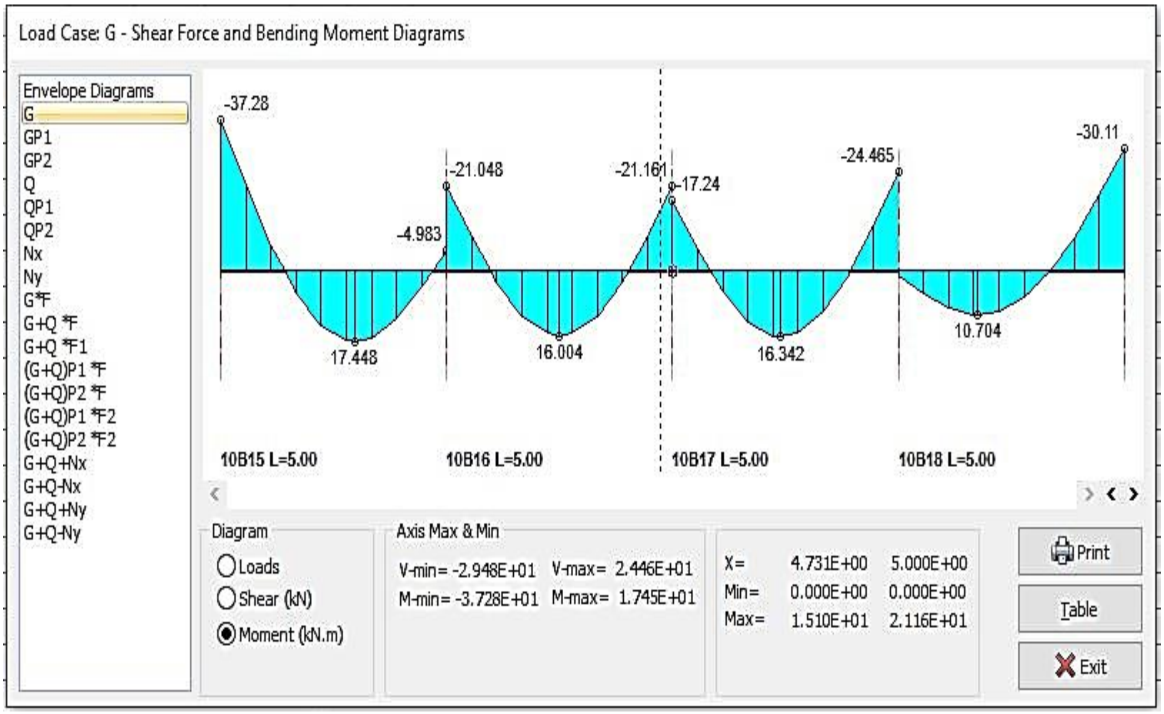

However, there are several problems and limitations to this technique. The steps and technique are more onerous, and thus take longer, because the analysis must be done floor by floor. The FE Analysis only considers the gravity load condition. Building analysis must still be performed to account for lateral load scenarios. In essence, one must perform and aggregate the

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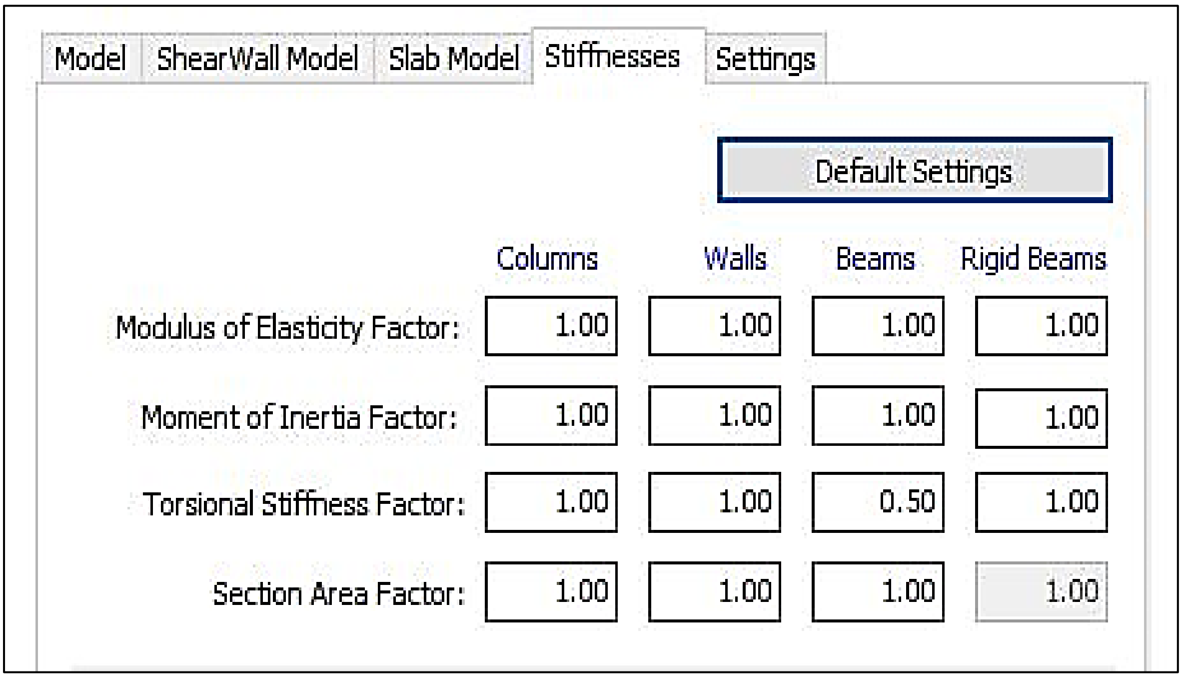
results of two analysis methods. The automatic beam load pattern (arrangement) is not considered. Some engineers may want to explore adopting the FE Chasedown results since they resemble classic or conventional analysis. Other engineers, however, may wish to know that pattern load has been considered and/or that a single analytical model is utilized for both gravity and lateral load instances. For this reason, we believe that the area factor adjustment method, as illustrated in the following section, is better.

Building Analysis, Area Factor Adjustment Methods

By selecting 'building analysis', a single frame model of the entire structure is generated and studied for all load scenarios and combinations. Prior to analysis, global stiffness modifications can be applied to member groups employed in the analysis model, with the default parameters indicated in *Figure 10a*.

Figure 10: Global stiffness modifications; and bending moment diagram for the comparison frame at the top storey

a



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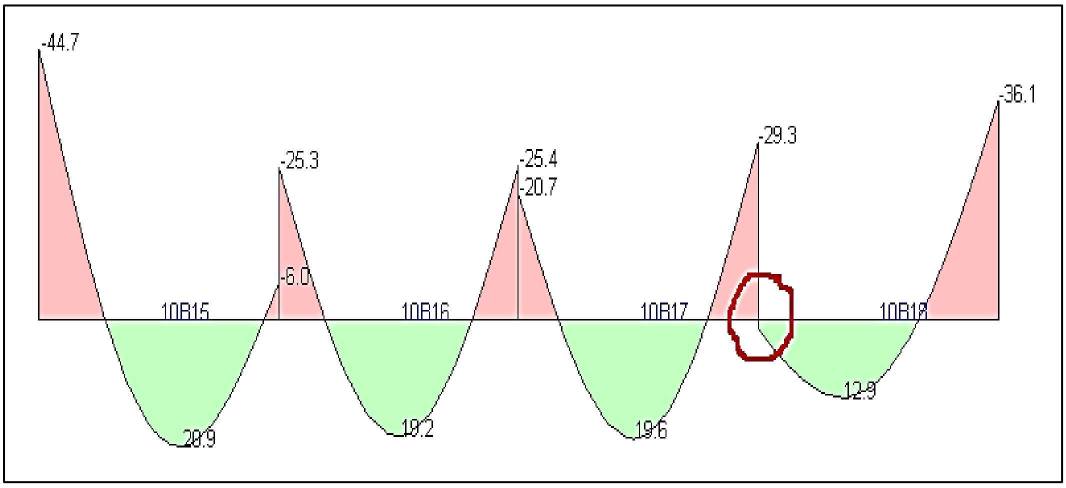

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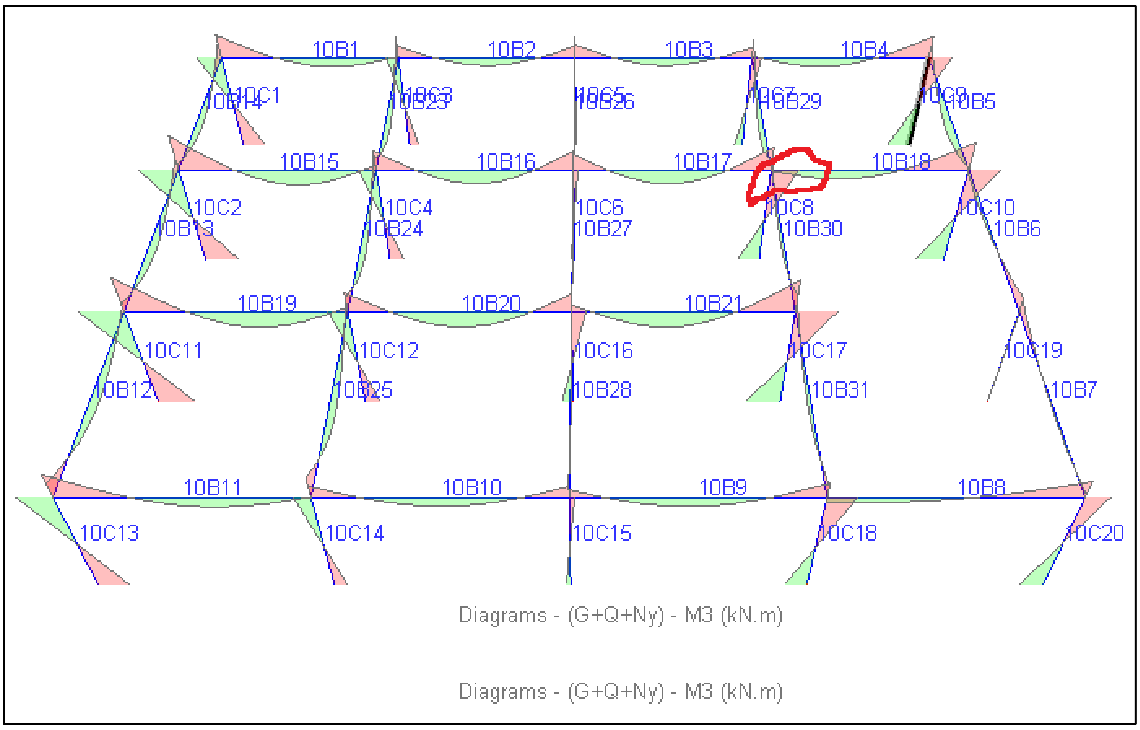
If the analysis is done with the above default settings, the bending moment diagram for the comparison frame at the top storey is shown in *Figure 10b*. There appears to be an anomaly, an unexpected sagging moment is occurring at the beam end (10B18) supported by the column as circled in red in *Figure 10b*. To gain a better understanding of why this is happening, we need to think about the 3D nature of the analysis model [6]. To begin with, let's display the above diagram (*Figure 10b*) in 3D along with the other beams on the top floor. The result is shown in ***Figure 11***

Figure 11: 3D along with the other beams at the top floor



There is a sagging moment at the beam end (10B18), which is supported by the column (10C8). This conclusion appears to contradict our "baseline" answer obtained from analysing the top floor as a discrete model, as demonstrated previously. This prompts two immediate questions. Why do the two models provide such different results? If we accept the baseline model's results as our target outcome, is it possible to alter the building analysis model to put it back in line with this target? Why do the two models provide such different results? To resolve this, we must compare the two deflection diagrams for the dead load situation, as shown in *Figure 12*

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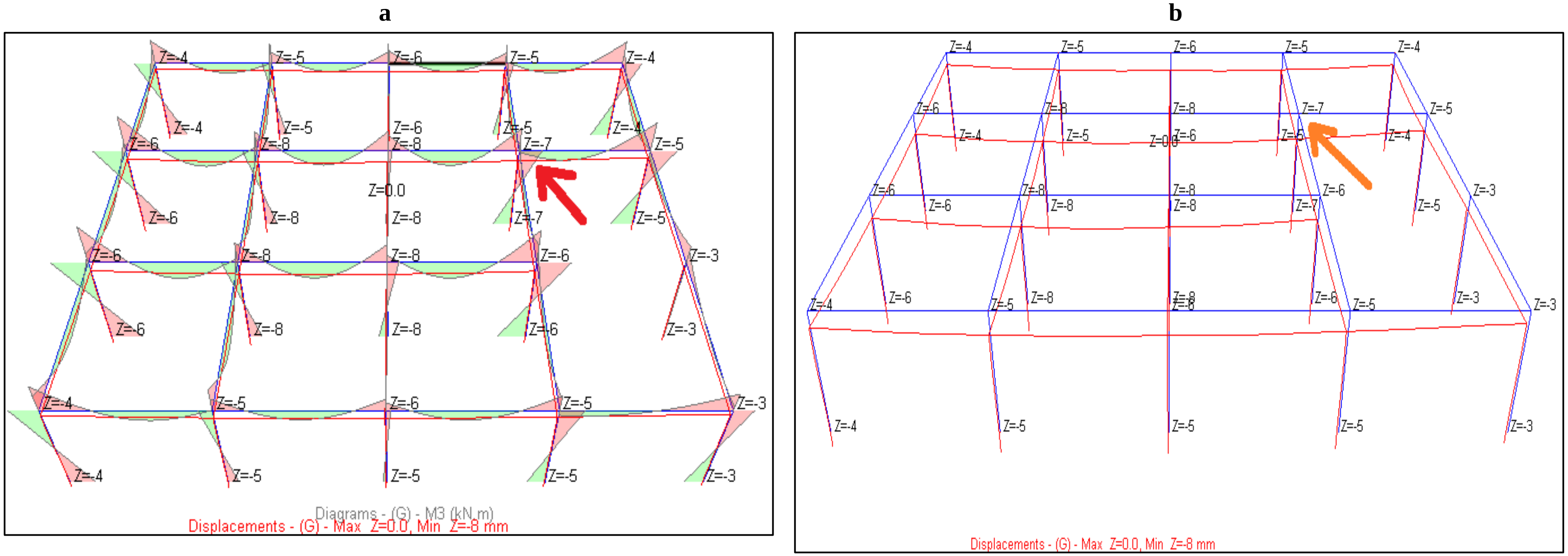
Figure 12: 3D "Z" displacement (m) for the top floor of the building analysis model



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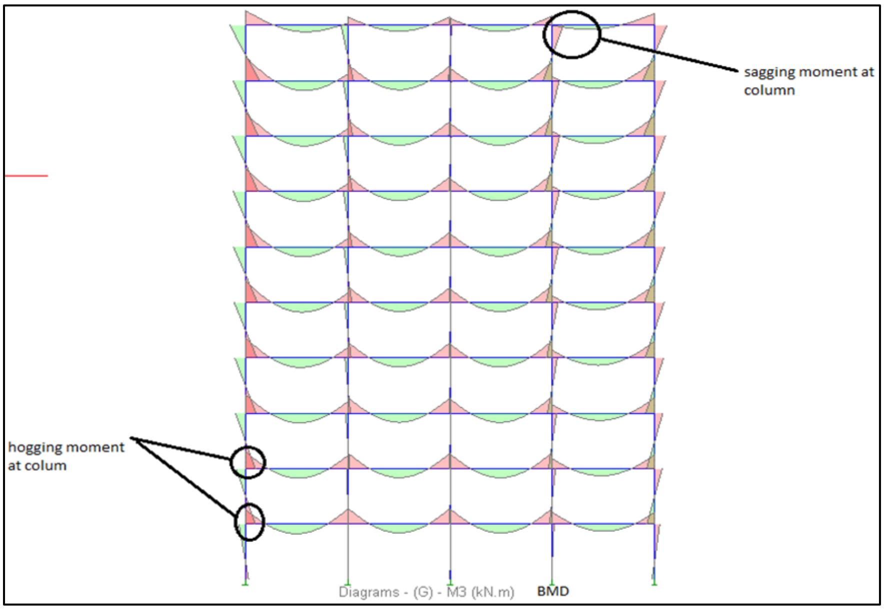
In the baseline model, the vertical deflections at the beam support points have been eliminated. This is not the case in the building analysis model - vertical deflections occur at the beam support points. Since stresses are greater in the columns, these deflections are greater at column support locations than at the wall support locations. The difference in these deflections is most obvious along the line of the frame on which the 'anomaly' in the bending moments was detected. The difference tends to increase in the upper stories. Evidence for this can be seen in the change of shape of the displacement & bending moment diagram along the line of the highlighted frame, as shown in the analytical model *Figure 13.*

Figure 13: The change of shape of the displacement and bending moment diagram

a



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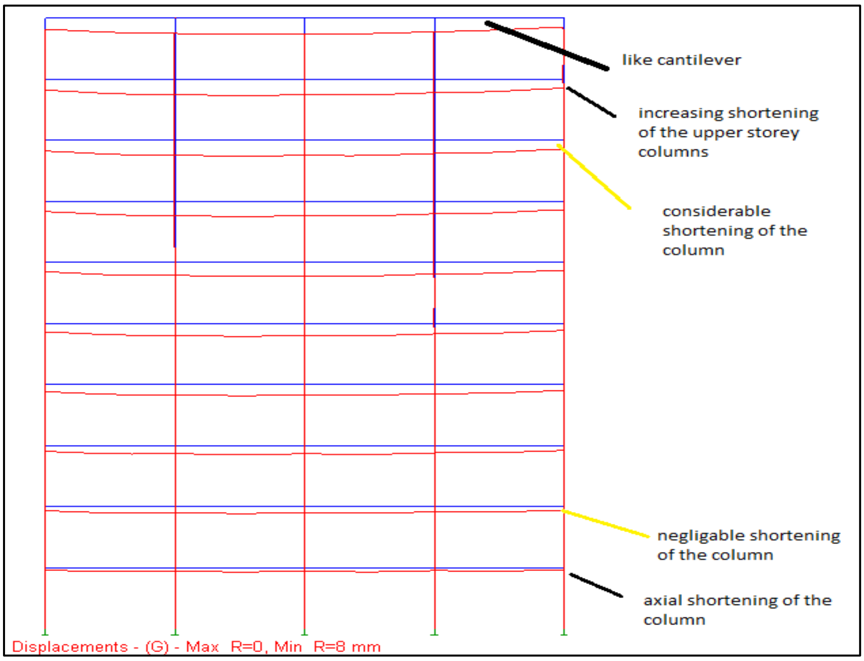

Differential axial deformations explain why the two models provide different results. Traditional sub-frame analysis disregards this effect. This article will address whether it is appropriate to

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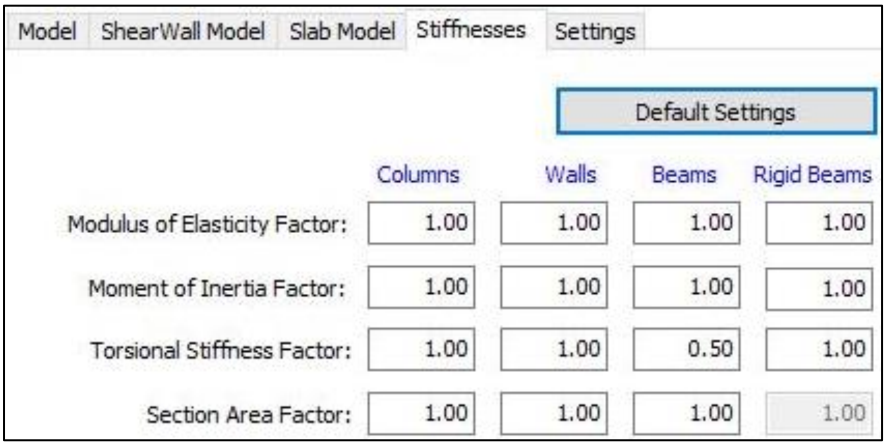
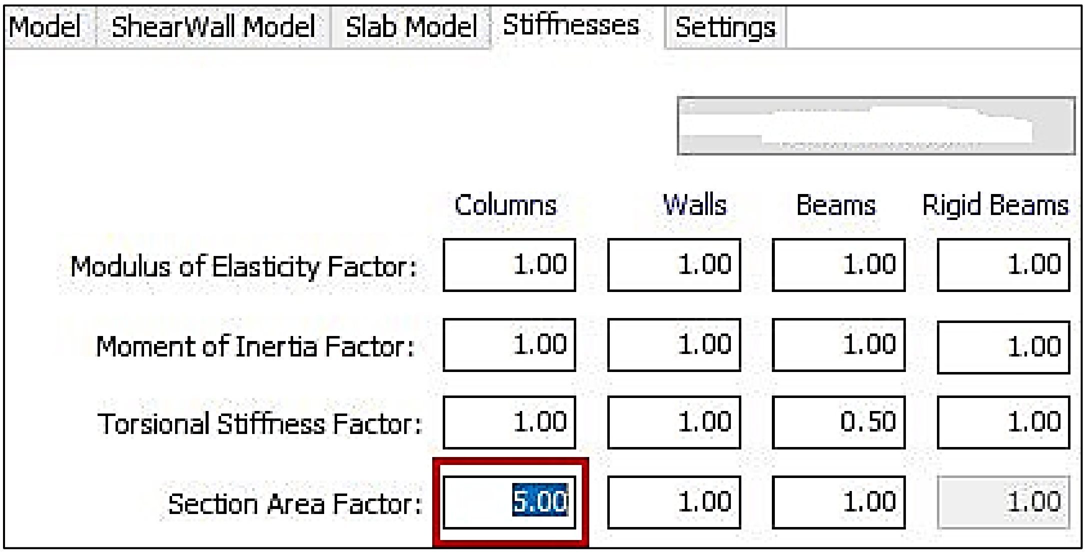
omit vertical deflection at supports when conducting sub-frame studies. Now, assuming that we want to disregard it, we must decide whether it is possible to eradicate it.

Figure 14: Default stiffness settings



To eliminate the Differential Axial Deformation Effect in building analysis, various adjustments can be made to member attributes. One effective method involves increasing the column area factor to reduce the difference in axial deformation between columns and walls. By adjusting stiffness settings, such as increasing the axial area factor for columns or walls, vertical deflections and bending moments can be minimized. Trials have shown that adjusting the column axial area factor is particularly beneficial without negative side effects. (*Figure 14*&*Figure 15*).

Figure 15: Area factor



Increasing the column area factor aims to diminish or eliminate the differential axial deformation, resulting in design forces more closely aligned with traditional methods (*Figure 16a* & *Figure 16b*). However, determining a reasonable upper limit for the column area factor adjustment requires engineering judgment, considering the trade-off between reducing DADE and maintaining structural integrity. The goal is to achieve a realistic set of design forces without fully addressing the consequences of differential axial shortening.

Comparisons of analysis results demonstrate that increasing the column area factor effectively reduces DADE, leading to outcomes similar to traditional sub-frame analysis. These methodologies offer practical strategies for mitigating DADE and ensuring structural stability in building designs.

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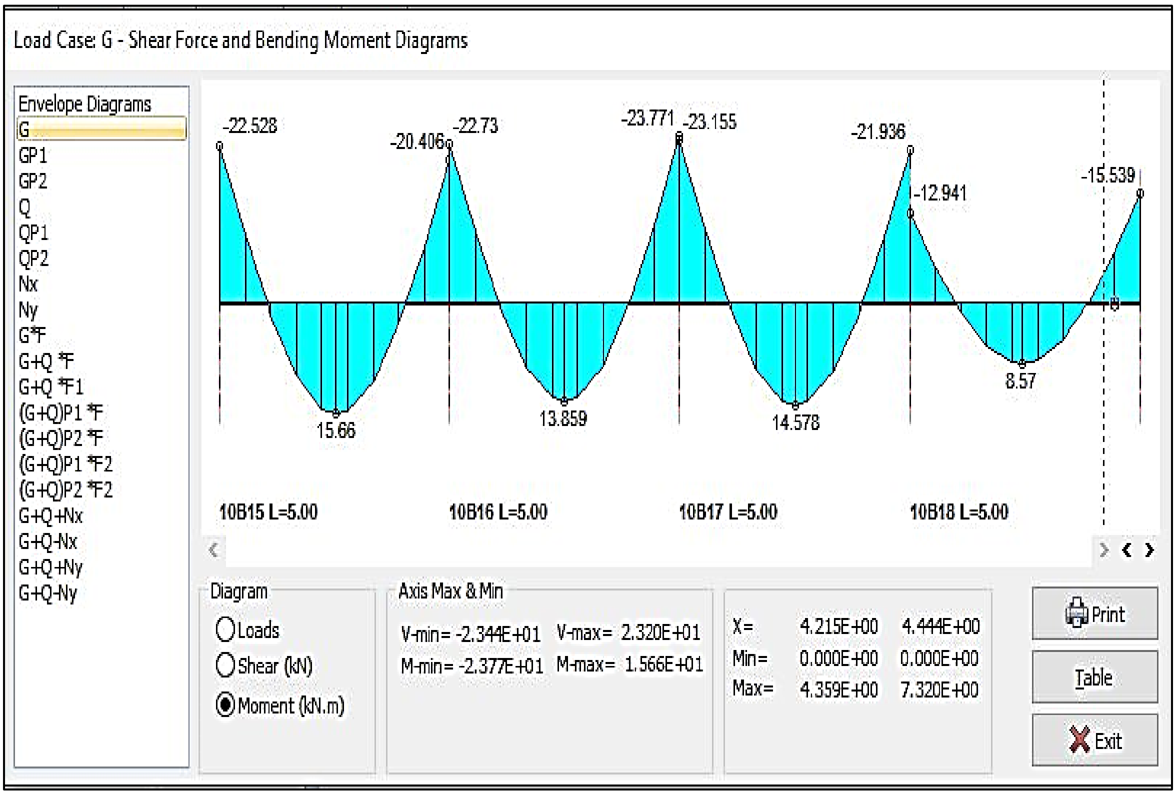
Figure 16: BMD & Vertical Deflection, Dead Load for AF = 5; and BMD & Vertical Deflection, Dead Load for AF = 10

a



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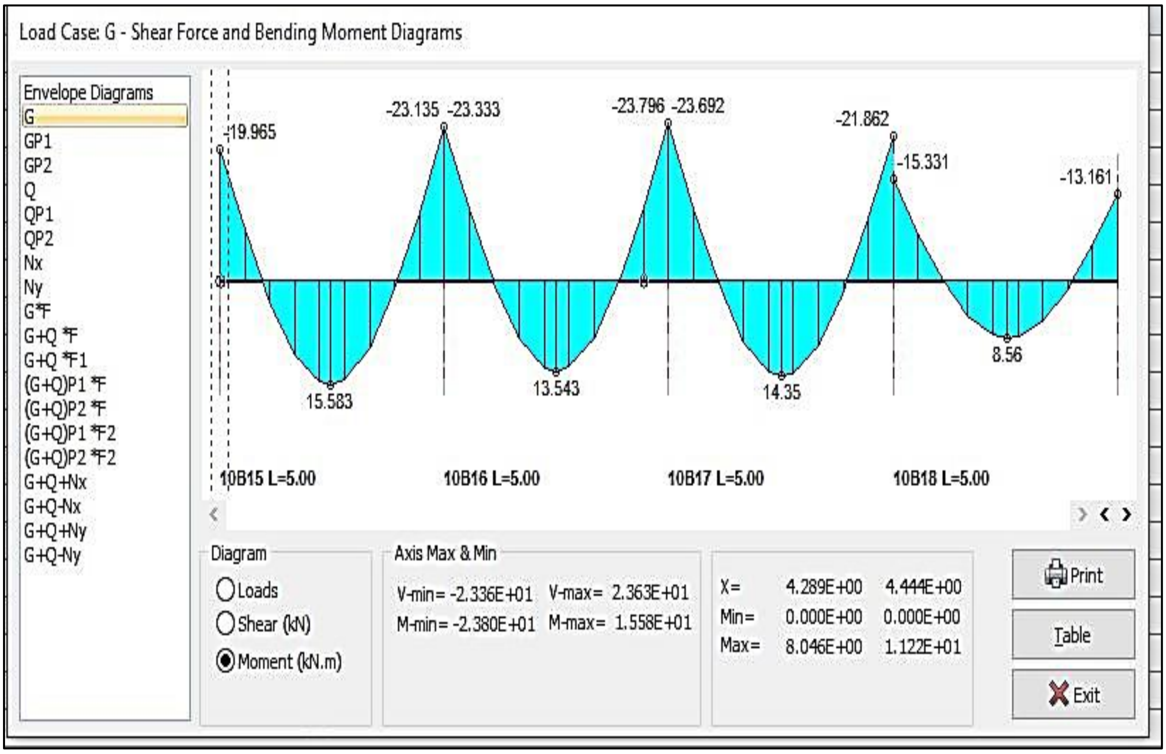

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Axial Load Comparison Report for FE and Building Analysis Methods

Table 1: Total loads (based on slab loads)

	Storey	Column	Wall	Beam	Slab	Ribbed Slab	Total
G - Dead Loads:	10 (+30.00m)	180.0	0.0	346.1	720.0	0.0	1246.1
	9 (+27.00m)	180.0	0.0	1540.7	720.0	0.0	2440.7
	8 (+24.00m)	180.0	0.0	1540.7	720.0	0.0	2440.7
	7 (+21.00m)	180.0	0.0	1540.7	720.0	0.0	2440.7
	6 (+18.00m)	180.0	0.0	1540.7	720.0	0.0	2440.7
	5 (+15.00m)	180.0	0.0	1540.7	720.0	0.0	2440.7
	4 (+12.00m)	180.0	0.0	1540.7	720.0	0.0	2440.7
	3 (+9.00m)	180.0	0.0	1540.7	720.0	0.0	2440.7
	2 (+6.00m)	180.0	0.0	1540.7	720.0	0.0	2440.7
	1 (+3.00m)	180.0	0.0	1540.7	720.0	0.0	2440.7
	Total						23212.3
Q - Live Loads:	10 (+30.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	9 (+27.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	8 (+24.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	7 (+21.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	6 (+18.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	5 (+15.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	4 (+12.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	3 (+9.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	2 (+6.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	1 (+3.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	Total						0.0

Table 2: Total loads (decomposed to beams)

	Storey	Column	Wall	Beam	Slab	Ribbed Slab	Total
G - Dead Loads:	10 (+30.00m)	180.0	0.0	1066.1	0.0	0.0	1246.1
	9 (+27.00m)	180.0	0.0	2260.7	0.0	0.0	2440.7
	8 (+24.00m)	180.0	0.0	2260.7	0.0	0.0	2440.7
	7 (+21.00m)	180.0	0.0	2260.7	0.0	0.0	2440.7
	6 (+18.00m)	180.0	0.0	2260.7	0.0	0.0	2440.7
	5 (+15.00m)	180.0	0.0	2260.7	0.0	0.0	2440.7
	4 (+12.00m)	180.0	0.0	2260.7	0.0	0.0	2440.7
	3 (+9.00m)	180.0	0.0	2260.7	0.0	0.0	2440.7
	2 (+6.00m)	180.0	0.0	2260.7	0.0	0.0	2440.7
	1 (+3.00m)	180.0	0.0	2260.7	0.0	0.0	2440.7
	Total						23212.3
Q - Live Loads:	10 (+30.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	9 (+27.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	8 (+24.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	7 (+21.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	6 (+18.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	5 (+15.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	4 (+12.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	3 (+9.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	2 (+6.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	1 (+3.00m)	0.0	0.0	0.0	0.0	0.0	0.0
	Total						0.0

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Table 3: Building analysis column and wall axial loads

Storey	G	Delta G	Q	Delta Q
10 (+30.00m)	1242.5	1242.5	0.0	0.0
9 (+27.00m)	3679.5	2437.1	0.0	0.0
8 (+24.00m)	6116.6	2437.1	0.0	0.0
7 (+21.00m)	8553.7	2437.1	0.0	0.0
6 (+18.00m)	10990.8	2437.1	0.0	0.0
5 (+15.00m)	13427.9	2437.1	0.0	0.0
4 (+12.00m)	15865.0	2437.1	0.0	0.0
3 (+9.00m)	18302.1	2437.1	0.0	0.0
2 (+6.00m)	20739.2	2437.1	0.0	0.0
1 (+3.00m)	23176.3	2437.1	0.0	0.0
Total		23176.3		0.0
Total Base Reactions: G = 23212.2 kN Q = 0 kN				

Table 4: FEA column/wall axial loads

Storey	G	Delta G	Q	Delta Q
10 (+30.00m)	1242.5	1242.5	0.0	0.0
9 (+27.00m)	3679.5	2437.1	0.0	0.0
8 (+24.00m)	6116.6	2437.1	0.0	0.0
7 (+21.00m)	8553.7	2437.1	0.0	0.0
6 (+18.00m)	10990.8	2437.1	0.0	0.0
5 (+15.00m)	13427.9	2437.1	0.0	0.0
4 (+12.00m)	15865.0	2437.1	0.0	0.0
3 (+9.00m)	18302.1	2437.1	0.0	0.0
2 (+6.00m)	20739.2	2437.1	0.0	0.0
1 (+3.00m)	23176.3	2437.1	0.0	0.0
Total		23176.3		0.0

RECOMMENDATION

To effectively address DADE's concerns and aim for its substantial elimination, a strategic approach is recommended. Initially, an analysis with an amplification factor (AF) of 1.00 is conducted, focusing on beam bending moments, vertical deflections of columns and walls at the top floor, and sway deflections in both directions. Following this analysis, an appropriate AF adjustment is determined based on the demonstrated approach. Subsequently, the analysis is rerun with the revised AF, and the results at the top floor are reviewed. If DADE appears to have been largely eliminated, the design of all column and wall members proceeds. However, if deflections remain largely unchanged, further consideration is warranted. In such cases, a second analysis with a lower AF is strongly recommended, particularly focusing on columns and walls.

Engineers have the option to emulate traditional design results, disregarding differential axial displacements, provided they are content with this approach. Two methods are proposed for emulating traditional design: the FE Chasedown Analysis and the Building Analysis using the Area Factor (AF) method. The FE Chasedown Analysis involves an automatic batch procedure, with finite element modelling of the slab being optional. This method closely mirrors traditional sub-frame analysis assumptions for gravity loads, necessitating a separate building analysis for lateral load cases. Conversely, the building analysis with the AF method offers simplicity and speed, considering pattern loading and allowing for the introduction of rigid zones for efficiency. However, applying a single area factor globally may not entirely eliminate differential axial deformation at all locations. Thus, engineers must weigh the pros and cons of each method to

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determine the most suitable approach for their specific design requirements

CONCLUSION ON DESIGN IMPACT

Based on the analysis provided, it is evident that considering upper and lower-bound solutions has a minimal effect on the overall construction cost, particularly for columns and walls where the majority of members remain unaffected. The FE Chasedown method is effective in eliminating differential axial deformation, but it lacks the ability to consider pattern loads at the upper bound. In contrast, the AF method, though slightly more time-consuming, offers the advantage of incorporating rigid zones and full pattern loading, potentially resulting in a net overall benefit.

Typical concerns raised by engineers include the desire for fixed values for the suggested area factor, potential side effects on force distribution and building deflection under wind loading cases, and whether employing FE Chasedown leads to over-designing the structure. Additionally, there are questions about the accuracy of solving these issues through staged construction analysis.

Regarding FE Chasedown, it does eliminate differential axial deformation, as demonstrated in the report. However, it does not account for pattern load cases, which limits its applicability. Therefore, while FE Chasedown remains a viable option, especially for software where patterning is not easily achieved, it may not be as comprehensive as the AF method in addressing both differential axial deformation and pattern load considerations.

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