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COMPARISON OF TWO- AND THREE-DIMENSIONAL ANALYSIS OF MODERATELY SIZED TALL BUILDINGS UNDER WIND LOADS

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ABSTRACT: In recent years Bangladesh has witnessed a growing trend towards construction of 15-20 storeyed buildings: almost all of these being situated in Dhaka. The tallest building in Bangladesh is the 30-storeyed Bangladesh Bank Annex Building. However, no extensive study has been conducted in Bangladesh to compare the different techniques available for the analysis of tall buildings. Here, a limited parametric study has been carried out on different moderately sized tall buildings. The parameters that have been varied are, building height, column size with height, and area of building. In this study symmetrical tall buildings have been analysed to get an overall idea of the behaviour of buildings when various parameters are varied. To conduct the parametric study, two standard software have been employed. Besides this, a software has been developed to conduct the first stage analysis of tall buildings by Khan and Sbarounis (1964) method. In the end, the results of the parametric study have been presented graphically and discussed in detail. What emerged from the study is that buildings up to 15-storey high can be conveniently analysed by discretizing them in the two-dimensional continua, without much loss of accuracy in the ensuing results when compared to their three-dimensional counterpart.

KEYWORDS: Tall Building, two-dimensional, three-dimensional, top displacement, base shear.

INTRODUCTION

It is difficult to distinguish the characteristic of a building that categorises it as tall. After all, the perception of tallness is a relative matter. In a typical single storey area a 5-storeyed building will appear tall. In Europe, a 20-storeyed building in a city may be called as high rise, but the citizens of a small town usually point to their skyscraper of six floors. In large cities such as Chicago and Manhattan, which are composed of a vast number of tall buildings, a structure must peer the sky around 70-100 storeys, if it is to appear tall in comparison to its immediate neighbours. Although the council of Tall Buildings and Urban Habitat considers buildings having 9 or more storeys as high-rise structures, tall buildings may not be defined in specific terms related to height or number of floors. There is no consensus on what constitutes a tall building or at what magic height, number of storeys or proportion a building can be called tall. Perhaps the dividing line should be drawn where the design of the tall structures moves from the field of

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statics into the field of structural dynamics. From the structural design point of view it is simpler to consider a building tall when it's structural analysis and design are in some way affected by the lateral displacement at the top of the building relative to its base.

Tall buildings can be analysed by idealising the structure into simple two-dimensional or more refined three-dimensional continuums. In two-dimensional methods several approximations are made and a particular column line has been chosen to analyse the building, in which total effectiveness of the building cannot be achieved. On the other hand, in three-dimensional analyses the whole building is taken for analysis and, thus, the structure can be modelled more realistically.

Several commercial software are available for two- and three-dimensional analysis of structures. Whereas softwares for two-dimensional analysis are usually inexpensive, the same for three-dimensional analysis may be very expensive and not quite easy to use. Since designers of moderately high buildings very often adopt two-dimensional analysis methods in the design office, a modest effort has been made in this study in order to understand the sensitivity of two- and three-dimensional analysis methods on various design parameters. A fuller picture of the study is available elsewhere in Noor (1995).

ANALYSIS METHODS

In this study two-dimensional analysis has been conducted by using the P1 module of MICROFEAP-II (1985-1987), the advanced extended version of XETABS (1995) has been used for three-dimensional analysis, and a computer code has been developed, Noor (1995), for analysing buildings using Khan and Sbarounis (1964) method.

BRIEF OUTLINE OF KHAN AND SBAROUNIS (1964) METHOD

In this method, the distribution of lateral loads among the shear wall and rigid frames of a building is obtained by a procedure, directly applicable to design. It does not require any simplifying assumptions about the structural properties of the components, and any initial assumptions about the deflected shape of the shear wall are subsequently checked by the analysis and corrections are made. The method can also be applied to frame torsion, base rotation and plastic rotation of shear walls at any point, axial deformation of columns and to walls that are terminated at intermediate levels. However, in the present study only the simple case (fixed base first stage analysis, Khan and Sbarounis, 1964) has been considered.

The deflected shape of an isolated shear wall, under any combination of lateral loads and moments can be found out by ordinary theory of bending, provided the moment of inertia, area etc. of the walls are known. Similarly for a rigid frame the deflections and slopes can be obtained under any combination of loads by the moment distribution or slope deflection methods. Thus, the only difficulty while solving a shear wall-frame interaction problem appears to be the correct estimation of interacting forces between the wall and the frame. The distribution of these forces is very complex and hence the present method does not make any assumption about these forces. The only condition to be satisfied by them, is that under a known system of external lateral loads, the deflected shape of the wall and the frame at the junction, must be identical.

To estimate these forces and the final deflected shape of the structure the total structure is divided into two systems - the wall system and the frame system. Then all the lateral loads are applied on the wall system and a deflected shape is assumed. After that the frame system is forced to deform in this deflected shape and the interaction forces and moments are calculated by moment distribution. If the assumed deflected shape of the wall is correct, the actual deflection of the wall under external loads and interacting forces should be the same as the assumed deflections. However, if the error exceeds the permissible limit, a new assumption on previous results is made and the process of iteration is repeated.

MODELING OF TWO- AND THREE-DIMENSIONAL BUILDING SYSTEMS

In this study, during three-dimensional analyses, buildings have been idealised as an assemblage of vertical frame and shear wall systems interconnected by horizontal floor diaphragms that are rigid in their place. A shear panel element has been used to enable modelling of shear walls. Axial, shear and bending deformations are considered during the analysis. Modelling of shear wall in two-dimensional analysis has been done using the concept of rigid end conditions between columns and beams. The buildings used in the study were symmetrical and rectangular in plan.

ANALYSIS SCHEME

The analysis scheme has been divided into two phases. In the first phase the accuracy of the Khan and Sbarounis (1964) method has been tested, comparing the results with those found from two-dimensional analysis. In the second phase a limited parametric study have been conducted by adopting both two- and three-dimensional analyses techniques. Here, several parameters have been selected in order to determine their effects on moment, shear and deflection at various locations.

PROBLEM IDEALIZATION

Three buildings having the same plan but different grid sizes have been selected to carry out the study. A typical plan and elevation have been shown in the Fig. 1.

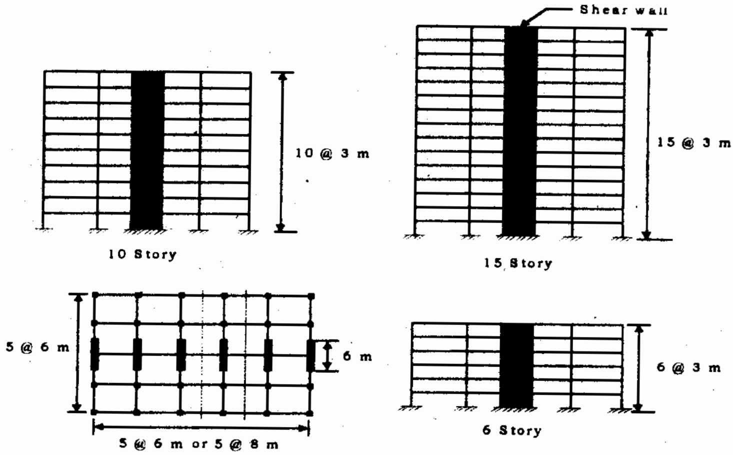

Fig 1. Plan and Elevation of 15-, 10- and 6-storeyed buildings studied

GEOMETRIC PARAMETERS

The details of the geometric properties adopted in various analyses of this study are available in Tables 1 to 6. The dimension of shear wall for both square and rectangular frames has been taken as 6 m x 0.3048 m. The same geometric properties have been used for both two- and three-dimensional analyses. The contribution of slab has been ignored altogether in this study.

Table 1. Square grid 15-storeyed structure

15 Storey	Square Grid Frame (Slab Thickness = 14 cm).					
	Beam section		Constant column section		Variable column section	
Storey no	Dimension (cm x cm)	Area (cm^2)	Dimension (cm x cm)	Area (cm^2)	Dimension (cm x cm)	Area (cm^2)
1-5	25.4 x 50.8	1290	72.4 x 72.4	5240	72.4 x 72.4	5240
6-10	25.4 x 50.8	1290	72.4 x 72.4	5240	59 x 59	3481
11-15	25.4 x 50.8	1290	72.4 x 72.4	5240	41.9 x 41.9	1756

Table 2. Square grid 10-storeyed structure

10 Storey	Square Grid Frame (Slab Thickness = 14 cm.)					
	Beam section		Constant column section		Variable column section	
Storey no	Dimension (cm x cm)	Area (cm^2)	Dimension (cm x cm)	Area (cm^2)	Dimension (cm x cm)	Area (cm^2)
1-5	25.4 x 50.8	1290	59 x 59	3481	59 x 59	3481
6-10	25.4 x 50.8	1290	59 x 59	3481	41.9 x 41.9	1756

Table 3. Square grid 6-storeyed structure

6 Storey	Square Grid Frame (Slab Thickness = 14 cm.)					
	Beam section		Constant column section		Variable column section	
Storey no	Dimension (cm x cm)	Area (cm^2)	dimension (cm x cm)	Area (cm^2)	Dimension (cm x cm)	Area (cm^2)
1-3	25.4 x 50.8	1290	45.7 x 45.7	2088	45.7 x 45.7	2088
4-6	25.4 x 50.8	1290	45.7 x 45.7	2088	32.4 x 32.4	1049

Table 4. Rectangular grid 15-storeyed structure

15 Storey	Rectangular Grid Frame (Slab Thickness = 15.24 cm.)							
	Long span beam section		Short span beam section		Constant column section		Variable column section	
Storey no	Dimension (cm x cm)	Area (cm^2)	dimension (cm x cm)	Area (cm^2)	Dimension (cm x cm)	Area (cm^2)	Dimension (cm x cm)	Area (cm^2)
1-5	25.4 x 63.5	1612	25.4 x 50.8	1290	81.3 x 81.3	6610	81.3 x 81.3	6610
6-10	25.4 x 63.5	1612	25.4 x 50.8	1290	81.3 x 81.3	6610	66 x 66	4356
11-15	25.4 x 63.5	1612	25.4 x 50.8	1290	81.3 x 81.3	6610	47 x 47	2209

Table 5. Rectangular grid 10-storeyed structure

10 Storey	Rectangular Grid Frame (Slab Thickness = 15.24 cm.)							
	Long span beam section		Short span beam section		Constant column section		Variable column section	
Storey no	Dimension (cm x cm)	Area (cm^2)	dimension (cm x cm)	Area (cm^2)	Dimension (cm x cm)	Area (cm^2)	Dimension (cm x cm)	Area (cm^2)
1-5	25.4 x 63.5	1612	25.4 x 50.8	1290	66 x 66	4356	66 x 66	4356
6-10	25.4 x 63.5	1612	25.4 x 50.8	1290	66 x 66	4356	47 x 47	2209

Table 6. Rectangular grid 6-storeyed structure

6 Storey	Rectangular Grid Frame (Slab Thickness = 15.24 cm.)							
	Long span beam section		Short span beam section		Constant column section		Variable column section	
Storey no	Dimension (cm x cm)	Area (cm^2)	dimension (cm x cm)	Area (cm^2)	Dimension (cm x cm)	Area (cm^2)	Dimension (cm x cm)	Area (cm^2)
1-3	25.4 x 63.5	1612	25.4 x 50.8	1290	50.8 x 50.8	2581	50.8 x 50.8	2581
4-6	25.4 x 63.5	1612	25.4 x 50.8	1290	50.8 x 50.8	2581	36.2 x 36.2	1310

LOAD CALCULATION

Only one load case has been considered in this study. Following the provisions of British Code CP3 (1972) method the wind load calculation has been done. Load case one: 0.9*Dead load + 1.3*Wind load.

A brief method of calculation of wind load has been given here. In this method, CP3 (1972), of analysis a dynamic wind pressure in psf, is calculated using the formula $q=0.00256V_s^2$, Here, V_s is the design wind speed, (in mph) calculated by using the expression $V_s=S_1S_2S_3V$, where,

V is the basic wind speed of the location under consideration, and S_1, S_2, S_3 are three parameters which are dependent on building height, ground roughness category, and building class, respectively. For the present study ground roughness has been taken as 4, and building class as 'B', CP3 (1972). Lateral load due to wind pressure has been varied along the height of the building. Whereas, in the case of 15-storeyed buildings, the lateral force was varied at three equally spaced locations along height, for 10- and 6-storeyed buildings the lateral force was varied only at two sections.

Live load and floor finish have been taken as 1.916 kN/m^2 (40 psf) and 0.958 kN/m^2 (20 psf), respectively. The load due to interior and exterior in-fill wall has been taken as 6.57 kN/m (450 lb/ft) and 13.13 kN/m (900 lb/ft), respectively. To calculate the wind load, storm of 120 mph (193 kph) along the short direction of the building has been considered.

MATERIAL PROPERTIES

In this study the compressive strength of concrete has been taken as 27.59 MPa (4000 psi). The modulus of elasticity of concrete (in psi) has been calculated using the relationship $E_c = 57000 \times \sqrt{f'_c}$, Where f'_c is the uniaxial cylinder strength of concrete in psi.

PARAMETRIC STUDY

The objective of the parametric study was to observe the effect of two parameters on two- and three-dimensional analysis of buildings. To find out the effect of column variability, the cross-sectional area of columns were varied in every five floors. Then the effect of such a variation on the magnitude of moment of column, shear and deflection was studied by conducting both two- and three-dimensional analyses. Again, additional runs were made by varying grid size of the structures and similar studies were conducted.

PRESENTATION OF RESULTS

In order to compare the results obtained in the present study, the magnitude of displacement, moment and shear has been normalised against corresponding free top displacement, free base moment and free base shear, respectively. These free top displacement, free base moment and free base shear were calculated as follows. A cantilever column has been chosen whose dimensions are same as the corresponding dimensions of the shear wall of the building under consideration. Load has been taken as the same lateral load, which has also been used in the analysis of the building. The top displacement, base moment and base shear of this cantilever column have been termed as free top displacement, free base moment and free base shear (Fig. 2).

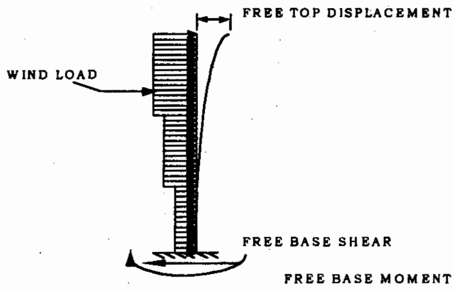

Fig 2. Free base shear, free moment, and free top displacement

KHAN AND SBAROUNIS METHOD VERSUS TWO DIMENSIONAL ANALYSIS

The deflections of various 15-, 10- and 6-storeyed buildings have been compared by analysing them using Khan Sbarounis (1964) method as well as by adopting two-dimensional analysis technique. The variation of displacement has been presented in Figs. 3 to 5. It has been observed that Khan and Sbarounis (1964) method always gives higher building drift in comparison to two-dimensional analysis conducted in this study. However, as the storey height decreased the difference between them also decreased. It is also clear from the curves that square grid structure gives less building drift than rectangular grid structures.

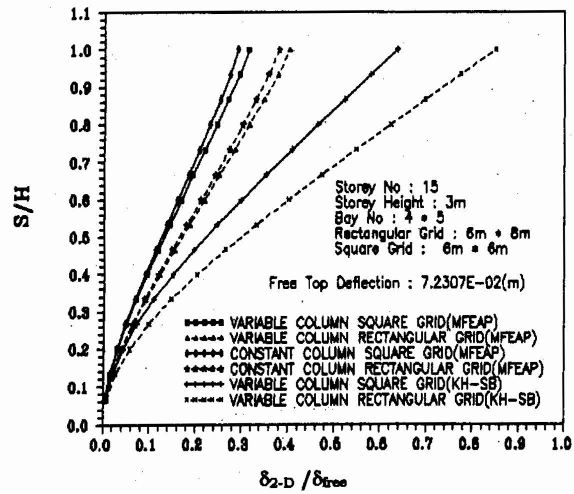

Fig 3. Displacement ratio ($\delta_{2\text{-}D}/\ \delta_{free}$) versus height ratio (S/H) for 15-storeyed buildings

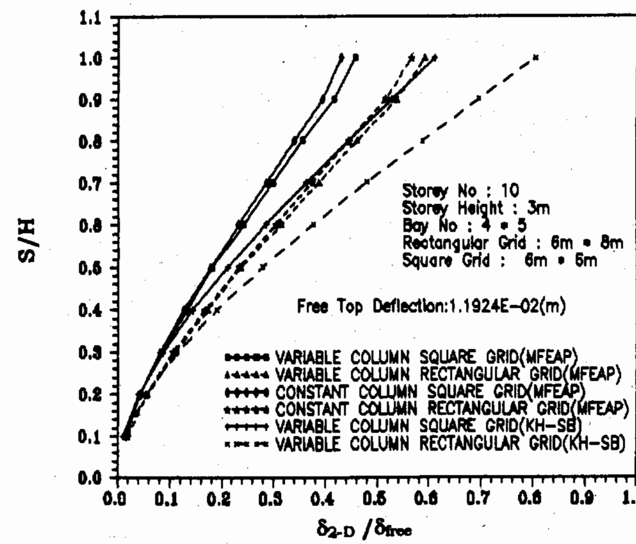

Fig 4. Displacement ratio ($\delta_{2\text{-}D}/\ \delta_{free}$) versus height ratio (S/H) for 10-storeyed buildings

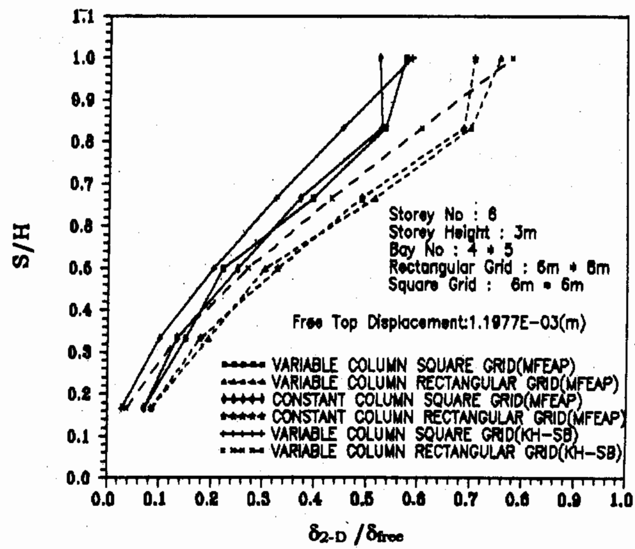

Fig 5. Displacement ratio ($\delta_{2\text{-}D}/\ \delta_{free}$) versus height ratio (S/H) for 6-storeyed buildings

THE PARAMETRIC STUDY

EFFECT OF VARIATION IN COLUMN SIZE ALONG HEIGHT

In order to understand the effect of variation of column size along height three buildings having symmetrical geometry with 15-, 10- and 6-storeyed each have been analysed. Table 7 deals with the adopted variation of column size along the height of buildings in this study.

Table 7. Location of column size variation along height of building

Storey	Column variation
15	1st-5th, 6th-10th, 11th-14th
10	1st-5th, 6th-10th
6	1st-3rd, 4th-6th

Effect on deflection: In Figs. 3 to 5 the effect of variation in column cross-sectional area on deflection ratio ($\delta_{2\text{-}D}/\ \delta_{free}$) of 2-D frames have been shown. It is clear that the buildings having variable column size along height undergoes higher drift than their constant column size counterpart. Similar studies were also conducted by analysing similar buildings using 3-D analysis methods (Noor, 1995); the ensuing results showed similar trend. In Table 8, the increase in drift at the top due to the use of variable column cross-section along height in comparison to buildings with no change in column cross-section has been given.

Table 8. Increase in drift at the top due to the use of variable column cross-section along height in comparison to constant column cross-section

Storey	variable column size / constant column size	
	Square bay	Rectangular bay
15	1.088	1.061
10	1.056	1.042
6	1.049	1.037

In Figs. 6 to 8, the ratio of displacement ($\delta_{2\text{-}D}/\ \delta_{3\text{-}D}$) at different heights as obtained from 3-D and 2-D analyses have been plotted against height ratio (i.e., storey height/building height) for 15-, 10- and 6-storeyed buildings, respectively. It is evident from these figures that the displacements obtained from either 2-D or 3-D analyses are not very much dependent on variation of column size along height and grid pattern as displacement in all the cases seem to follow a certain

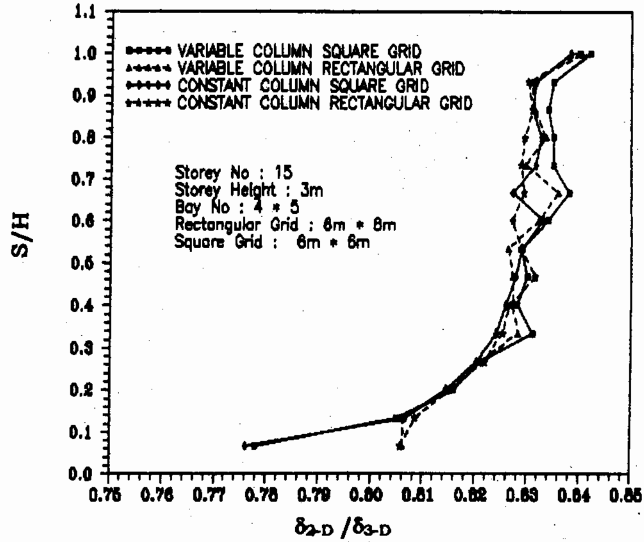

Fig 6. *Displacement ratio ($\delta_{2-D}/\delta_{3-D}$) versus height ratio (S/H) for 15-storeyed buildings*

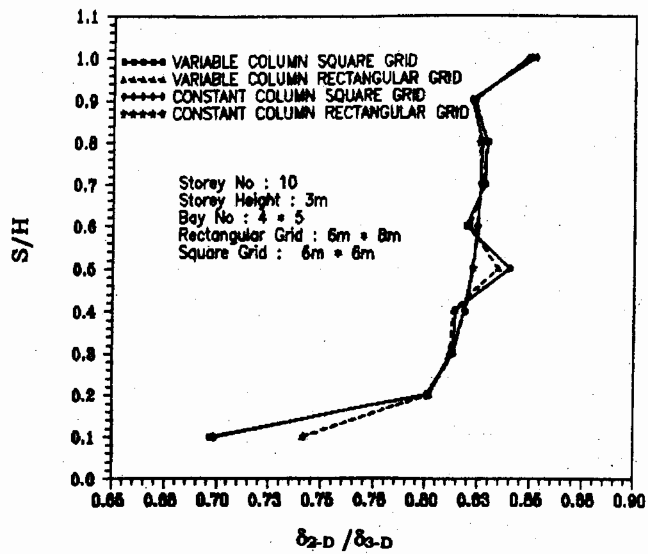

Fig 7. *Displacement ratio ($\delta_{2-D}/\delta_{3-D}$) versus height ratio (S/H) for 10-storeyed buildings*

pattern. The displacement obtained from 3-D analyses ($\delta_{3\text{-}D}$) are, of course, smaller than those obtained from 2-D analyses.

Effect on shear and moment: The effect of variability in column size along height on shear has been shown in Figs. 9 to 11 by undertaking 2-D analysis. It can be observed that the top storey is affected by a very high amount of shear. Additional studies available elsewhere in Noor (1995) confirms that similar trend was also found when the buildings reported in this study were analysed in the 3-D continuum. The figures show that a sudden increase in the amount of shear takes place at locations where column changes its cross section. This phenomenon could not be noticed in the structures that had constant column size along the building height.

In an effort to understand the role of analysis techniques, grid pattern as well variation of column size along building height, the ratio of shear as obtained from 2-D and 3-D analysis ($V_{2\text{-}D}/V_{3\text{-}D}$) has been plotted against height ratio (S/H) in Figs. 12 to 14 for buildings having 15-, 10- and 6-storeyed each. It is interesting to note that the ratio $V_{2\text{-}D}/V_{3\text{-}D}$ oscillates about 1.0 within a very narrow band. This points to fact that for the structures studied here either 2-D or 3-D analysis would have yielded results, which could lead to satisfactory design. Exercises similar to shear were also conducted for moment. The ratio of moment as obtained from 2-D and 3-D analysis ($M_{2\text{-}D}/M_{3\text{-}D}$) has been plotted against height ratio (S/H) in Fig. 15 for buildings having 15-storeyed buildings.

CONCLUSIONS

The following are the conclusions that can be derived, albeit tentatively, from the limited parametric study that has been reported in this paper.

The Khan and Sbarounis (1964) method of 2-D analysis of buildings has been found to give very much high values of building drift in comparison to 2-D finite element analysis. This method, thus, may only be used in preliminary analysis of structures.

Buildings having moderate height when analysed by 2-D analysis methods and subjected to wind pressure always show slightly higher drift than their 3-D counterparts.

The magnitude of moment and shear at different heights for various buildings has been found to be almost independent of the analysis techniques adopted, as they seem to vary in a very narrow band.

The acceptable performance of 2-D analysis method instead of 3-D analysis method has been found to be unconstrained of variation of column cross-section along height and grid size.

The magnitude of moment and shear changes suddenly if cross-sectional area of column changes along height.

In all the buildings studied, at the top free end of the frame, higher

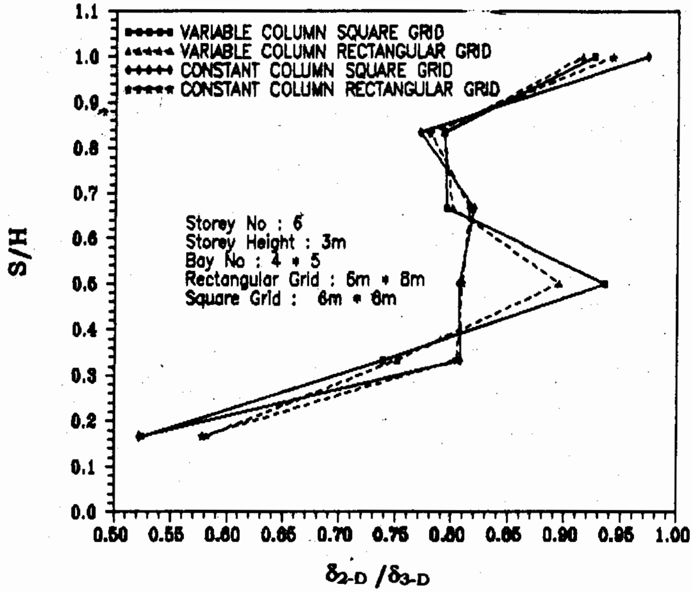

Fig 8. *Displacement ratio ($\delta_{2\text{-}D}$/ $\delta_{3\text{-}D}$) versus height ratio (S/H) for 6-storeyed buildings*

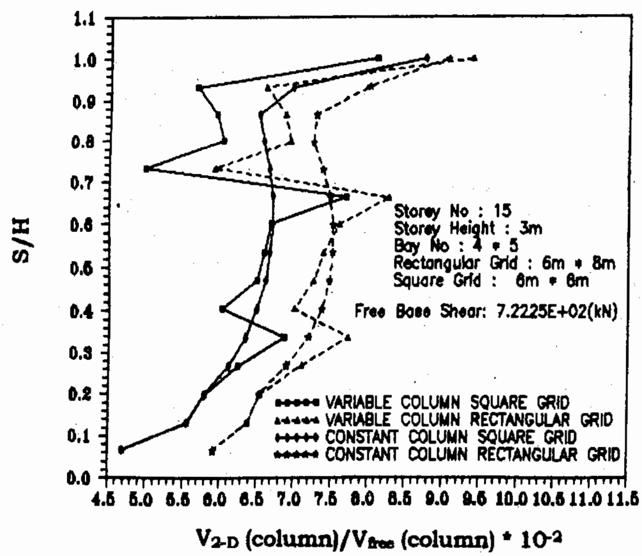

Fig 9. *Shear ratio ($V_{2\text{-}D}$/V_{free}) versus height ratio (S/H) for different column size along height and grid size for 15-storeyed buildings*

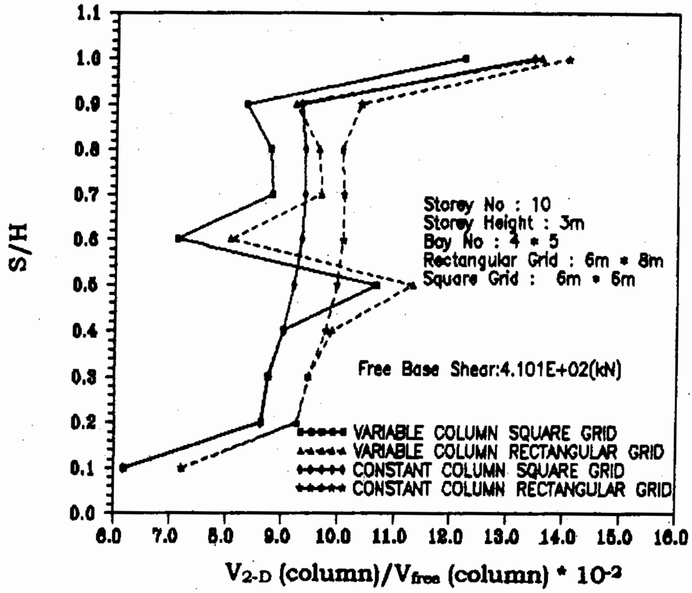

Fig 10. *Shear ratio ($V_{2\text{-}D}/V_{free}$) versus height ratio (S/H) for different column size along height and grid size for 10-storeyed buildings*

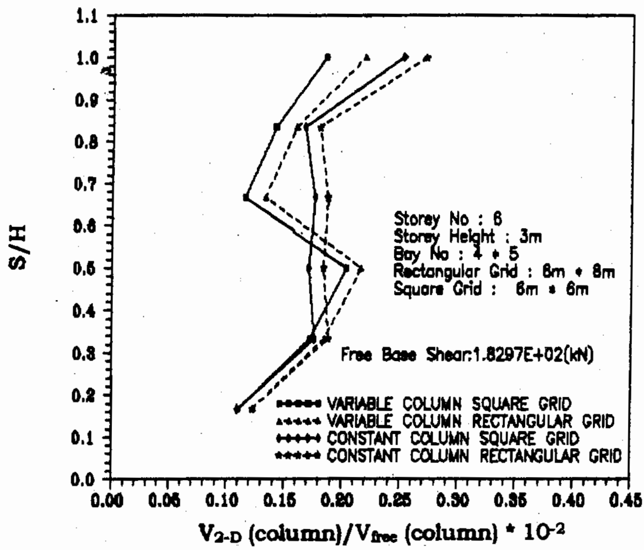

Fig 11. *Shear ratio ($V_{2\text{-}D}/V_{free}$) versus height ratio (S/H) for different column size along height and grid size for 6-storeyed buildings*

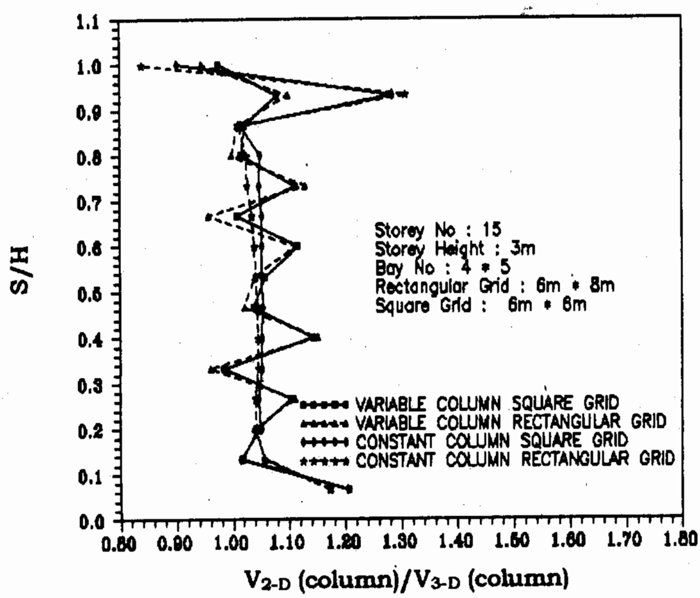

Fig 12. Shear ratio ($V_{2\text{-}D}$/ $V_{3\text{-}D}$) versus height ratio (S/H) for different column size along height and grid size for 15-storeyed buildings

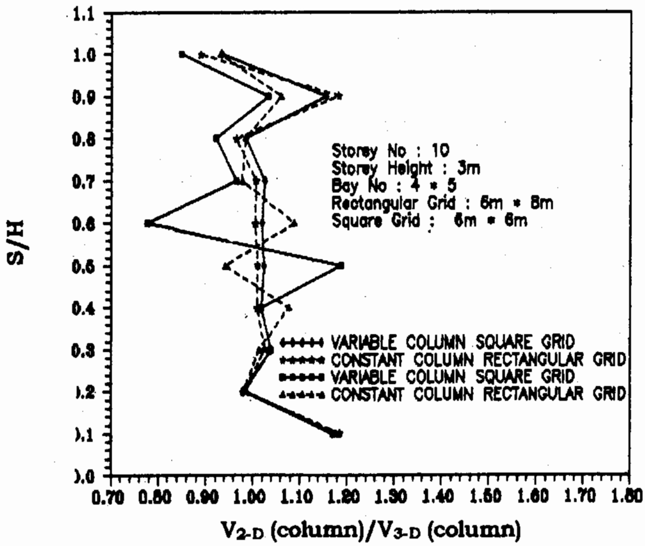

Fig 13. Shear ratio ($V_{2\text{-}D}$/ $V_{3\text{-}D}$) versus height ratio (S/H) for different column size along height and grid size for 10-storeyed buildings

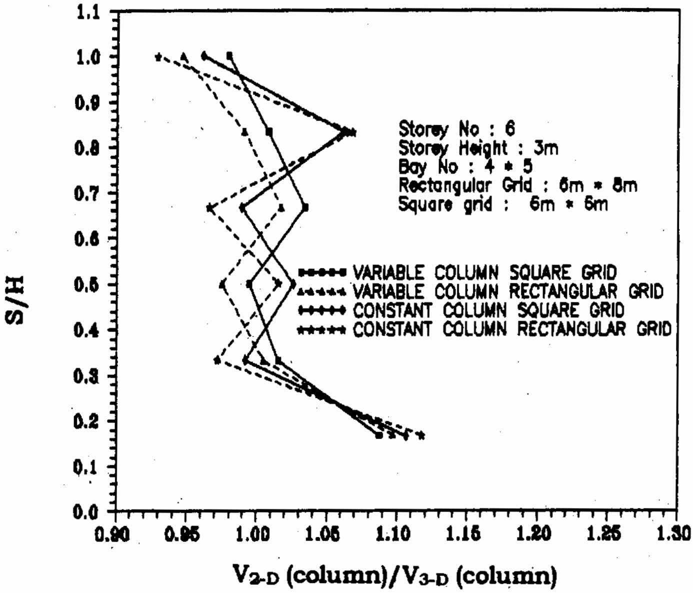

Fig 14. *Shear ratio ($V_{2\text{-}D}/V_{3\text{-}D}$) versus height ratio (S/H) for different column size along height and grid size for 6-storeyed buildings*

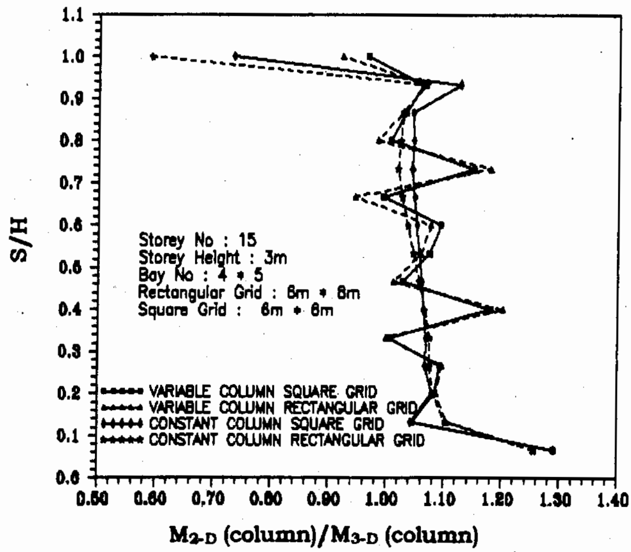

Fig 15. *Moment ratio ($M_{2\text{-}D}/M_{3\text{-}D}$) versus height ratio (S/H) for different column size along height and grid size for 15-storeyed buildings*

amount of shear and moment values have been observed in comparison to similar ends located in other stories of the same column. If construction phasing is adopted, this should be taken into cognisance.

Adoption of constant column cross-section throughout its whole length may lead to a decrease in the drift of the buildings.

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NOTATIONS

2-D	two-dimensional analysis
3-D	three-dimensional analysis
$\delta_{2\text{-}D}$	deflection produced by two-dimensional analysis
$\delta_{3\text{-}D}$	deflection produced by three-dimensional analysis
δ_{free}	free top displacement
H	building height
KH-SB	Khan and Sbarounis
$M_{2\text{-}D}$	moment produced by two-dimensional analysis
$M_{3\text{-}D}$	moment produced by three-dimensional analysis
M_{free}	free base moment
MFEAP	MICROFEAP
S	storey height
$V_{2\text{-}D}$	shear produced by two-dimensional analysis
$V_{3\text{-}D}$	shear produced by three-dimensional analysis
V_{free}	free base shear