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Simplified Finite Element Modelling of Multi-storey Buildings: The Use of Equivalent Cubes

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ABSTRACT: Finite element modelling is frequently used to overcome experimental limitations in predicting and analysing the performance of structures. However, constrained by software restrictions, 3-D analysis of high-rise buildings is still challenging and complex. This paper discusses how to substructure different parts of a multi-storey building with cubes having equivalent stiffness properties. As a result, the mesh density of the whole building is reduced significantly and the computational time and memory normally consumed by such complex structural dimensions and material properties will also be reduced. The simplified analysis results of a high-rise frame structure with a concrete core have been used to explore the reliability of this method.

KEYWORDS: Multi-story Buildings, Equivalent cubes

1 INTRODUCTION

Finite element modelling is frequently used to overcome experimental limitations in predicting and analysing the performance of structures. In designing and analyzing the performance of high-rise buildings, it is especially important that an effective modelling technique be involved because of the complexity of the real structural behavior and the difficulties of full scale measurement.

To date, various modelling methods have been developed to analyse the performance of high-rise buildings [1-6]. The “Finite Story Method” introduced by Pekau et al. [1, 2] can reduce the unknowns of each storey in a high-rise building thus improving greatly the computing efficiency. The program developed by Oztorun et al. [3] has a special mesh generation subroutine and graphics program for the finite element analysis of shear walls in buildings. Beams or columns can be easily added or deleted in this program, which makes the modelling process more convenient. Mahendran et al. [4] believed that 2-D modelling analysis is not sufficient to predict the real performance of structures, so a 3-D modelling method for steel portal frame buildings is necessary. Poulsen et al. [5] gave details of how to consider the reinforcing bars and the tension/ compression behaviour of concrete in the limit state analysis of reinforced concrete plates subjected to in-plane forces. This is especially useful for the analysis of single reinforced elements. When modelling high-rise structures, where there are often concerns about node limitations and growing computational time and memory capacity of finite element analysis tools such as ANSYS, this method might be appropriately used in the substructure. A supper-element method introduced by Kim et al [6] for modelling shear wall structures is a method involving substructures. This method can easily achieve equal accuracy within reduced computing time.

It is also found that a great deal of modelling work has focused on the seismic or wind behaviour of structures [7-16] since these two types of lateral loads are the most serious external loads which may cause severe damage to high-rise buildings. Almost all of these models are about limit state analysis or prediction. People can now be confident about the seismic or wind analysis of framed [7, 14] and reinforced concrete shear wall structures [8] because of research within above area. However, most of these methods are based on 2-D models which involve a lot of simplifications compared to the real performance of a 3-D structure. Even though some 3-D models were used in the analyses, those models were limited to modelling single elements. It appears that, the above situation is due largely to the limitations of current FE analysis tools. As pointed by Oztorun et al. [3], due to the large and complex amount of input requirements and node limitations, the utilization of some other finite element analyzing software such as SAP90, etc. seems impractical.

Constrained by software restrictions, 3-D analysis of high-rise buildings is a big challenge, especially when analyses of the contributions of non-structural components to the building stiffness are required. To focus on the interaction details between structural and non-structural components, a simple but efficient primary structural model needs to be developed first.

This study concerns the development of a simple primary structural model. A method called “The Equivalent Cubic Method” is presented together with a calibration analysis of the Force-Displacement (F-D) relationship under static loading conditions.

2 STRUCTURAL MODEL

The proposed structure is a 32-storey high-rise reinforced concrete building. The height of each storey is 3m, and the floor plan is composed of a concrete core and rigid frame as shown in Figure 1.

To simplify the modelling and analysis procedure, this floor plan has been divided into series of sets of 9 blocks, which can be categorized into 3 different types according to dimensions and properties of their structural elements (Figure 2).

Area type I is the 15×15 m concrete core block. It includes a set of 0.4m-thick shear walls, 4 head beams of shear walls with cross section area of 0.6×0.6 m, and 4 columns of 0.8×0.8 m cross section area standing at the 4 corners of the core (Figure 2).

Area type II refers to the four corner parts of the frame (Figure 2). Within those 45×45 m areas, orthogonal beams divide each area into 9 sections of 15×15 m (Figure 2).

Area type III involves the four 45×15 m rectangular areas which have common walls with the core area. Similar to type II, the rectangular floor slab is supported by 3 beams along its longer span (Figure 2).Details of each element are provided in Table 1.

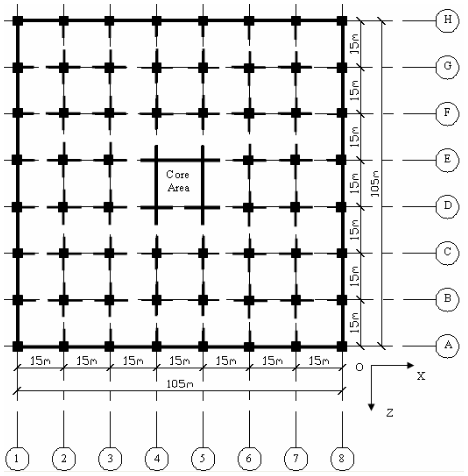


Figure 1. Typical Floor Plan of the 32-Storey High-rise Building

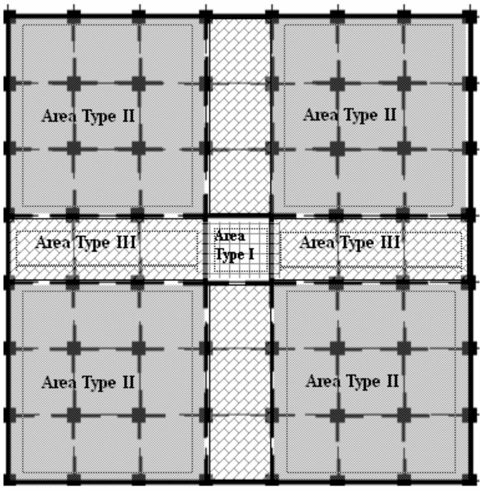


Figure 2. Divide the Floor Plan into 9 Blocks According to the Dimension

3 EQUIVALENT MODEL

In this study, the commercial software package ANSYS 10.0 has been used as the analytical tool. The largest constraint in this structural model is that the computational capability of ANSYS will be influenced by both the computer hardware and the meshing density. The challenge for this simulation process is to save both computing time and memory by efficiently reducing the overall meshing density of the structure.

The aim of this study is to find an efficient equivalent model to represent the real structural model for the serviceability analysis of high-rise buildings. Some details such as connection properties, etc. can be simplified. And, when designing the models, following assumptions have been made:
Ignore openings in the structure;
The material used is pure concrete without reinforcement;

All structural components (beams, columns, walls, and floor slabs) are considered have rigid connections to each other;
The procedure for the model simplification is:

- Structural model. Create a one-storey concrete core model of the structure (Type I) according to the component details and material properties given in previous section. The mesh elements used by ANSYS have been listed in Table 2;
- Static analysis 1. Process static analysis of this core block. Plot the Force-Displacement (F-D) relationship of the top edge point of the block.
- Cubic model. Build a 3×3×3 m cubic model, with the 4 side-faces as walls, and the top and bottom as floor slabs, and the linear joints as beams and columns respectively. The mesh elements used by ANSYS have been listed in Table 2.

Table 1. Details of Structural Components

Area Type	Structural Component	Area (m^2)	Thickness (m)	I_{zz} (m^4)	I_{yy} (m^4)	Re-bar Diameter (mm)	Concrete grade (Mpa)
Type I	Beam	0.36		0.0108	0.0108	N16~N36	32
	Column	0.64		0.0341	0.0341	N16~N36	80~32
	Wall		0.4			N16~N36	
	Floor slab		0.2			N12~N36	32~40
Type II	Beam I	0.36		0.0108	0.0108	N16~N36	32
	Beam II	0.16		0.0021	0.0021	N16~N36	32
	Column	0.64		0.0108	0.0108	N16~N36	80~32
	Internal Wall		0.2			N16~N36	
	External Wall		0.4			N16~N36	
	Floor slab		0.2			N12~N36	32~40
Type III	Beam I	0.36		0.0108	0.0108	N16~N36	32
	Beam II	0.16		0.0021	0.0021	N16~N36	32
	Column	0.64		0.0108	0.0108	N16~N36	80~32
	Internal Wall		0.2			N16~N36	
	External Wall		0.4			N16~N36	
	Floor slab		0.2			N12~N36	32~40

- Static analysis 2 & F-D relation calibration. Repeat the static analysis in step 2 on the cubic model. Use the F-D relationships achieved from both step 2 and step 4 in calibrating.
- Equivalent cubic model. Finally, adjust the properties of structural components and get the equivalent cubic model of the one-storey concrete core block from the calibration process in step 4.
- Other Type of Area of Structure. Repeat the above step 1-5 to get the equivalent cubic models of block types II and III (all the cubic models should be 3×3×3 m because of the geometric considerations).

Relevant concrete material properties and modelling elements used throughout the building are detailed in Table 2. Figure 3 presents a representation of boundary gridlines with cubic areas and Table 3 details boundary constraints for each area.

Table 2. Meshing Elements Used in ANSYS10.0

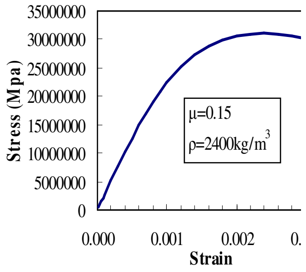
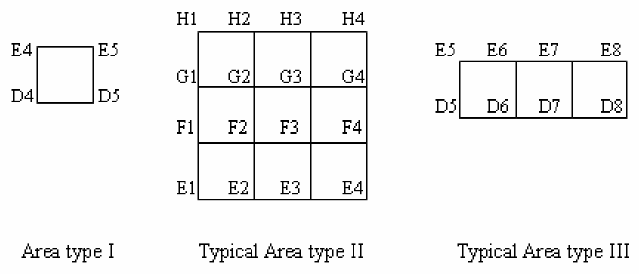
	BEAM4	SHELL63	Concrete Property
Beam	√		
Column	√		
Wall		√	
Floor Slab		√	

Figure 3. Boundary Definition of Different Area Type

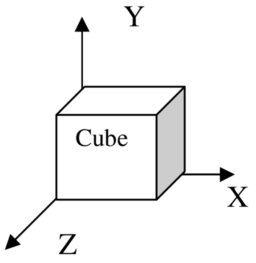


4 RESULT OF CALIBRATION

Calibration of F-D relations of structural models and cubic models has been presented in Figure 4. In the static analysis, a concentrated external load F=2×108 N has been applied to the top middle point of each model. From Figure 4, the maximum top corner displacements of the structural core model and the equivalent cubic model are 26.8mm and 27.36mm respectively, i.e. the deviation is only 2.11% (Table 4). The F-D relations of structural models and the equivalent cubic models calibrate with each other perfectly. It is observed that when subject to external static loads, the equivalent cubic model for each part of the structure has almost the same behaviour as the relevant part of real structure.

The calibration of the F-D relationships that may occur to cubic model in an asymmetric condition when under the lateral concentrated loads is plotted in Figure 5. From the results, the maximum difference from that calibration is only 1.78% (Table 5). It is found that similar to the symmetric model, the equivalent cubic model can perform in exactly the same way as the real structure in both directions.

Table 3. Boundary Conditions of the Model

		UX	UY	UZ	ROTX	ROTY	ROTZ	Reference Frame
Typical Area Type I	D4-E4	--	0	--	--	--	--	
	E4-E5	--	0	--	--	--	--	
	E5-D5	0	0	0	0	0	0	
	D5-D4	--	0	--	--	--	--	
Typical Area Type II	E1-F1-G1-H1	--	0	--	--	--	--	
	H1-H2-H3-H4	--	0	--	--	--	--	
	H4-G4-F4-E4	0	0	0	0	0	0	
	E4-E3-E2-E1	--	0	--	--	--	--	
	F1-F2-F3-F4	--	0	--	--	--	--	
	G1-G2-G3-G4	--	0	--	--	--	--	
	E2-F2-G2-H2	--	0	--	--	--	--	
	E3-F3-G3-H3	--	0	--	--	--	--	
Typical Area Type III	D5-E5	--	0	--	--	--	--	
	E5-E6-E7-E8	0	0	0	0	0	0	
	E8-D8	--	0	--	--	--	--	
	D5-D6-D7-D8	--	0	--	--	--	--	
	D6-E6	--	0	--	--	--	--	
	D7-E7	--	0	--	--	--	--	

Under surface loads such as pressure, because of the difference in geometrical dimensions, the results are not so close. Similarly, owing to the spatial difference, and inequality of density distribution, distinct differences exist in the modal shapes of the two types of models.

The calibration results under different loading conditions show that this simplified method of modelling high-rise structures is suitable in static analysis for structural serviceability. It can simulate the exact F-D performance of a structure and thus can effectively save computational time and memory. Moreover, there are two other main advantages in using this simplified model to analyse the behaviour of a high-rise building.

This “Equivalent Cubic Method” can be conveniently used in modelling different buildings. The stiffness calibration between the structural model and the cubic model can be readily conducted no matter what kind of floor plan, element properties, or material properties need to be involved. Furthermore, asymmetric structures can really be modelled by this cubic approach.

A further benefit of this simplified model is the convenience it would bring to the analysis of the influence of different non-structural components to high-rise building performance. Non-structural components can easily be modelled using shell or spring elements and connected to the main structural part,

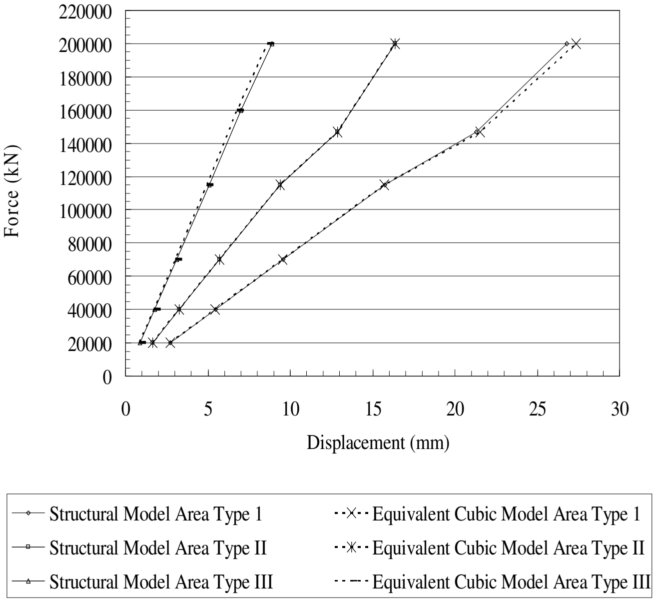


Figure 4: Calibration of F-D Relation of Structural Models and Equivalent Cubic Models

Table 4. Comparison of the Displacements of Structure Models and Cubic Models under Lateral Load

Force (kN)	Displacement (mm)								
	Type I Model	Cubic Model I	Difference I (%)	Type II Model	Cubic Model II	Difference II (%)	Type III Model	Cubic Model III	Difference III (%)
20000	2.730	2.729	0.02	1.332	1.332	0.02	0.886	0.860	2.95
40000	5.465	5.460	0.10	2.665	2.664	0.05	1.774	1.721	2.98
70000	9.572	9.558	0.15	4.666	4.662	0.07	3.105	3.011	3.01
115000	15.747	15.717	0.19	7.669	7.661	0.10	5.104	4.948	3.05
147000	21.296	21.535	1.12	10.509	10.495	0.13	6.995	6.778	3.10
200000	26.800	27.364	2.11	13.351	13.331	0.15	8.887	8.608	3.14

Table 5: Comparison of Displacements of Asymmetric Concrete Core Model and Cubic Model under Lateral Load

Force (kN)	Displacement (mm)					
	Core Model X-Direction	Cubic Model X-Direction	Difference X-Direction (%)	Core Model Z-Direction	Cubic Model Z-Direction	Difference Z-Direction (%)
20000	2.372	2.414	1.78	2.612	2.612	0.00
40000	4.748	4.830	1.72	5.229	5.225	0.07
70000	8.314	8.455	1.69	9.162	9.147	0.16
115000	13.673	13.897	1.64	15.086	15.039	0.31
147000	18.748	19.044	1.58	20.729	20.605	0.60
200000	23.833	24.196	1.53	26.628	26.180	1.68

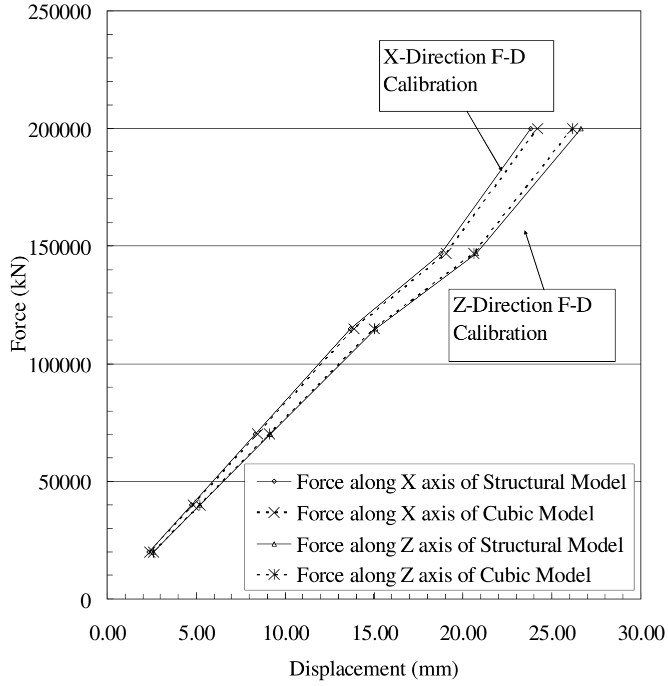


Figure 5: Calibration of F-D Relations of Asymmetric Concrete Core under Lateral Concentrated Load

5 CONCLUSION

This study developed an "Equivalent Cubic Method" to simplify modelling problems when analysing the static properties of high-rise buildings. A typical 32-storey high-rise building has been modelled with one storey blocks. F-D relationship calibration has been carried out to find the proper simplified cubic model. The following findings have been identified in this study:

- The "equivalent cube method" can be broadly used in static analysis concerned with the serviceability of high-rise buildings. It can efficiently simplify the model and reduce structure dimensions and mesh density and thus reduce the computation time and memory requirements;
- The accuracy of this method appears to be high for the structure analyzed when subjected to a concentrated external force. According to this study, the difference between the real structural model and the equivalent cubic model can be as low as 3%;
- This equivalent cubic method can be extended to the asymmetric structures. Even the asymmetric structure can be simplified using this "equivalent cubic method" and a satisfactory result achieved;
- The equivalent cubic method is beneficial for analysing the influence of non-structural components on the overall performance of high-rise buildings. In using this model, the non-structural components can conveniently be modelled by shell or spring elements connected to the main structural cubes depending on their connection conditions;

- When under pressure or when doing modal testing, owning to the complexity of structural forms and mass distribution, etc. differences between the structural model and equivalent cubic model will appear. So far, according to this study, this equivalent cubic method is not suitable for dynamic analysis.

6 RECOMMENDATIONS FOR FURTURE WORK

Further investigation focusing on the overall behaviour of the structural model built using the equivalent cubic method needs to be conducted to ensure the connection properties between storeys work correctly. Performance of the cubic model with attached non-structural components will also be analysed, as the connection properties and material properties of non-structural components may change with different scaling factors.

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