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SEISMIC RESPONSE OF RC FRAME-CORE WALL STRUCTURE WITH HIGH THICK-SLAB TRANSFER STOREYS

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ABSTRACT

The elastic earthquake response of reinforced concrete (RC) frame-core wall structures with high thick-slab transfer storeys was studied. The response spectrum analysis method of mode decomposition was used to investigate the influence of the earthquake intensity, location of the thick-slab transfer storeys, transfer slab thickness and lower storey stiffness on the structural response of these parameters as the structural vibration period, inter-storey displacement and storey shear force. The results demonstrated that the inter-storey displacement and the storey shear force increase with an increase in earthquake intensity. The translational period decreases and the torsion period increases for higher transfer storeys. The structural dominant displacement is increasingly changed from the displacement in upper storeys to the displacement in lower storeys, and a share of the storey shear force increases in frame-supporting columns adjacent to transfer storeys. An overly large transfer slab thickness is disadvantageous to lower storeys because it can amplify the torsion effects of global structure. The structural period ratio increases with an increase in the thickness of core walls, while the structural period ratio decreases with an increase in the cross-section of frame-supporting columns.

KEYWORDS: Frame-Core Wall Structure, High Thick-Slab Transfer Storeys, Seismic Response, Storey Displacement, Storey Shear Force, Period Ratio

INTRODUCTION

With the rapid development of tall buildings, architectural functions are becoming integrative. To fulfil the need for large amounts of space at lower floors and less space on higher floors, tall buildings with transfer storeys have been widely adopted (Fu 1999; Wang and Wei 2002; Huang et al. 2004; Li et al. 2006; Lu et al. 2008) in China, where the transfer slab structure is the best structural scheme to meet the design requirements. In recent years, thick-slab transfer storeys have been designed for higher positions in structures to the point where the position of the transfer storeys exceeded China's code limit (JGJ3-2010). For instance, frame-supporting shear wall structures with thick-slab transfer storeys located at the 4th ~ 8th storey have had some engineering application where the building was located in a seismic area with a design acceleration of 0.1 g (Fu et al. 2010; Rong and Wang 2004). When considering the economic benefits, buildings with transfer storeys located below the third storey are often not acceptable by building owners. Tall buildings with transfer slabs have some unique advantages (Peng and Li 2003; Fu et al. 2010), for instance, the arrangement of the vertical elements above a transfer storey can be very flexible and will not be limited by the axial grids. Because the lateral stiffness, carrying capacity, and mass of tall buildings with transfer storeys are usually not continuous along their height, the dynamic response of these structures that are subjected to strong ground motion differs from those of regular structures (Aydin 2007; Lee and Ko 2007; Sarkar et al. 2010; Rajeev and Tesfamariam 2012). Thus, the features of structures with high thick-slab transfer storeys differ from those of structures without these transfer storeys. Wang and Wei (2002) investigated the seismic behaviour of a high-rise building with a higher-level transfer floor. Their research results indicated that the modal seismic action at the transfer storey increases evidently with an increase in the height of the transfer floor because of the greater mass of the transfer storey, but the natural period and vibration mode of the overall structure is changed slightly, and the storey seismic shear and moment below the transfer storey are increased. It is noted that the mode number needs to be added when analysing the seismic action and internal forces of the structural components. Su et al. (2002) used various methodologies including response spectrum analysis (RSA), manual calculation, pushover analysis (POA) and equivalent static load analysis (ESA) to conduct the seismic assessment for the structural performance of structures with a transfer plate under potential seismic actions. The assessment provides a general indication of the seismic vulnerability of the structures. Peng and Li (2003) proposed a new method to analyze the global performance of high-rise building structures with a thick-slab transfer storey. Rong and Wang (2004) analysed the effect on the dynamic properties and seismic responses of the structures with a higher transfer slab storey. Their findings revealed that the abruption of storey drift and seismic shear would be avoided when both ratios of lateral stiffness and storey drift are limited because of the influence of the transfer slab with a large mass and stiffness. Li et al. (2006) studied a high-rise building structure with a 2.7-m-thick transfer plate. A micro-concrete model representing the high-rise building was constructed in 1:20 scale. Shaking table tests were conducted, and the model was subjected to earthquake actions representing minor, moderate, major, and super-major earthquakes for a region of moderate seismic intensity. The majority of the damage and failure occurred at the storey above the transfer plate. To minimise the damage, it is desirable to strengthen the walls between the 4th and 15th floors and to reduce any change in stiffness within the transfer plate zone. Lu et al. (2008) studied a super tall building with a high-level transfer storey. A scaled model (1/30) was made and tested on the shaking table to study its dynamic characteristics and seismic responses and to evaluate its capacity to withstand earthquakes. The test results show that the structural system is an ideal solution for the building to withstand earthquakes. The inter-storey drifts and the overall torsions meet the requirements regulated by China’s Code. Fu et al. (2010) introduced the ductile slab-column connection measures such as haunched slabs, presented some test results and indicated that the adequately reinforced flat slab-column connection, which is essentially subjected to punching shear, may have good ductility under strong earthquake action. Because the theoretical research on high-rise buildings with high thick-slab transfer storeys is not yet comprehensive, it is not recommended to apply this research in high seismic areas in China, even though a practical engineering analysis has been performed. Therefore, a systematic investigation of the seismic response of this structural type is needed.

OBJECTIVE AND METHOD

In this paper, the main objectives are to (1) investigate the dynamic behaviour of vertical irregular structures with high thick-slab transfer storeys; (2) analyze the influence of 4 parameters (thickness of transfer slab, location of the transfer storey, earthquake intensity, and lower storey stiffness) on the structural seismic behaviour; and (3) propose some useful suggestions for structural seismic design according to research results and other related research findings. For these objectives, a simplified practical RC frame-core wall structure is selected as the research object. The elastic seismic response and dynamic properties are investigated through a response spectrum analysis method with the ETABS software package. The engineering model is described in simple terms below.

A 26-storey RC frame-core wall structure with the transfer storey located at the 9th storey is used in this study. The structural schematic diagram is shown in Figure 1. A seismic design acceleration of ground motion of 0.1 g is assigned, and the site characteristic period is 0.4 s. The summary of the architectural properties are presented as follows:

1. Five storey heights are used in the model. The height of the first storey is 4.5 m, and the height of the second storey is 4.2 m. The heights of the 3rd through 8th storeys are 3.6 m, and the height of the transfer storey is 4.0 m. The heights of the other storeys are 3.0 m.
2. The elevation of the building eave is 82.3 m, and the top core tube stretches out above the roof.
3. The lower standard storey below the transfer storey is shown in Figure 1(b), and the upper standard floor is shown in Figure 1(c). The 14th through 17th storeys and the 21st through 22nd storey cantilevers are 1.8 m relative to the lower adjacent storey.

To have a clear transfer mechanism for load action and architectural function, a thick-slab transfer scheme is adopted. The thickness of the transfer slab is 1.6 m, and the thickness of the adjacent upper and lower floor slabs is 0.2 m. For the large-span storeys below the transfer storey, a secondary beam floor system with a 0.10-m slab is used, and a non-beam floor system with a 0.15-m slab is adopted in the upper storeys. The specified dimension and material strength for beams and columns are shown in Table 1. Both plane and vertical arrangements comply with China’s design code requirements except for two conditions, namely, the transfer storey located at the 9th storey and the complex thick-slab transfer system.

Table 1：Specified Dimension and Material Strength for Beams and Columns

Storey	Frame Columns		Frame Beams		Secondary beams		Shear Wall	
	SD (mm^2)	CS (N/mm^2)	SD (mm^2)	CS (N/mm^2)	SD (mm^2)	CS (N/mm^2)	SD (mm^2)	CS (N/mm^2)
1~8	1300×1300	26.8	300×800	20.1	200×600	20.1	350	26.8
9	1300×1300	26.8	/	/	/	/	350	26.8
10~14	1100×1100	20.1	250×650	20.1	/	/	300	20.1
15~20	900×900	20.1	250×650	20.1	/	/	250	20.1
21~26	800×800	20.1	250×650	20.1	/	/	200	20.1

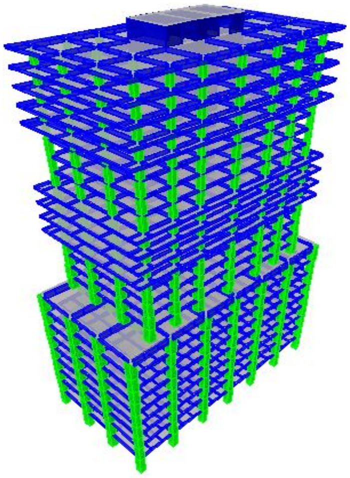
Note: SD denotes sectional dimension; CS denotes concrete strength

The characteristic strength of the flexure reinforcement is 360 N/mm^2, and the characteristic strength of the shear reinforcement is 270 N/mm^2.

The SATWE and PMSAP programs in China are utilised to perform structural analysis and design. All of the primary controlling parameters are in accordance with China's current code. Allowing for a 5% accidental eccentricity under uni-directional seismic action, the design results compared to China's design codes [(GB50011 (2010); JGJ3 (2010)] are shown in Table 2 (while Y is the weak direction). The storey shear capacity ratio is defined as the ratio of the storey lateral shear capacity to that of the next storey above.

Table 2: Summary of Structure Properties

Controlling Parameters	Design Value	Code Limit
Period ratio	0.8964	<0.9
Maximum inter-storey displacement ratio for Y direction	1.38	<1.5
Stiffness – Weight ratio for Y direction	7.38	>2.7
Storey shear capacity ratio of the 8th storey for Y direction	0.87	≥0.8
Storey shear capacity ratio of the 10th storey for Y direction	0.80	≥0.8
Lateral stiffness of the transfer storey to the adjacent upper storey	3.28	>0.60
Shear-weight ratio	0.0214	>0.016
Section area of the frame-supporting columns (the 1st to the 9th storey) is 1300×1300 mm^2, and the maximum axial compression ratio is 0.6≤0.6.		
The thickness of the wall is 350 mm and the maximum ratio of axial compression is 0.41< 0.5.		



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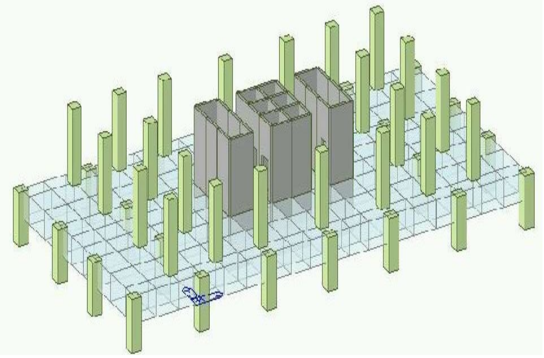

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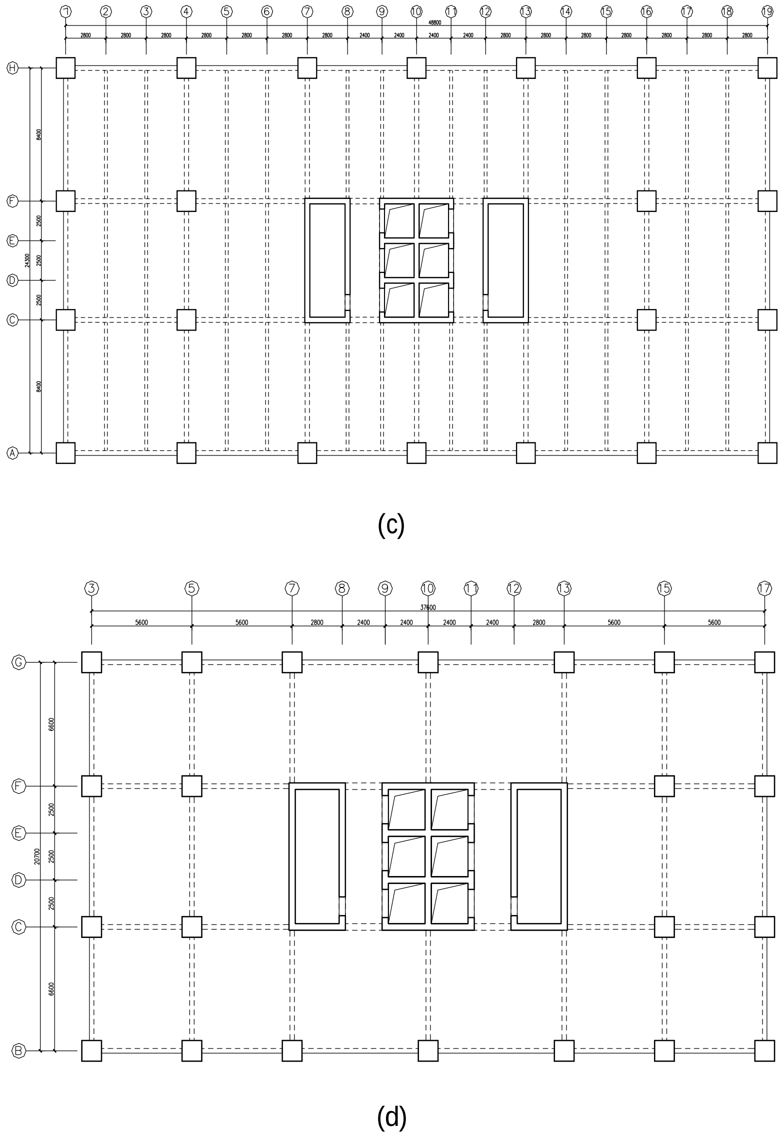


Fig. 1 Structural schematic diagram (a) The 3D view of the engineering model, (b) The 3D view of the transfer storey, (c) The lower standard storey below the transfer storey and (d) The upper standard storey below the transfer storey

PARAMETRIC ANALYSIS AND RESULTS

For a structure with a high thick-slab transfer storey, a thick slab, larger weight and larger stiffness of the transfer storey are unfavourable factors for structural seismic resistance, which will lead to the formation of weak storeys in lower storeys for this type of structure when subjected to ground motions. Thus, in the following section, the influences of the earthquake intensity, transfer storey location, transfer slab thickness and lower storey stiffness will be investigated.

1. Influence of Earthquake Intensity

Values for the seismic influence coefficient α are designated as 0.04, 0.08, 0.12 and 0.24 (corresponding to design basic ground motion acceleration values of 0.05 g, 0.10 g, 0.20 g and 0.40 g). The value of α can be calculated from α=Sa/g, where Sa is the value of the acceleration spectrum and g is the acceleration of gravity. In addition, the earthquake responses in the Y direction were studied through a response spectrum analysis.

The general lateral displacement pattern is shown in Figure 2, which demonstrates that the maximum inter-storey displacement of the structure occurs in the upper storey and the second maximum inter-storey displacement occurs in the lower storeys. Because of the sudden change in lateral stiffness for the upper and lower storeys adjacent to the transfer storey, there is a remarkable discontinuity change in the inter-storey displacement curve.

In the case in which the transfer storey is at the 9th storey, the curves of the inter-storey displacement and the storey shear force are shown as Figure 3 and Figure 4, respectively. These figures show that the inter-storey displacement and storey shear force increase with an increase in earthquake intensity. The differences between the inter-storey displacement and shear force among the storeys are not obvious when the structure is subjected to lower earthquake intensity; however, the difference is considerable when the structure is subjected to higher earthquake intensity. Therefore, this type of structural system should not be selected in a high seismic zone because of its poor seismic behaviour.

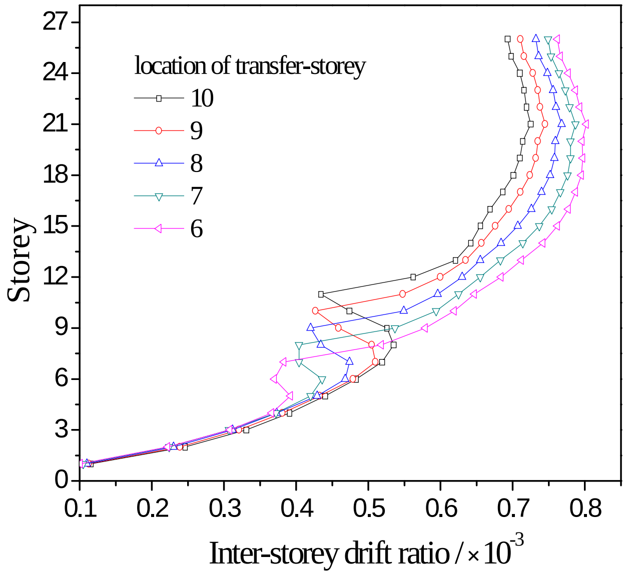


Fig. 2 Inter-storey displacement mode of the structure

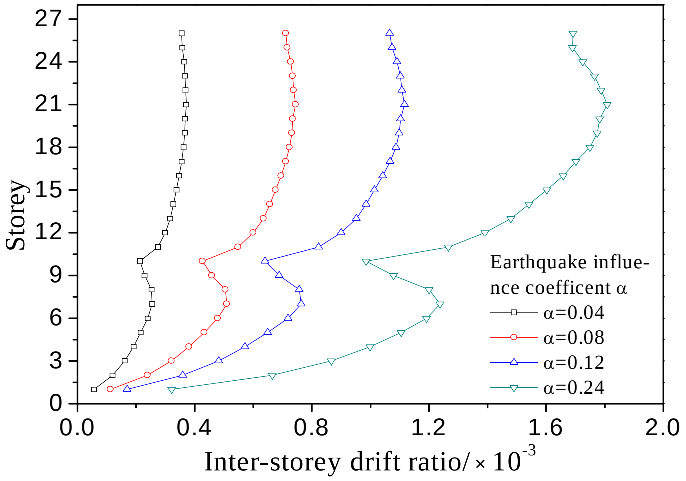


Fig. 3 Influence of earthquake intensity on inter-storey displacements

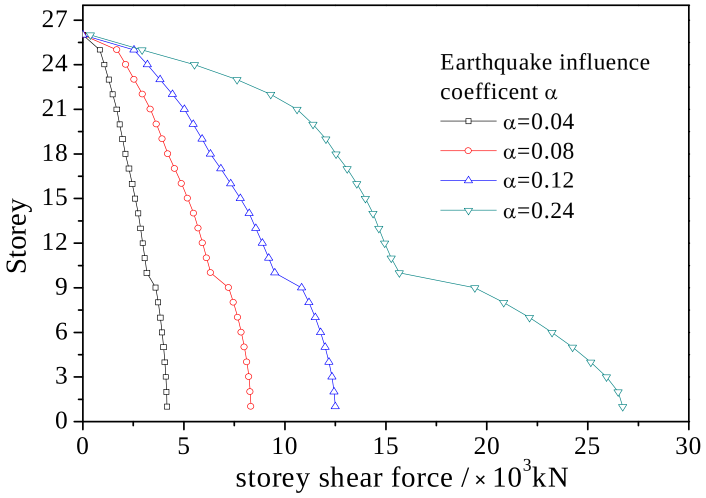


Fig. 4 Influence of earthquake intensity on storey shear force

2. Influence of Transfer Storey Location

To investigate the influence of the transfer storey location on the dynamic response of the structure, five numerical models were established. The five models were identical except for the location of the transfer storey (the transfer storey was located at the 6th, 7th, 8th, 9th, and 10th storey). The dynamic characteristic, inter-storey displacements and storey shear force under different earthquake intensities were compared. The research results indicate that the global stiffness increases at higher transfer storeys, which results from the increasing number of storeys below the transfer storey. Because of the large mass, the structural vibration mode is changed in the transfer storey; hence, the period ratio (torsion period/translational period) increases with a rise in the transfer storey, which is unfavourable to seismic resistance. The primary dynamic characteristics are shown in Table 3.

A higher location of the thick-slab transfer storey weakens the seismic behaviour of the lower storeys. Figure 5 shows that the lower storey displacements rapidly increase, while the upper storey displacements decrease with a higher location of the transfer storey. The research results indicate that the influences of the thick-slab transfer storey location on seismic behaviour are significant when the structure is located in a higher earthquake intensity area (as shown in Figure 2), and the structural displacement is gradually dominated by the lower storeys rather than the upper storeys.

Table 3: Influence of Location for the Thick-Slab Transfer Storey on Structural Dynamic Characteristics

Transfer Storey Location	6	7	8	9	10
Y period /s	1.954	1.914	1.885	1.873	1.870
Torsion period/s	1.436	1.448	1.470	1.498	1.524
X period /s	1.431	1.417	1.407	1.404	1.400
Y period ratio	0.735	0.757	0.779	0.800	0.815
X period ratio	1.003	1.022	1.045	1.067	1.088

The location of the transfer storey can also influence the storey shear force and the shear force distribution of the transfer storey and the storeys below the transfer storey. The research results demonstrate that the shear force increases rapidly with the higher location of the transfer storey, and there is a sudden change adjacent to the transfer storey, as shown in Figure 6. In the transfer storey and the adjacent lower two storeys, the proportion of shear force for the core walls decreases, while there is an opposite trend for the frame-supporting columns (shown in Figure 6(b)). The higher location of the transfer storey is unfavourable for a frame-supporting column. Therefore, it is unfavourable for seismic resistance to design the transfer storey at a high position on the basis of that single fact. These results are similar to those obtained by others (Rong and Wang 2004; Xu et al. 2000).

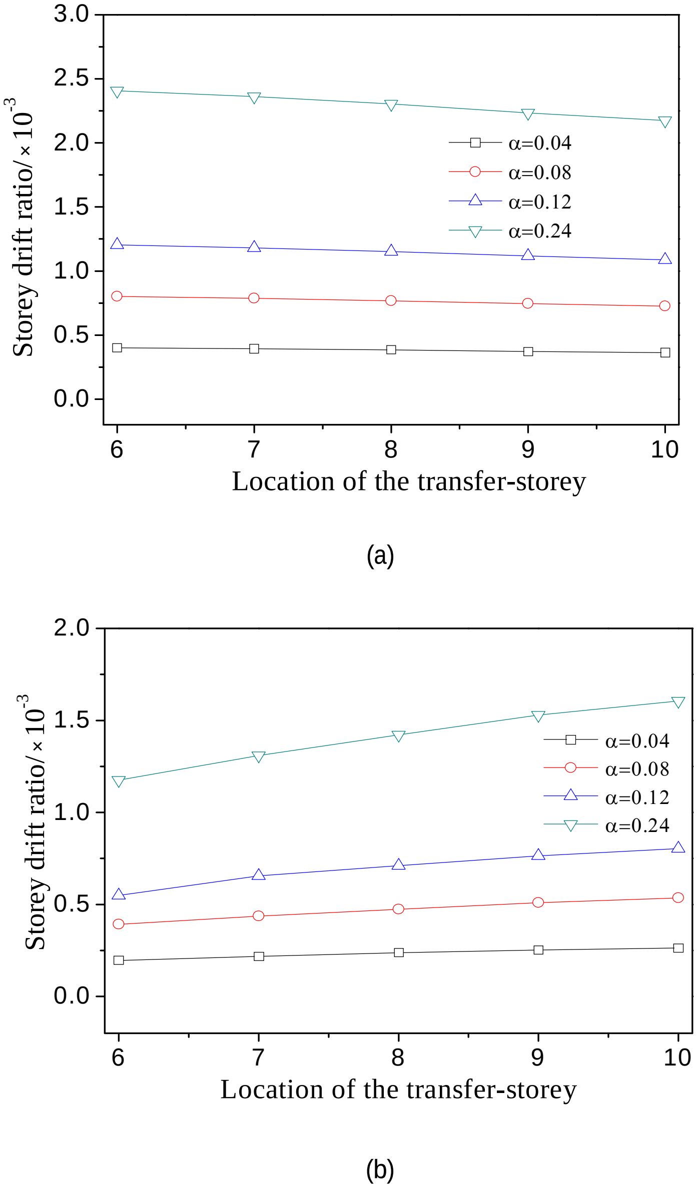
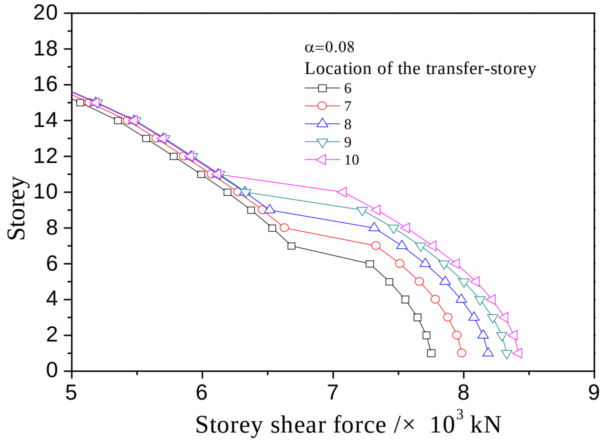


Fig. 5 Influence of the location for the thick-slab transfer storey on the structural maximal inter-storey displacement (a) Maximal storey displacement among upper storeys (b) Maximal storey displacement among lower storeys

3. Influence of Transfer Slab Thickness

To investigate the influence of the transfer slab thickness on the structural dynamic behaviour, the transfer slab thickness was set in the range of 1.4 m to 2.2 m. Table 4 shows that the torsion period increases and the translation period decreases with the transfer slab thickness, meaning that the period ratio increases. As the transfer slab is thickened, the displacements of the storeys influenced by the transfer storey decrease (shown in Figure 7(a)), and the storey shear force obviously increases for the storeys below the transfer storey (shown in Figure. 7(b)).



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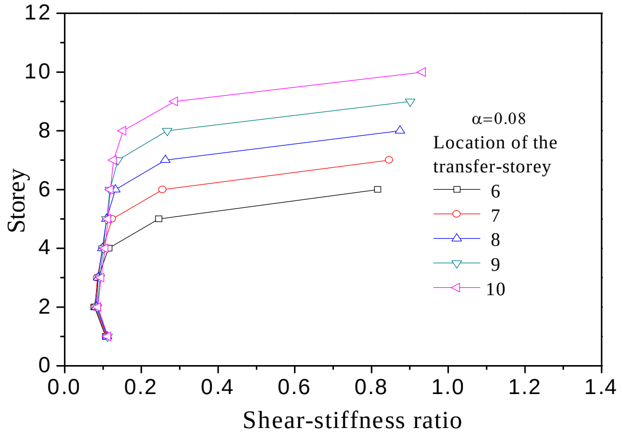


(b)

Fig. 6 Influence of the location for the thick-slab transfer storeys on the structural storey shear force and distribution (a) Influence on storey shear force (b) Influence of the number of storeys below the transfer storey on the shear force distribution

Table 4: Influence of transfer slab thickness on structural dynamic characteristics

Slab thickness/m	**1.4**	**1.6**	**1.8**	**2.0**	**2.2**
Y period /s	1.896	1.873	1.852	1.835	1.819
Torsion period/s	1.492	1.498	1.504	1.510	1.517
X period /s	1.417	1.404	1.391	1.380	1.368
Y period ratio	0.787	0.800	0.812	0.823	0.834
X period ratio	1.053	1.067	1.081	1.094	1.109

The thickness of the transfer slab can also influence the shear force distribution of the storeys adjacent to the transfer storey. It is found that the storey shear force proportions of frame-supporting columns decrease, while the proportion of the core wall increases with an increase in the transfer slab thickness (shown in Figure 7(c)). This is unfavourable to the seismic resistance behaviour of the core-wall. As a whole, the increasing thickness of the transfer slab is unfavourable to the seismic resistance of the lower storeys, while the confining effects of a thick slab to the upper part of the structure is substantially greater than the amplifying effects. In other words, the increasing thickness of the transfer slab will not always magnify the seismic response of the storeys above the transfer storey.

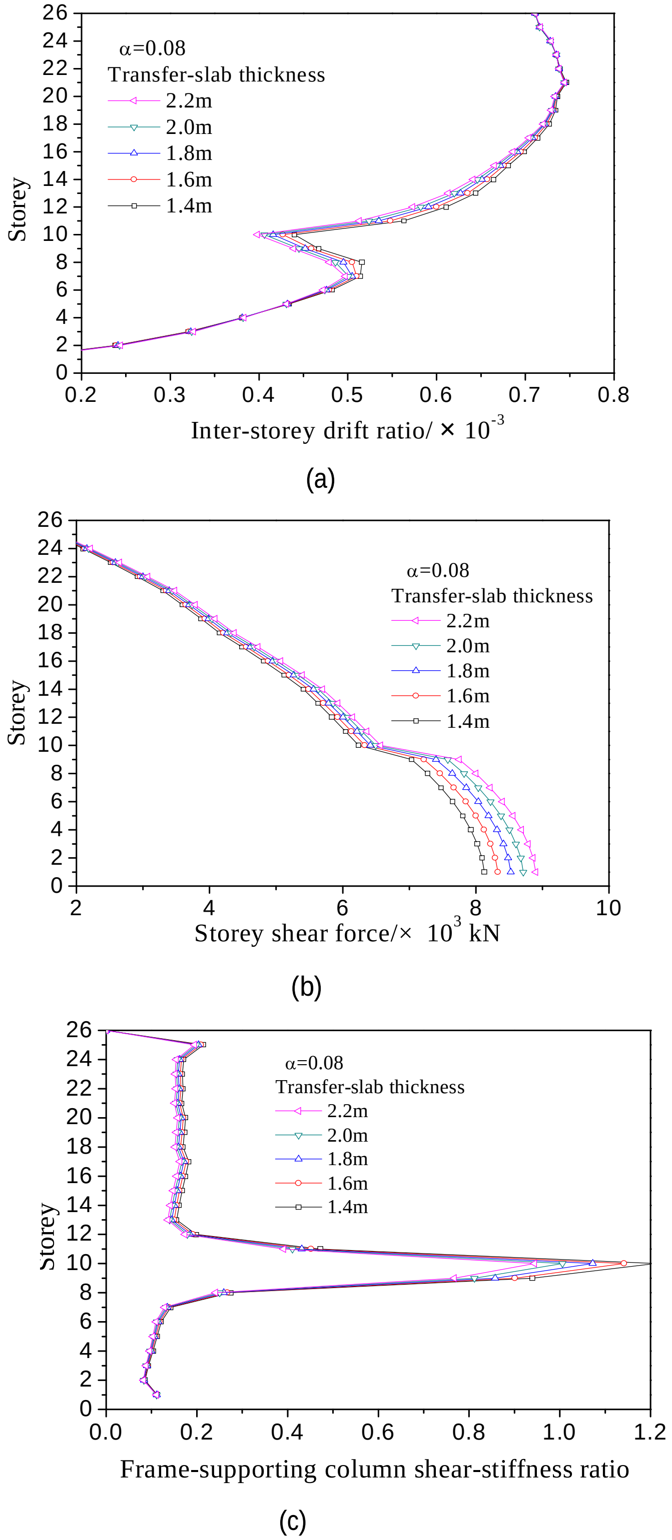


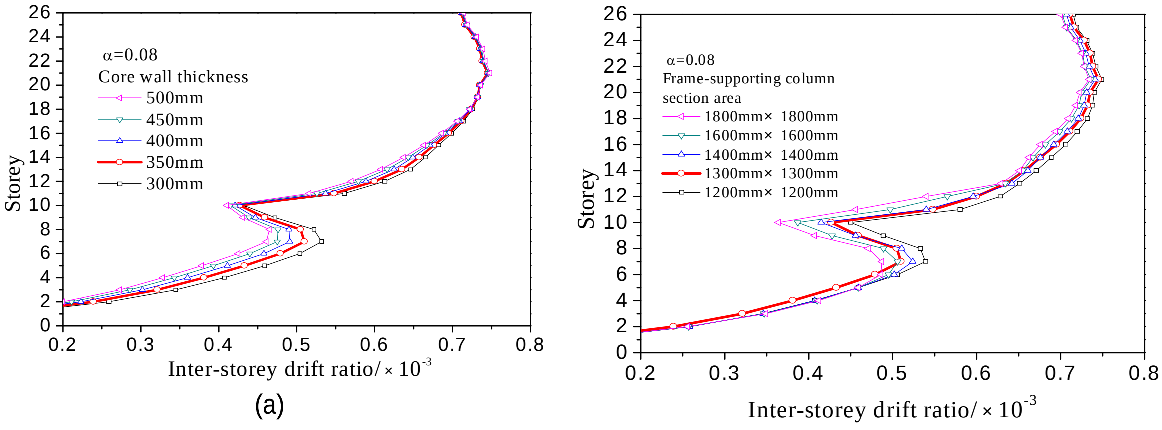
Fig. 7 Influence of transfer slab thickness on the structural inter-storey displacement, storey shear force and proportion (a) Influence of transfer slab thickness on inter-storey displacements (b) Influence of transfer slab thickness on storey shear force (c.) Influence of transfer slab thickness on the frame-supporting column shear stiffness ratio

4. Influence of Lower Storey Stiffness

The influence of the lower storey stiffness on the structural dynamic characteristics is introduced in this section, and two means of changing the lower storey stiffness are discussed, namely, changing the thickness of the lower storey core wall and changing the column sections. In this study, the structure with the transfer storey located at the 9th storey is investigated, and the dynamic response for 10 cases (the thickness of the core-wall ranging between 300 mm and 500 mm and the column section ranging between 1200 mm × 1200 mm and 1800 mm × 1800 mm) with different lower storey stiffness values are shown in Table 5. Figure 8 indicates that both thickening the core wall and enlarging the sections of the frame-supporting columns can reduce the inter-storey displacement. However, it is more convenient to thicken the shear wall to obtain the same overall stiffness level.

Table 5: Influence of the lower storey stiffness on structural dynamic characteristics

Shear-wall Thickness/mm	**300**	**350**	**400**	**450**	**500**
Y period /s	1.928	1.873	1.825	1.785	1.749
Torsion period /s	1.561	1.498	1.445	1.399	1.359
X period/s	1.456	1.404	1.360	1.321	1.288
Y period ratio	0.810	0.800	0.792	0.784	0.777
X period ratio	1.072	1.067	1.063	1.059	1.055
Column Section Area/mm^2	**1200×1200**	**1300×1300**	**1400×1400**	**1600×1600**	**1800×1800**
Y period/s	1.959	1.873	1.899	1.845	1.799
Torsion period /s	1.576	1.498	1.545	1.511	1.477
X period /s	1.479	1.404	1.434	1.393	1.357
Y period ratio	0.804	0.800	0.814	0.819	0.821
X period ratio	1.066	1.067	1.077	1.085	1.088



(a)

(b)

Fig. 8 Influence of lower storey stiffness on structural maximal inter-displacements (a.) Influence of the core wall thickness (b.) Influence of the section area of the frame-supporting column

Improving the lower storey stiffness can result in both favourable and unfavourable effects, as shown in Table 5. For instance, the structural stiffness increases with an increase in the thickness of the shear wall, which results in decreasing both the translation and torsion periods. However, the translation period decreases more rapidly, so the period ratio decreases, which is favourable for structural seismic resistance. In contrast, the structural translation period also decreases with increases in the cross-section of the frame-supporting columns, while the torsion period does not always decrease, so the period ratio generally increases, which is unfavourable for seismic resistance. These results are in agreement with those obtained in other studies (Rong and Wang 2004). Therefore, both favourable and unfavourable aspects should be taken into account to improve the structural seismic behaviour by enhancing the lower storey stiffness.

DESIGN RECOMMENDATIONS

Based on the parametric analysis above and the related research findings (Fu 1999; Wang and Wei 2002; Rong and Wang 2004; Li et al. 2006; Lu et al. 2008 and Fu et al. 2010) in China, some seismic suggestions for tall buildings with high thick-slab transfer storeys are proposed.

1. Tall buildings with high thick-slab transfer storeys have very complicated structural systems, possessing complex global and local earthquake responses. The dynamic response of the structure will be more complex in a high seismic area. To improve the structural safety, the authors suggest that the earthquake intensity (corresponding to the ground motion acceleration or the seismic influence coefficient) selected for seismic design should be increased to 1.5 times that of the design seismic parameters.

2 With the higher location of the thick-slab transfer storey, the inter-storey displacement and shear force are gradually dominated by the lower storeys rather than the upper storeys. The proportions of shear force for the frame-supporting column increase in the transfer storey and the adjacent lower storeys; therefore, more attention should be paid to controlling the maximum inter-storey displacement of the lower storeys. The lower storey stiffness should be enhanced, for example, by enlarging the core wall thickness. To improve the ductility of the frame-supporting column, the axial compression ratio should be controlled at less than 0.6, and the total shear proportion for the frame-supporting columns should not be less than 0.25 Q0 (where Q0 is the storey shear force).

3. A higher transfer storey can also amplify the torsion effects, so the period ratio and displacement ratio of the structure should be strictly controlled.

4. Thickening the transfer slab can amplify the structural torsion effect, which will result in an unfavourable influence on the lower storey seismic resistance. Therefore, on the condition that the slab meets the design requirements, such as flexure capacity, shear capacity and local impact capacity, the transfer slab thickness should be as thin as possible. According to the related research findings, a thin slab with haunch can be adopted to enlarge the section area of the column or wall to sustain an impact force.

5. To improve the bearing conditions, outrigger beams can be added to the transfer slab to connect the columns or shear walls. The floor slabs of the upper two storeys and lower two storeys adjacent to the transfer storey should be designed as 200-mm thick to efficiently transfer the horizontal earthquake action.

SUMMARY AND CONCLUSION

In this paper, the dynamic responses of tall buildings with high thick-slab transfer storeys were studied with a response spectrum analysis method, and the influences of four factors on the responses were investigated. The following conclusions can be drawn from the results.

1. As the earthquake intensity increases, the inter-storey displacements and shear force on the structure increase. This tendency will be more obvious with higher earthquake intensities, so that the seismic fortification intensity of this type of structure should be improved appropriately.

2. With a higher transfer storey, the period ratio will increase, and the structural displacement is gradually dominated by the lower storeys rather than the upper storeys. Meanwhile, the proportion of storey shear force for the frame-supporting columns will be enlarged in the storeys adjacent to the transfer storey.

3. Thickening the transfer slab is unfavourable for the seismic resistance of the lower storeys, and the torsion effect can be amplified; so, the thickness of the transfer slab should be rigidly controlled.
4. The structural period ratio increases with thicker core walls, while it decreases with larger column cross-sections. Therefore, both the favourable and unfavourable effects should be taken into account to improve the structural seismic behaviour by enhancing the stiffness of the lower storeys.

All the conclusions above are proposed based on the elastic response spectrum analysis method, and a comparison with elastic dynamic historical analysis results should be conducted in later studies. The structural load carrying capacity will be a primary factor when a structure reaches an elastic-plastic state, and the related characteristics should be studied in future.

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