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DYNAMIC ANALYSIS OF R. C. BUILDINGS WITH TRANSFER FLOORS MODELLED AS THICK SHELLS, RIGID DIAPHRAGM, AND RECTANGULAR FINITE SOLID ELEMENTS

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Abstract

Transfer floors in multi-storey buildings are mainly used to have widely spaced columns below transfer floors to accommodate business areas or other similar purposes, while upper floors, with more suitable spacing of columns or walls, are used for hotels, offices or residence apartments. Transfer floors may take several structural forms most common of which are thick slabs and deep girders. The design of transfer structures is currently outside the codes guidance and require special treatment and engineering judgment. Planted columns or walls on thick plates or deep girders are the usual method of construction of this type of buildings. Transfer slabs were often modelled by designers as rigid diaphragms. Similarly, transfer deep girders were often considered rigid, and as such planted columns and walls on the transfer floors are considered fixed at the bottom. Previous research has recommended that transfer slabs or girders be considered as flexible shells or beam elements not as rigid diaphragms in order to include the effect of the flexibility of transfer floor and capture the true structural behaviour of the transfer floor building. The purpose of this paper is to investigate the behaviour of transfer floor buildings under seismic excitation by modelling transfer slabs as thick shells, rectangular 8-node finite solid elements and as rigid diaphragms. The considered 3-D reinforced concrete building was analysed for gravity and seismic loading using response spectrum and linear time history analysis utilising SAP2000 software. Results of the investigation were summarized, and conclusions were drawn out. It was found that modelling transfer floors by thick shell or rigid diaphragm elements show similar structural results, which are different from 8-node rectangular finite solid elements. Such differences are manifested in longer periods of vibration ((more flexible behaviour), and less vertical displacements of the transfer slab. In all cases, designers have to check punching shear stress in the transfer slab under planted columns.

Keywords: Base shear, Diaphragm, Dynamic analysis, Irregularity, Mode shape, Rigid/flexible base, Storey drift, Transfer floor buildings.

1. Introduction

Transfer structures, such as thick slabs and deep girders, can be defined as structures that transmit heavy loads from columns or walls acting on its top and redistribute them to widely spaced columns or walls below [1, 2]. The architectural purpose of constructing buildings with transfer structures is to have wide spaces below to accommodate business plazas. Therefore, transfer structures are aften located at the lower parts of buildings. However, there are actual examples where transfer floors were constructed at two or more different height locations in buildings [3]. Buildings with transfer slabs or girders are considered irregular buildings when seismic analysis is considered. This irregularity may produce a soft or weak story mechanism which can be detrimental to structures [4, 5].

Both theoretical and experimental studies of buildings having transfer floors have been carried out. Shaking table experiments of scaled models of such buildings were carried out [3, 6]. A review of previous research on buildings with transfer floors was summarized by Su [2] and Abdlebasset et al. [7]. The following points of interest were the main points discussed in previous studies.

- The presence of a highly stiff transfer floor may result in the production of a soft storey below which may result in excessive lateral deformation. Some researchers have studied the effects of changes in lateral stiffness of substructures above and below a transfer structure on the seismic response of buildings [2]. Shake-table tests conducted by Li et al. on buildings with transfer plates highlighted deficiencies in the code-approach of using the lateral stiffness ratio for detecting soft storey collapse mechanism [6]. The most critical soft storey mechanism is expected when the transfer floor is located at a level close to 40% of the height of the building [8].
- Another point discussed by researchers is the transfer plate flexibility (rigidity). It was shown that transfer plate flexibility affects both the local and the global response behaviour of the building [2, 9, 10]. It is found that transfer girders system is more flexible than transfer slab system [11]. A. Gomez-Bernal et al concluded in their work that local flexural rotations of transfer structures should not be ignored [2, 12]. Many researchers [10] and designers ignore the deformation of the transfer floor and adopt rigid plate and rigid diaphragm in their work. Researchers recommended that transfer structures should be modelled by flexible beam, plate, or even solid elements [2, 8].
- A third point discussed is the effect of vertical positioning of transfer floor on the seismic response of the building. It is found that the degree of abrupt change in the inter-storey drifts increased with increasing height of the transfer structure [4, 8, 11]. It is shown that a transfer floor at 10% of the building height from bottom produces maximum base shear [4].
- Linear and nonlinear analysis were also investigated in previous work of transfer floor buildings. A transfer floor consisting of a thick slab at 20% of the 50-floor building height was investigated using linear and nonlinear analysis. It is found that story shear, story moment, lateral displacement and base-shear were all less in nonlinear analysis than in linear analysis [1].
- Another point discussed by researchers is the techniques used to construct transfer-floor buildings, and the effects of time dependent material properties on the performance and design of such buildings [13, 14].

2. Buildings Description and Method of Analysis

The purpose of this paper is to investigate the seismic behaviour of transfer-buildings during earthquake excitation with transfer-slab modelled in 3 different methods, namely, as flexible thick shells, as rectangular 8-node finite element solids, and as rigid diaphragms. In a rigid diaphragm slab, in-plane deformation is zero (x and y strains=0), but out-of-plane deformation of the slab is not affected. Thick shell modelling of a slab has no effect on membrane (in-plane) behaviour but affects plate bending behaviour due to the account of shear deformation. Shear deformation in thick slabs may be significant when ratio between shell thickness and the span of plate-bending is greater than 1/5 to 1/10 [14]. In the considered building model, this ratio is 800/5000 =0.16, which is within this range. A slab modelled as 8-node rectangular solid elements will have a translational degree of freedom at each node, but all rotational degrees of freedom are not activated. However, in the considered mode, the rotational degrees of freedom at each node are activated because some of these nodes are connected to frame elements in the model such as columns in the ground and first floor [14].To achieve the purpose of this paper, a three-dimensional r. c. building with transfer slab is considered. Table 1 gives a general description of the building and loadings applied. The irregularity of this building is mainly in the presence of the transfer slab. The position of the core walls is slightly off-centre of the building and as such produces little horizontal eccentricity. Cross sections of r. c. slabs, beams, columns, and core walls were all analysed and designed using SAP2000 software. All members passed ACI 318-14 requirements [15] for loading combinations 1, 2, and 3 which are described in Table 1.

Table 1. Properties of the building and applied loads.

Building property	Description
Number of floors	8
First floor height	8 m
Other floors height	3.5 m
No. of bays in the x and y directions	8 bays
Length of bays in the x and y directions	5 m and 4 m respectively
Concrete strength of all elements	34.5 MPa (5000 psi)
Transfer slab thickness	0.8 m as thick shell (model 1), rigid diaphragm (model 2), or solid elements (model 3).
All other floor slabs	0.2 m thick modelled as thin shells
Ground floor columns	1.2×1.2 m except one central column (No.13) 1.4×1.4 m
Ground beams	0.8 m deep and 0.4 m wide except two central beams connected directly to the core walls (No. 36 and 56)
All other floors beams	0.5 m deep ×0.3 m wide
All other floors columns	0.6×0.6 m
Ground floor core wall	0.3 m thick modelled as thin shell
Core wall	0.2 m thick modelled as thin shell
Dead and live load on the transfer slab	5.0 and 3.0 kN/m^2 respectively
Dead and live load on all other floor slabs	3.0 and 3.0 kN/m^2 respectively.
Response spectrum used	UBC 97: Type B, Distance =15 km, Soil Sc, Zone factor= 0.4, Direction: U1, Importance: I=1, Overstrength factor =8.5, QCS, SRSS,
Time History	El Centro record of N-S acceleration using modal analysis adopting eigenvectors.
Load Combinations:	Comb1: linear add, both dead and live 1.0 Comb2: linear add, all dead, live and response spectrum 1.0. Comb3: linear add, both dead and time history 1.0

Three models of the transfer slab are considered. These are flexible thick shell, rigid diaphragm, and 3-dimensional, 8-node solid finite elements. The slab of solid elements is done by extruding the thick shell slab according to the procedures described in SAP 2000 software. The solids transfer slab is modelled by two or four layers of solid elements. Each solid element is 2.5×2.0×0.4 m or 0.833x1.0x0.2 m in the x, y, and z directions as will be explained later. All building models are identical in geometry, applied loads, and seismic acceleration. As mentioned in Table 1, two ground beams and one ground column are made larger than other ground beams and columns because the reinforced concrete design required enlarging the sections to comply with the ACI code requirements [15]. Figures 1 and 2 shows elevation of the X-Z and Y-Z planes of the transfer slab building with some columns and joints' numbers.

Analysis of the models is carried out for the loads and seismic excitations using SAP200 software. Response spectrum of the UBC97 and the N-S record of El Centro acceleration are used for the seismic analysis.

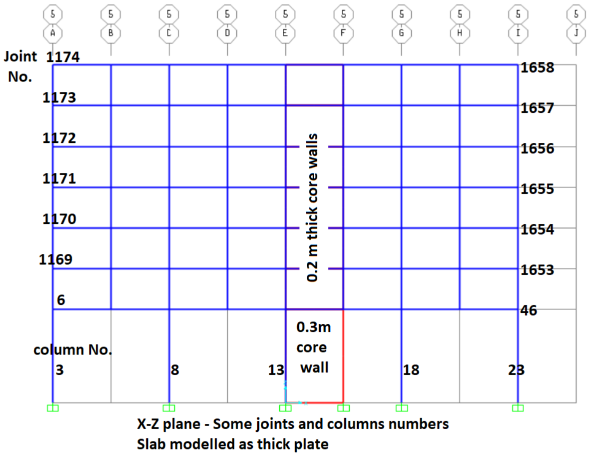

Fig. 1. X-Z plane of the transfer slab building showing some columns and joints' numbers.

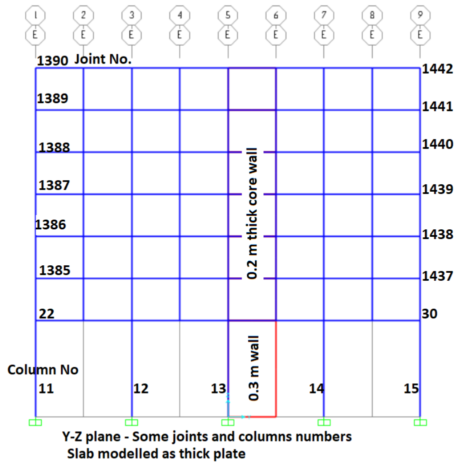

Fig. 2. Y-Z plane of the transfer slab building showing some columns and joints' numbers.

3. Analysis Results

Analysis of the transfer slab building with its three models is analysed under the actions of dead and live loads, response spectrum, and El Centro acceleration record. Load combinations 1, 2, and 3 are described in Table 1. Analysis results are discussed in the following paragraphs.

3.1. Analysis under load combination 2 (Dead+Live+Response spectrum)

Analysis of the transfer-slab building modelled as thick shell elements under load combination 2 (dead+live+UBC97 response spectrum) reveals the deformed shape shown in Fig. 3. Figure 4 displays shear forces in some selected columns in a section passing through the core wall as shown. Table 2 shows the lateral displacements and story drifts of the right side joints in Fig. 3.

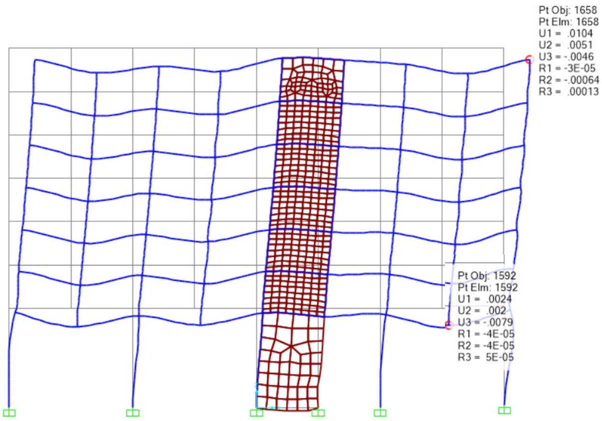

Fig. 3. Deformed shape of the transfer-slab building at a section through the core wall with transfer slab modelled as thick shell and as rigid diaphragm.

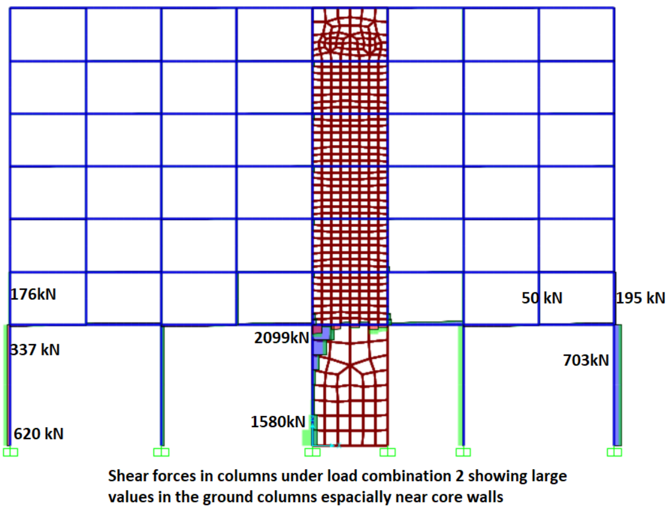

Fig. 4. Shear forces in some columns of transfer slab building at a section through the core wall with transfer slab modelled as thick shell and as rigid diaphragm.

Table 2. Horizontal displacements and storey drifts of the right-hand side of Fig. 3 under load combination 2.

Joint	Lateral displacement mm	Storey Drift %
1658	10.4	0.026
1657	9.5	0.037
1656	8.2	0.04
1655	6.8	0.43
1654	5.3	0.046
1653	3.7	0.037
46	2.4	0.03

Analysis of the transfer slab building with transfer slab modelled as a rigid diaphragm reveals exactly the same results as for the thick shell slab. It can be noted from Table 2 that the average story drift of the upper floors is around 0.038% whereas the ground floor story drift is 0.03%. UBC97 and ASCE7-10 specify a maximum story drift ratio between two successive stories of 1.3 so that the vertical irregularity can be ignored. All storey drift ratios obtained from Table 2 are within UBC97 limitation except for the upper storey [7]. It is noted also that the deformation takes the shape of a shear deformation due to the presence of the stiff core walls and ground floor columns. The ground floor core walls are 0.3 m thick which are thicker than the 0.2 m upper walls as necessitated by the ACI design requirements. The analysis results revealed that most of the shear forces are taken by the ground floor columns and core walls. Therefore, based on the storey drift results in Table 2, a 'soft storey' mechanism is not likely to occur at the ground floor due to the stiff ground columns and core walls. Based on the low values of the ground floor drift values, the writer suggests that a practical way of avoiding a soft story mechanism in transfer floor buildings, is to have a central thick core walls and very stiff ground columns. Some researchers [2] have indicated that not every transfer structure automatically leads to a soft storey, which is in agreement with the writer's suggestion. The ground floor of the analysed building as shown Table 2 does not attract a high lateral drift as is expected [2].

Analysis of the transfer slab building with transfer slab modelled as 8-node solid rectangular finite elements under load combination 2 (dead+live+UBC97 response spectrum) shows the deformed shape and columns shear forces shown in Figs. 5 and 6.

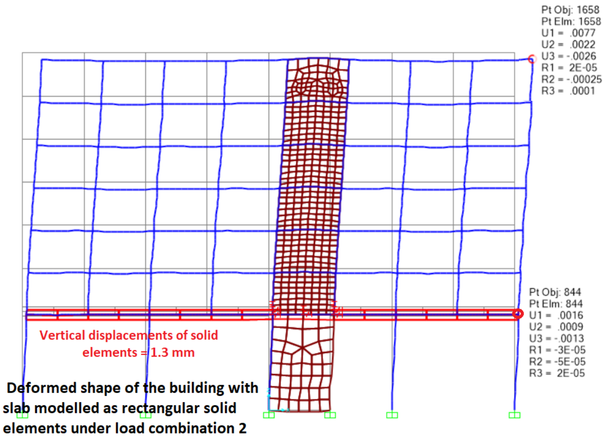

Fig. 5. Deformed shape of the transfer slab building with slab modelled as 8-node finite elements at a section through the core wall.

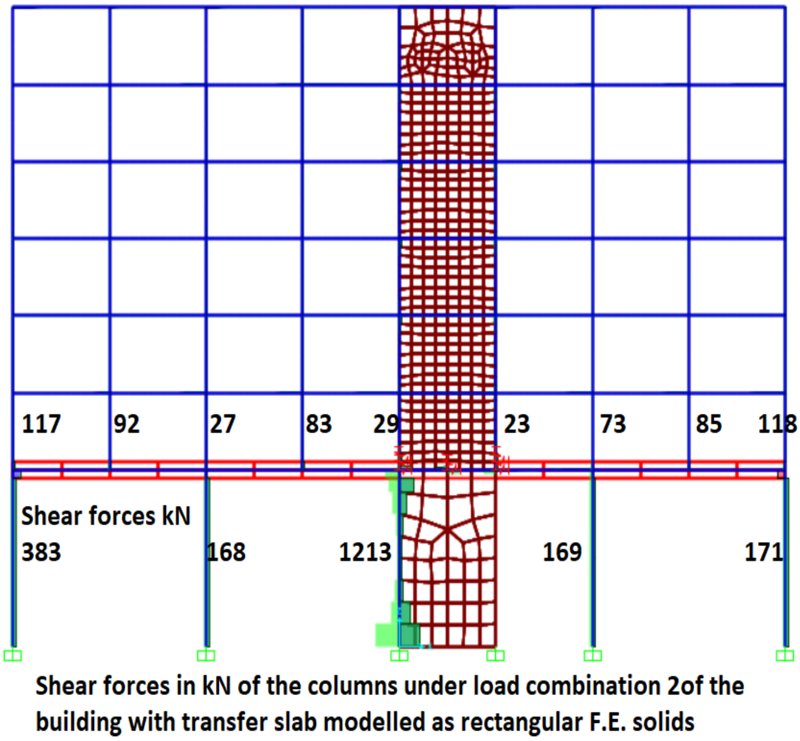

Fig. 6. Shear forces in the columns transfer slab building with slab modelled as 8-node finite solid elements at a section through the core wall.

The deformation displayed in Fig. 5 is again a shear mode of deformation as for the thick-shell and rigid diaphragm models. Table 3 shows the horizontal displacements and storey drifts of the right side joins of Fig. 5. The results of the storey drifts and columns and core wall shear forces are not the same as for the tick shell and rigid diaphragm models. The vertical displacements of the transfer slab modelled as thick shell and rigid diaphragm are more than their counterparts of the slab modelled as solid finite elements. For example, joint 1592 in the thick shell model is displaced 7.9 mm down compared to 1.3 mm in the solid elements model.

However, both deformations are within accepted vertical deflections of 1/250. That is 7.9/8000 = 9.9x10-4, which is less than 1/250. This indicates that the transfer slab modelled as thick shell elements or rigid diaphragm exhibit more flexibility than the transfer slab modelled as rectangular finite solid elements. The extra flexibility of the thick shell and rigid diaphragm modelling may be responsible for the extra storey drifts.

It is concluded that the thick shell and rigid diaphragm models produce the same structure output, and that is different from the output of the 8-node solid elements. However, it is not possible or appropriate with the present techniques to conclude which modelling is more accurate or more representative of the real structure behaviour, although some researchers [8] commented that a slab modelled as solid finite elements is more representative of the real behaviour of the structure. Experimental work may help decide on that.

Table 3. Horizontal displacements and storey drifts of the right-hand side of Fig. 5 under load combination 2.

Joint	Lateral displacement mm	Storey Drift %
1658	7.7	0.023
1657	6.9	0.031
1656	5.8	0.034
1655	4.6	0.034
1654	3.4	0.031
1653	2.3	0.031
46	2.0	0.02

3.2. Analysis under load combination 3 (Dead + Live + Time History)

Analysis of the transfer slab building under load combination 3 (dead + live +Time history) is carried out for the three models. Figs. 7-9 show the base shear variation during 10 seconds of the application of the El Centro record of acceleration for the transfer slab building with the slab modelled as rectangular finite solid elements, thick shell elements, and rigid diaphragm respectively.

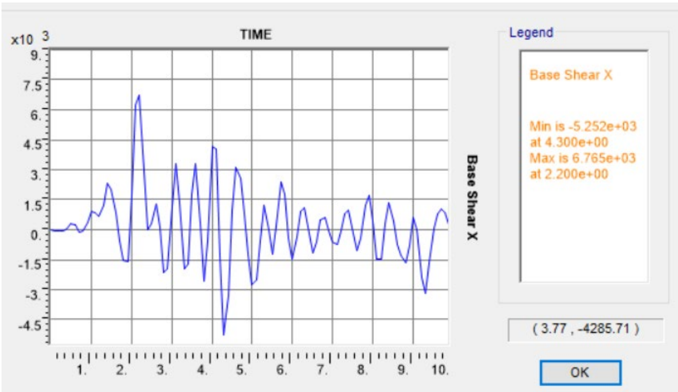

Fig. 7. Base shear (kN) in the *x* direction of the building with the transfer slab modelled as rectangular finite solid elements.

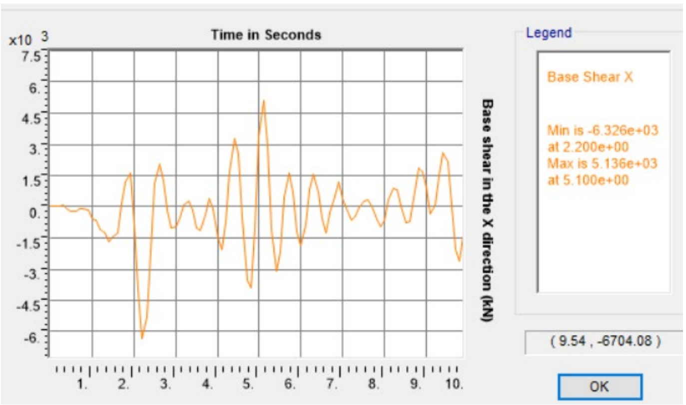

Fig. 8. Base shear (kN) in the *x* direction of the building with the transfer slab modelled as thick shell elements.

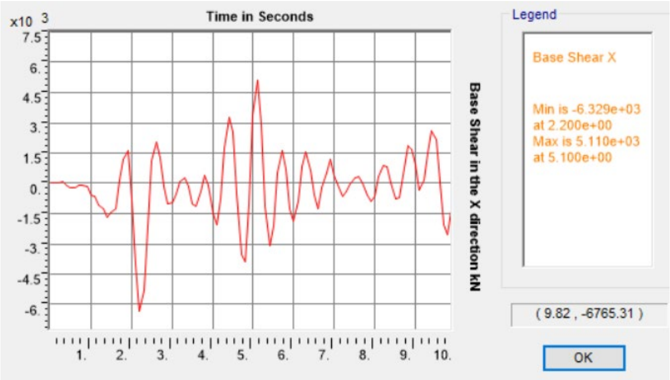

Fig. 9. Base shear (kN) in the *x* direction of the building with the transfer slab modelled as rigid diaphragm.

Figs. 10, 11, and 12 show time history of the horizontal displacement of the top right joint (1658) in the finite elements solids, thick shell, and rigid diaphragm models respectively.

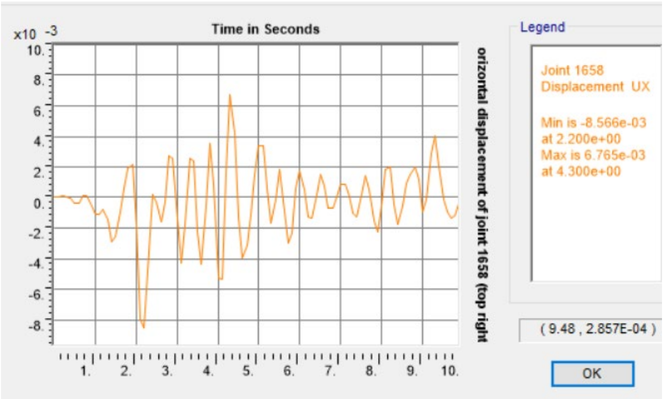

Fig. 10. Horizontal displacement of the top right joint (1658) under the action of El Centro record of acceleration in the finite element solid model of the transfer slab

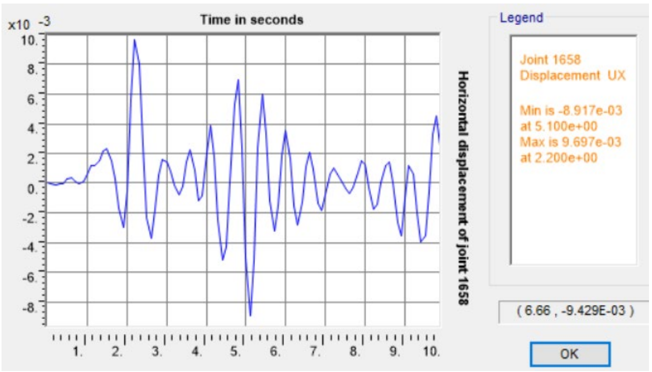

Fig. 11. Horizontal displacement of the top right joint (1658) under the action of El Centro record of acceleration in the thick shell model of the transfer slab

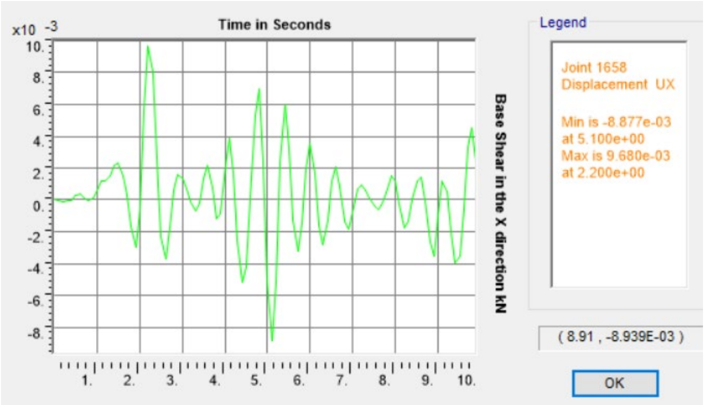

Fig. 12. Horizontal displacement of the top right joint (1658) under the action of El Centro record of acceleration in the rigid diaphragm model of the transfer slab.

Examining these 6 figures, the following points can be noted:

- Base shear plots of the thick shell and rigid diaphragm are very similar except for some variation in the peak values. The peaks occur at the same time points.
- Similarly, horizontal displacements of joint 1658 plots of the thick shell and rigid diaphragm models are very similar except for some variation in the peak values. The peaks occur at the same time points.
- Base shear and horizontal displacement plots of the finite solid element model are inverted images of their counterparts of the other two models with little variation in the values and one peak point. In fact, the inverted shape of these plots has no significance because they only imply the positive or negative direction of the horizontal *x* displacement or the base shear.
- Based on this discussion, it is concluded that all three modelling techniques of transfer slab yield comparative structural output without significant variations that may affect the ultimate design requirement.

3.3. Shear stress in the thick shell slab

An important check a designer has to take care of is the shear stress in the transfer slab directly below the planted columns. Table 4 shows the shear stresses in some joints of shell elements 53 and 54 which are in the vicinity of column number 1818 which is resting directly on the transfer slab (see Fig. 13). Structural analysis shows that all shear stresses in the thick shell elements below planted columns are found within the allowable shear stresses of concrete of f'c = 34.5 MPa (5000 psi).

Table 4. Shear stresses in the thick shell slab below column no. 1818 resting on transfer slab.

Combination	Shell element	Joints	Shear stress kN/m^2	Shell element	Joints	Shear stress kN/m^2
Comb 2	53	1525	1035.71	54	36	433.29
Comb 2	53	1585	150.59	54	1592	222.08
Comb 2	53	1592	-139.21	54	1599	-83.05
Comb 3	53	1525	557.95	54	36	315.27
Comb 3	53	1585	100.26	54	1592	143.65
Comb 3	53	1592	-28.81	54	1599	105.31

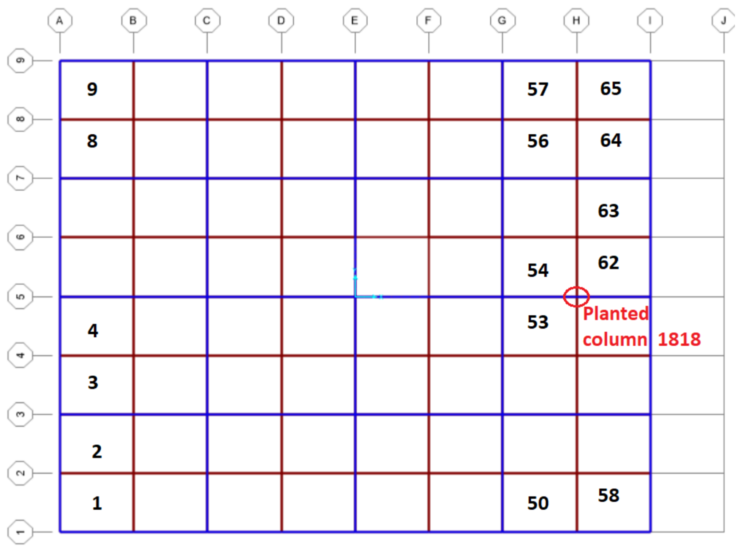

Fig. 13. X-Y plane at transfer slab level. Elements numbering showing the location of planted column 1818 and the shell elements around it.

3.4. Modal analysis-periods of vibration

Table 5 shows the values of periods of vibration of the building models. Periods of vibration of the thick-shell and rigid diaphragm model are considered the same, and they are longer than those of the solid elements transfer slab model. This fact confirms the previous statement concluded that the thick-shell and rigid diaphragm models are more flexible than the solid elements model.

Table 5. Periods of vibration in seconds of the three models.

Slab model / Mode No.	Building with thick shell transfer slab	Building with Rigid diaphragm transfer slab	Building with solid F.E. solid transfer slab
Mode 1	0.625642	0.625107	0.584888
Mode 2	0.613225	0.612725	0.502600
Mode 3	0.599612	0.598737	0.497668
Mode 4	0.234784	0.234253	0.216593
Mode 5	0.211696	0.211195	0.198379
Mode 6	0.211126	0.210292	0.194886
Mode 7	0.147723	0.147522	0.143252
Mode 8	0.114623	0.113726	0.111244
Mode 9	0.112447	0.111469	0.108302
Mode 10	0.107234	0.107224	0.09105
Mode 11	0.107147	0.107138	0.072559
Mode 12	0.102684	0.102665	0.070611

3.5. Transfer slab divided into smaller rectangular finite elements

In order to investigate the effect of reducing the size of the rectangular 8-node finite solid elements of the analysis results, the solid elements are further divided such that the slab will consist of 4 layers and each solid element will be 0.833x1.0x0.2 m in the x, y, and z directions respectively. Analysis is carried out for the same loading and seismic excitation. It is found that dividing the solid elements into smaller sizes produces only very small variations in the periods of vibration, in the story drifts, and shear forces in the columns and core walls. Hence, it is concluded that a finer mesh of solid finite elements does not produce significant variations in the structure response.

4. Conclusions

The following conclusions can be drawn from the analysis and design of the transfer building under vertical and seismic loading described.

- A transfer floor in the form of a thick slab with planted columns above and widely spaced columns below does not necessarily lead to a soft storey mechanism under seismic excitation if the lateral storey drift at the transfer level is low enough.
- Continuous core walls through the height of the transfer building together with well-designed ground columns with symmetrical or nearly symmetrical positioning is considered a practical design technique to alleviate the detrimental effects of interrupting the vertical load path of the building and prevent the occurrence of a soft storey mechanism.
- Three modelling techniques are used for a transfer slab in this paper. These are thick shell elements, rigid diaphragm, and finite solid elements.
- A transfer building with thick shell and rigid diaphragm models of the transfer slab shows similar structural analysis results such as periods of vibration, joint displacements, and shear and moment forces values under vertical and seismic loading.
- A building with transfer slab modelled by 8-node rectangular finite solid elements shows different structural analysis results than the other two models. That includes longer periods of vibration ((more flexible behaviour), and less vertical displacements of the transfer slab.
- Punching shear stress in the transfer slab under planted columns has to be carefully checked by designers to keep them below allowable shear stress of concrete.
- Experimental investigation is recommended for transfer building models to compare with theoretical results to decide on the most suitable modelling technique for transfer slab.

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