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EARTHQUAKE INDUCED SHEAR CONCENTRATION IN SHEAR WALLS ABOVE TRANSFER STRUCTURES

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ABSTRACT

Due to various architectural constraints and multi-functional requirements for modern buildings, combined structural forms, which typically include shear wall systems in higher zones and moment resisting frames together with core walls in lower zones, are commonly used for these buildings. Transfer structures are often introduced to transfer the loads from higher to lower zones. Previous experimental and numerical studies have demonstrated that the exterior walls above the transfer structure are particularly vulnerable structural members under seismic loading. In this paper, a qualitative model is presented for simulating the shear concentration effect in exterior walls with consideration of the local deformations of transfer structures. A parametric study was carried out to validate the model and to quantify various factors which may influence the shear concentration effect. A shear concentration factor (*SCF*), which can measure the intensity of shear stress concentration in the exterior walls, is defined. Based on the numerical study, design principles are recommended to seismic engineers for minimizing the adverse shear concentration effect on exterior walls under seismic loads.

Keywords: Shear walls, shear concentration, seismic, transfer structures, concrete

1. INTRODUCTION

Due to a shortage of land and multi-functional requirements in many metropolitan areas such as Sydney, Hong Kong and Singapore, high-rise buildings with different usages in higher and lower zones are very popular. Combined structural systems with shear wall systems in higher zones, together with moment-resisting frames and core walls in the lower zones, are widely adopted for these buildings. The introduction of transfer structures between the high and low zones of a high-rise building has become common. A typical modern residential development in Hong Kong with transfer structures supported by columns and core walls is shown in Figure 1.

The seismicity level of these metropolitan areas is either low or moderate, and the peak ground accelerations are all within 0.1 to 0.2 g for a 475-year return period earthquake. Most of the buildings constructed in these regions have been designed to resist only wind and gravity loads, and usually lack the ductility and redundancy to resist seismic loads. In addition, high-rise buildings with transfer structures often have stiffness and mass irregularities at the transfer level, which are prone to severe damage in a moderate earthquake. The seismic behavior of buildings with transfer structures has been studied through shaking table analyses (Ye *et al*., 2003; Gao *et al*., 2003; Huang *et al*., 2004; Xu *et al*., 2005; Wu *et al*., 2007; Li *et al*., 2006). The previous studies have demonstrated that under horizontal seismic excitations, soft storey type failures below the transfer level rarely occurred, probably due to the fact that this failure mechanism has been extensively studied (Su *et al*. 2002; Li *et al*. 2003) and effective design provisions have been established in various seismic design codes (ICC 2006, ICBO 1997, EC8 2005, Chinese National Standard 2001 and Chinese National Specification 2002). However, significant damage to exterior walls and floor slabs does occur above the transfer level (see Figure 2), as many building designers overlook this type of failures. Numerical studies (Xu *et al*., 2000; Chen and Fu, 2004; Rong *et al*., 2004) have illustrated that under seismic excitation, the horizontal shear force distribution did not follow the proportion of lateral stiffness in each storey; an abrupt change of shear forces on exterior walls occurred at stories in the vicinity of the transfer level (Figure 3). This sudden increase in shear force can lead to brittle shear failure of exterior walls above the transfer level. A comprehensive review of the seismic response of concrete buildings with transfer structures was conducted by Su (2008).

In this paper, the mechanism for the formation of shear concentration in shear walls based on the local deformation of transfer structure is presented. A parametric study was conducted to validate the proposed mechanism and to study the factors that influence the shear concentration effect. The findings in this study enable building designers to have a better understanding of the seismic induced shear concentration in exterior shear walls in modern buildings with transfer structures.

2. FORMATION OF SHEAR CONCENTRATION AT EXTERIOR WALLS

Transfer structures such as transfer plates and transfer girders are often massive and stiff. Their presence can affect the displacement responses of the entire building under seismic excitation and cause an abrupt change in the inter-storey drifts above and below the transfer level. Many researchers (Zhang *et al*. 2000; Zhang *et al*. 2003; Qain and Wang 2006) have suggested ignoring the out-of-plane deformations of the transfer plate and adopting rigid plate and rigid diaphragm assumptions in seismic or wind load calculations. However, the authors propose that such local deformations are the primary cause of the abrupt change in shear at the exterior walls and should not be neglected in seismic analyses.

Figure 4 illustrates the local deformations of a transfer plate under lateral loading. The interaction of deformations between the transfer structure, exterior walls, core walls and floor slabs is depicted in Figure 5. Under horizontal earthquake loads, the central core wall deflects as a vertical cantilever and takes nearly all the base shear. Since the transfer plate and the core wall are joined together monolithically, the joint of the plate and core wall is rotated in a similar manner. The global rotation of the plate is restrained by the edge columns, leading to the development of a pair of push-and-pull forces in the columns and local deformations of the transfer plate. Likewise, rotations of the core wall θ_c and exterior walls θ_e at transfer level are different from each other. To reduce the rotation incompatibility between the two walls, the slabs above the transfer level are deformed and in-plane compressive or tensile restraining forces are generated in the slabs. These horizontal reactions transmitted from the core wall to the exterior walls are the origin of the abrupt change of shear forces and the shear concentration near the transfer level. The amount of horizontal reactions generated depends on the difference in rotations between the core wall and exterior walls, as well as the flexural stiffness of walls. Shear failure may occur in exterior walls when the shear stress is excessive. Moreover, slabs can be damaged by the high tensile stresses. In the following sections, the mechanism for the formation of shear concentration at exterior walls will be validated numerically and the factors that influence the shear concentration effect will be investigated.

3. COMPUTATIONAL MODELING

Numerical simulations have become a popular and reliable analytical tool for seismic analysis of buildings (Gao *et al*. 2003; Huang *et al*. 2004 and Wu *et al*. 2007). Conventional elastic analyses were able to satisfactorily capture the real dynamic behavior of buildings under frequent earthquakes (Su 2008). In this study, the commonly available finite element package ETABS (Habibullah 1999) is used to conduct the numerical simulation. Simple linear-elastic dynamic analysis is employed to illustrate the effect of local deformation of transfer structure and to quantify various factors which influence the shear force concentration at exterior walls above the transfer structure.

Two-dimensional 30-storey building models (see Figure 6) were constructed based on the frame-shear wall buildings with transfer structures that are commonly found in China and Hong Kong (Gao *et al*. 2003; Chen and Fu 2004; Rong and Wang 2004; Li et al. 2006). In the models, a full elevation center wall is incorporated, while the exterior walls are introduced only above the transfer floor. A transfer beam is located at the 3rd floor, whereas columns are provided below the transfer beam to support the exterior walls. To increase the lateral stiffness of the structure, coupling beams are used to connect the center wall and exterior wall on each floor above the transfer level. To ensure the results obtained are sufficiently general and representative of real applications, four models with different wall dimensions, as listed in Table 2, were generated. Model A has a 9m-long center wall, while Model B has a 6m-long center wall. The lengths of Models A and B are both equal to 21m. Models A and C have the same arrangements in center wall length and coupling beam length, except that Model C has 4m exterior walls. Finally, Model D has 1.5m exterior walls and a model length of 26m, which is same as that in Model C.

The building heights of all the models are 94.5m. The storey heights below and above the transfer level are 4.5m and 3m, respectively. The basic dimensions of various structural components are shown in Figure 6. The material properties adopted in the simulation are shown in Table 1. The models are incorporated with a floor mass density of 5.5kN/m^3, which is the average density of typical residential blocks in Hong Kong (Su *et al*., 2003).

The response spectrum (see Figure 7) stipulated in the National Standard (2001) with Seismic Intensity VII and maximum spectral acceleration of 0.16g is used in the response spectrum analysis. A damping ratio of 5% to the critical is adopted, and modal combination of the square root of the sum of the squares is employed. The computed fundamental vibration periods of the models range from 2.6 to 3.5 sec.

4. RESULTS AND DISCUSSION

4.1 Shear Concentration in the Exterior Walls

The inter-storey drifts of the center wall, exterior wall, and column of Model A are shown in Figure 8. A significant change in inter-storey drifts at the exterior wall is observed at the first two stories above the transfer level. Similar changes are not found at the centre wall, hence there is a large difference in rotations between the centre wall and exterior walls. The shear force distributions in the center wall, exterior wall and column are presented in Figure 9. It can be observed that at the same position above the transfer lever, there is an abrupt change of shear force in both the center wall and exterior walls. Horizontal shear is transferred from the centre wall to the exterior walls and the horizontal shear increases to the maximum just above the transfer level. The result demonstrates that the difference in the inter-storey drifts between the exterior walls and centre wall above the transfer level is the primary factor causing the shear concentration at the exterior walls. The findings further support the mechanism discussed in Section 2 for the formation of the shear concentration. Despite that only planar models are considered in this analysis, the proposed mechanism for the formation of shear concentration at the exterior walls can be easily extended to other three-dimensional buildings with centre core walls and exterior walls resting on column-supported transfer plates.

In order to quantify the effects of shear stress concentration in exterior walls above the transfer level, a Shear Concentration Factor (*SCF*) is defined in equation (1),

$$SCF = \frac{V_{wj} \sum_{i=1}^{n} A_{wi}}{V_t A_{wj}} \tag{1}$$

where A_{wj} is the shear area, V_{wj} is the maximum horizontal shear force of the j^{th} shear wall at the transfer level, V_t is the maximum storey shear above the transfer structure, and n is the number of shear walls. The SCF is aimed at comparing the maximum horizontal shear stress resisted by the exterior wall to the average shear stress above the transfer level. When the *SCF* approaches one, there is no shear concentration. In contrast, when there is shear concentration at the exterior wall, the factor can go up to 4 or above.

4.2 Effect of Transfer Beams

In this section, the influence of the depth of transfer beams on the *SCF* is studied. The transfer beam depth is increased from 1.4 m to 2.4 m while all other dimensions remain unchanged. Figure 10 shows the variation of the *SCF* against the depth of transfer beam for Models A to D. The *SCFs* of all the models are steadily reduced with the increase in the beam depths. However, the rates of reduction vary among different models; for example, Model B reduces from 5.3 to 2.8 while Model C reduces from 3.7 to 3.2. As mentioned in section 2, the shear concentration is associated with the difference in rotations between the center wall and exterior walls above the transfer structure. Figure 11 depicts the rotation difference (θ_j-θ_c) between the exterior wall and centre wall. The rotation difference for Model B is effectively reduced from 0.00047 rad to 0.00025 rad when the depth of the transfer beam is increased. The rates of reduction for the *SCF* (5.3/2.8 =1.89) and for the rotation difference (0.00047/0.00025 =1.88) are very similar. The results clearly reveal that the amount of shear force transfer from the center wall to the exterior walls above transfer level depends on the difference in wall rotations. A stiffer transfer beam can decrease its own deformations and moderate the difference in rotations as well as the shear transfer between the center wall and exterior walls.

In order to study the extent of reduction in the *SCF* due to the increase of beam depth, the beam stiffness in Model A is hypothetically increased by 10 and 100 times. Figure 12 shows the shear force distributions in the exterior wall. Even when a rigid transfer beam is used, shear force concentration in the exterior wall above the transfer structure is still observed. This demonstrates that the effect of shear concentration is partially due to the intrinsic behavior and interaction of a coupled centre wall and shear wall structure on a restraint boundary; such effect cannot be completely eliminated.

4.3 Effect of Exterior Walls

To investigate the effect of exterior wall stiffness on the *SCF*, the exterior wall length is increased from 1 m to 5 m while keeping the other properties and dimensions unchanged. The seismic response of all the models was calculated, and Figure 13 plots the variations in *SCF* against the length of exterior walls. The variations of all the models are very consistent. *SCF* reaches a peak value of around 3.8 when the wall length is approximately 2 to 3 m (which is comparable to the transfer beam depth of 2 m), and *SCF* reduces to around 3 when the wall lengths reduce to 1m or increase to 5 m. It appears that an unfavorable combination of the transfer beam depth and shear wall length (or beam stiffness and wall stiffness) can worsen the shear concentration. This is reasonable as when the flexural stiffness of the transfer beam deviates significantly from that of the exterior walls, the weaker structural components (either the transfer beam or the exterior walls) will deform more and the amount of in-plane deformation and in-plane force generated in the slabs will be less. The induced seismic shear forces in exterior walls should also be smaller.

4.3 Effect of Center Walls and Columns

The center wall thickness and the column size are varied in turn, while the other dimensions remain unchanged, in order to investigate their effect on the *SCF*. Figures 14 and 15 illustrate the effects of varying the length of centre walls and size of columns, respectively, on the *SCF*. The *SCFs* vary within a narrow range from 3.2 to 3.8. The result shows that *SCF* is relatively insensitive to the change in the centre wall length or column size. It is likely that the flexural stiffness of the centre wall and the axial stiffness of the columns provided are already high enough; a further increase in the stiffness does not have much effect in reducing the shear concentration.

4.5 Effect of Storey Height above the Transfer Structure

The effect of storey height above the transfer structures on the SCF is studied in this section. When the storey height just above the transfer level is increased from 3 m to 9 m, the *SCF* reduces significantly from the maximum value of 3.7 to around 1.0 for

Models A, B and D, and to 2.3 for Model C (see Figure 16). Obviously, providing a higher storey height above the transfer level can decrease the flexural stiffness of the exterior walls and can effectively reduce the shear force concentration in the exterior walls.

4.6 Effect of Vertical Positioning of the Transfer Structure

In this section, the vertical location of the transfer beam is relocated from the 3rd storey to the 6th, 9th and 12th stories respectively. The total number of stories remains unchanged. The variations of the *SCF* with the level of the transfer beam are shown in Figure 17. The *SCF* is found to be greatly increased from around 3.5 to more than 7.0. Similar findings have been mentioned by other researchers (Xu *et al*., 2000; Geng and Xu, 2002; Wang and Wei, 2002 and Zhang *et al*., 2003). When the transfer beam is placed at a high level, the structures below the transfer structure become more slender. The rotation of the centre wall, as well as the difference in rotations between the center wall and exterior walls, will be increased. As the shear transfer between the walls is essentially proportional to the difference in wall rotation, a larger rotation difference will cause more shear forces to transfer from the centre wall to the exterior walls and worsen the shear concentration at the exterior walls. For seismic resistant design, the transfer level should be located at a lower storey (e.g. less than 5 stories above ground according to GB50011-2001).

4.7 Effect of Stiffness Degradation of Center Wall below the Transfer Level

From the shaking table analyses, significant stiffness degradations were observed below the transfer level when the models subjected to rare (or major) earthquakes. To simulate the inelastic behavior of the building during major earthquakes, the stiffness of the center wall under the transfer level is reduced, while the other dimensions and properties are kept constant. Figure 18 shows the variations of *SCF* due to the reduction of wall stiffness below the transfer level. When the center wall stiffness below the transfer level is reduced to 60% of the original value, the *SCF* increases by about 30% to 4.5. These results imply that stiffness degradation below the transfer level could moderately increase the shear concentration at the exterior walls. Hence the walls below the transfer level should be detailed to have the capacity to undergo seismic effects without loosing significant stiffness. Otherwise, the effect of stiffness degradation on the increase in the shear demands at the exterior walls should be duly designed.

5. CONCLUSIONS

A numerical study has been conducted, aimed at improving the general understanding of the shear concentration effect on exterior walls above transfer structures under seismic loads. A parametric study was carried out and the major findings of the study are summarized as follows:

1. Local deformations of the transfer structures, as validated by the numerical study, are the primary reason for the formation of shear concentration in exterior walls. Rigid plate and rigid diaphragm assumptions which ignore such local deformation should not be used in the numerical simulations of seismic response of buildings with transfer structures. The transfer structures, the slabs, and coupling beams should be modeled by flexible beam, plate, or even solid elements wherever it is appropriate.
2. A shear concentration factor (*SCF*) is defined for comparing the maximum horizontal shear stress taken by the exterior wall to the average shear stress

above the transfer level. *SCF* approaches one when there is no shear concentration, and can go up to four or above when a shear concentration exists. The present study reveals that shear concentration can be very serious in exterior walls under seismic loading. Hence shear checking should be conducted for exterior walls, in particularly, at one and two storey above the transfer level.

3. Stiff transfer beams can moderate, but not eliminate, the shear concentration. The effect of shear concentration is partially due to the intrinsic behavior and interaction of a coupled centre wall and shear wall structure on a restraint boundary.
4. Shear concentration in interior walls is sensitive to an increase of storey height above the transfer level, but is not sensitive to the change in stiffness of centre walls and edge columns below the transfer level. An increase of storey height above the transfer level is helpful in reducing the adverse shear concentration effect.
5. Placing the transfer structure at a high level can remarkably increase the shear concentration effect. The numerical study found that the *SCF* can go up to seven when the transfer beam is placed at the 9th floor. For seismic design, the transfer level should be limited to a lower storey (e.g. less than 5 stories above ground).
6. Under major (rare) earthquakes, inelastic deformation would likely occur at the centre wall below the transfer structure. Stiffness degradation of the centre wall below the transfer structure could lead to a moderate increase in the *SCF* by approximately 30%.

6. ACKNOWLEDGEMENTS

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Table 1. Material properties of the models

Property	*Value*
Concrete grade	30 MPa
Poisson's ratio	0.2
Modulus of elasticity	30 GPa

Table 2. Dimensions of the models

Model	*a (m)*	*b (m)*	*c (m)*	*Total length (m)*
A	1.5	4.5	9	21
B	1.5	6	6	21
C	4	4.5	9	26
D	1.5	7	9	26

where:

a = exterior wall length

b = coupling beam length

c = center wall length

Figure 1. A residential development in Hong Kong with transfer structures

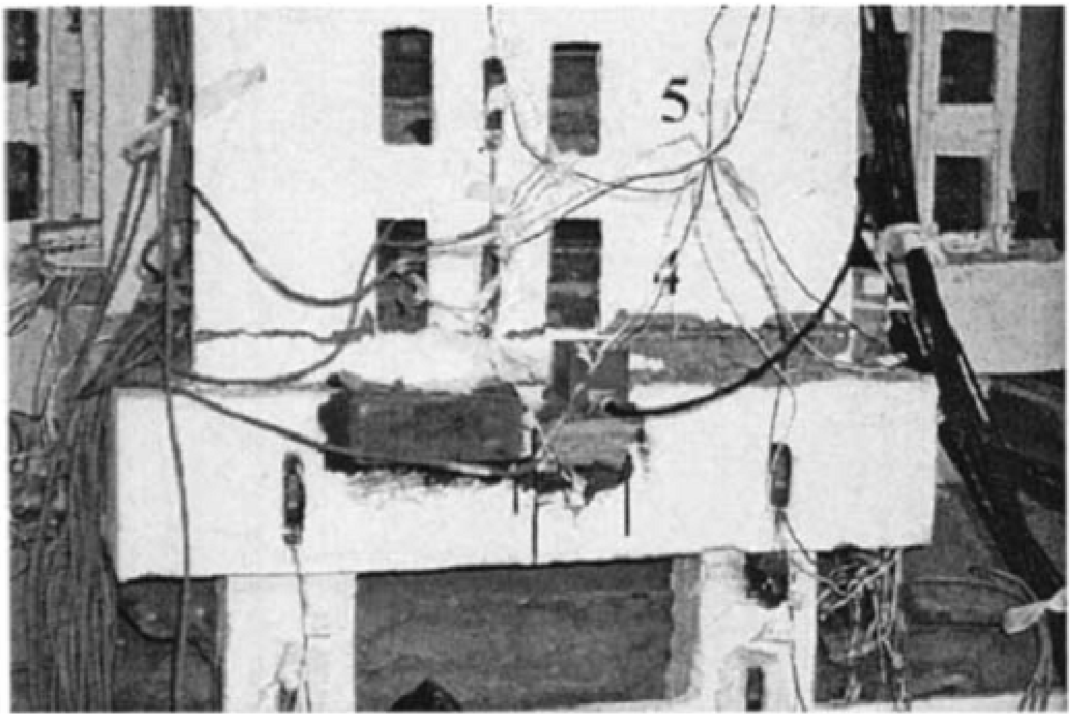

Figure 2. Structural failure on exterior walls at transfer level (Li *et al*., 2006)

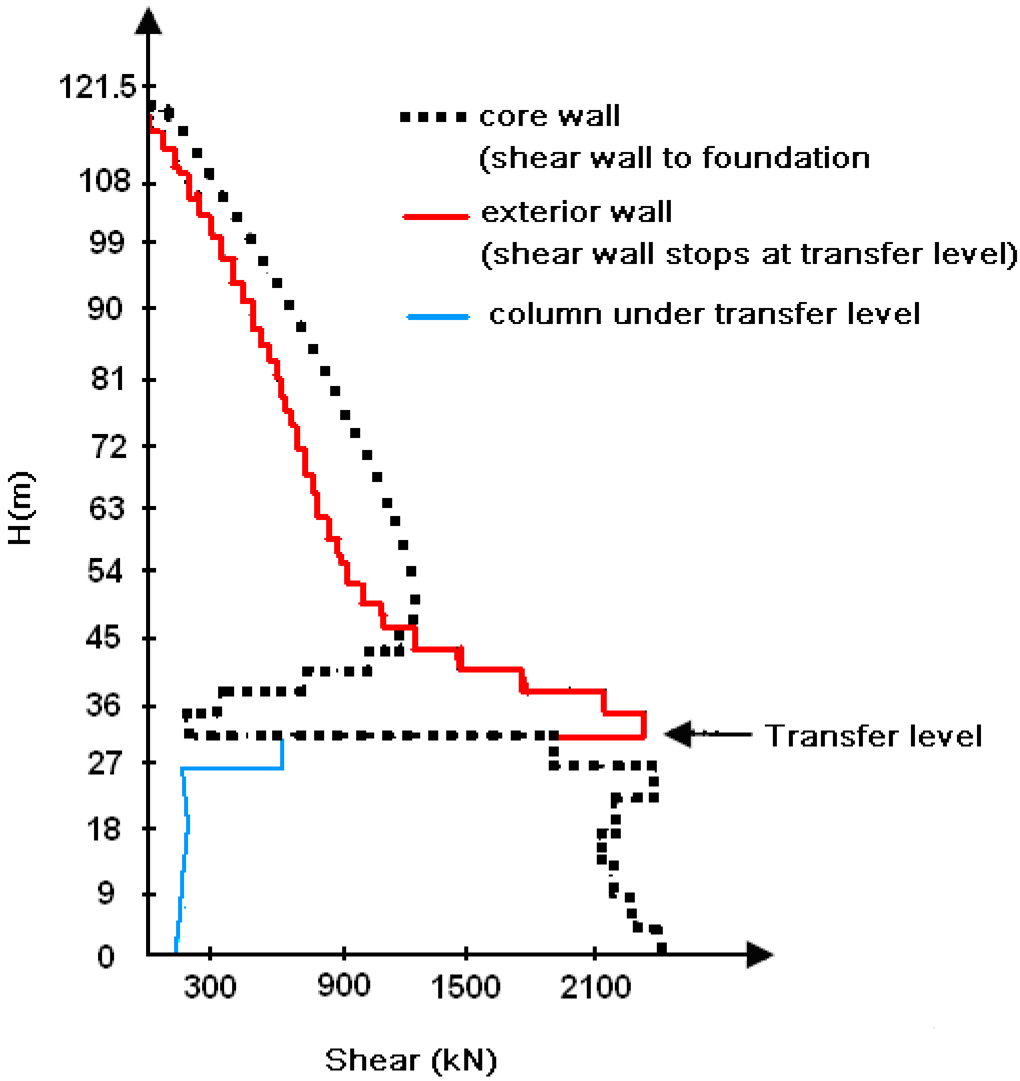

Figure 3. Shear force distribution (Xu *et al*., 2000)

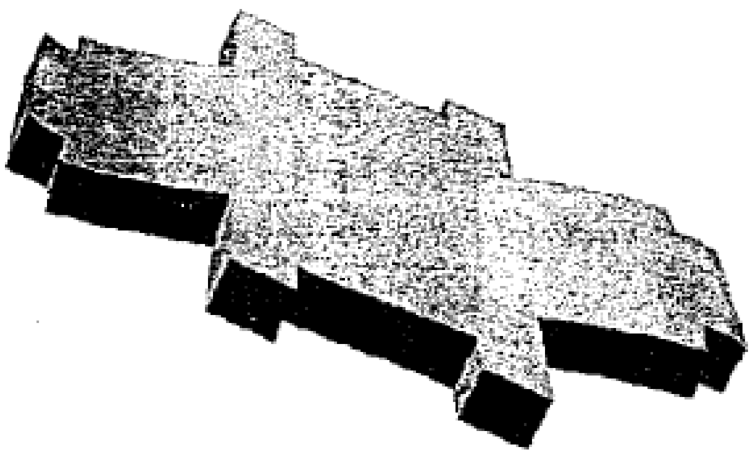

Figure 4. Local deformation of a transfer plate under lateral loading (Li, 2005)

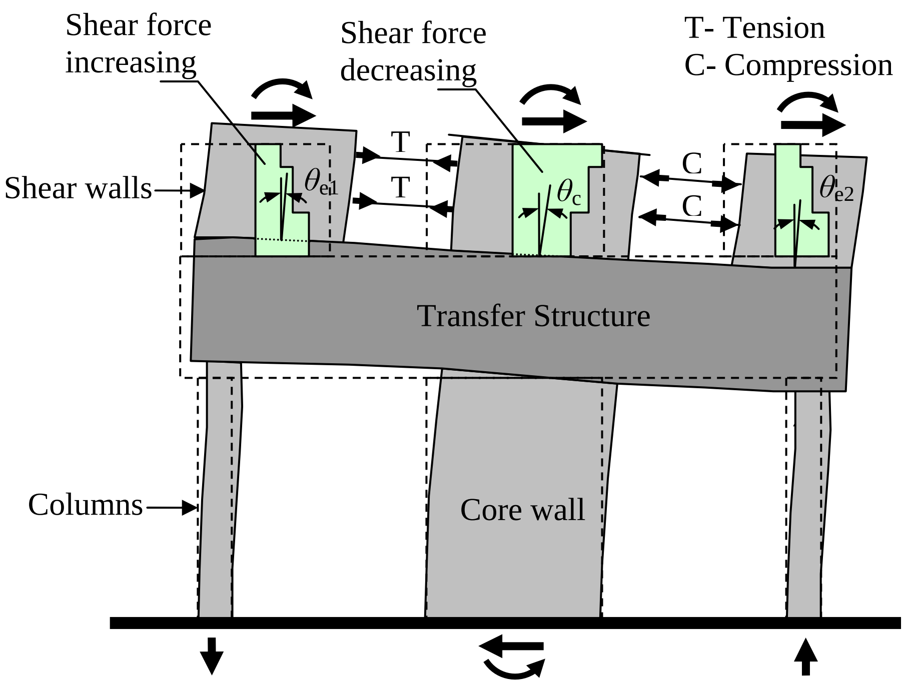

Figure 5. Local deformation of the transfer structure and shear concentration at the exterior

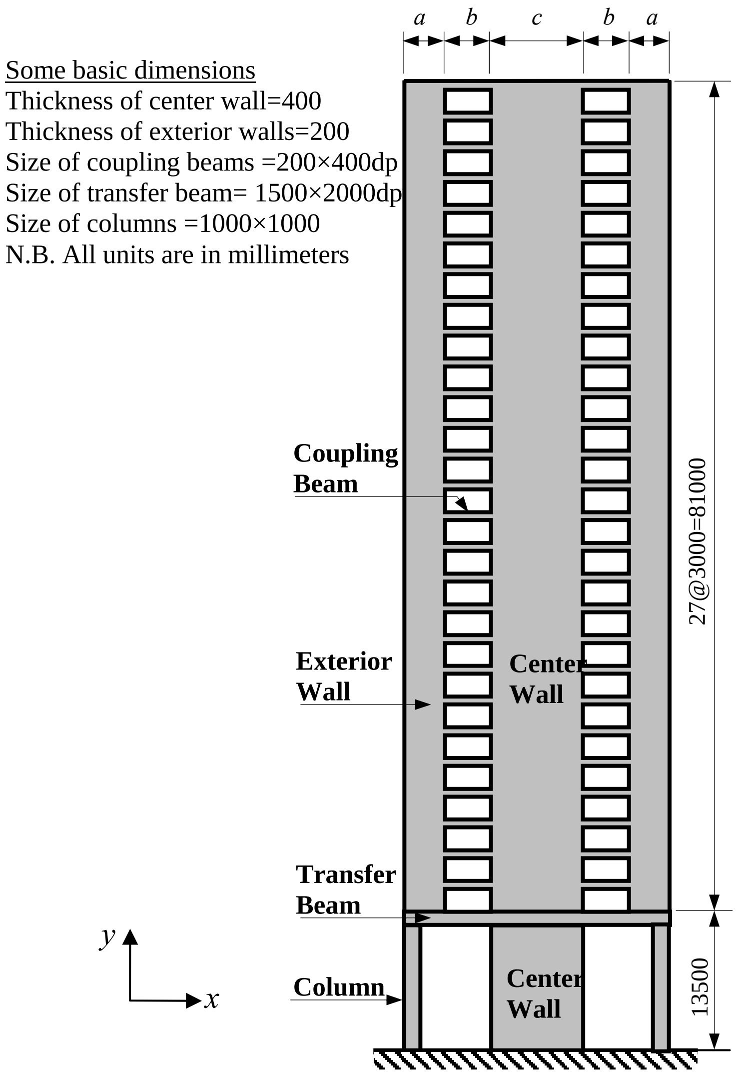

Figure 6. A typical structural arrangement of the numerical model

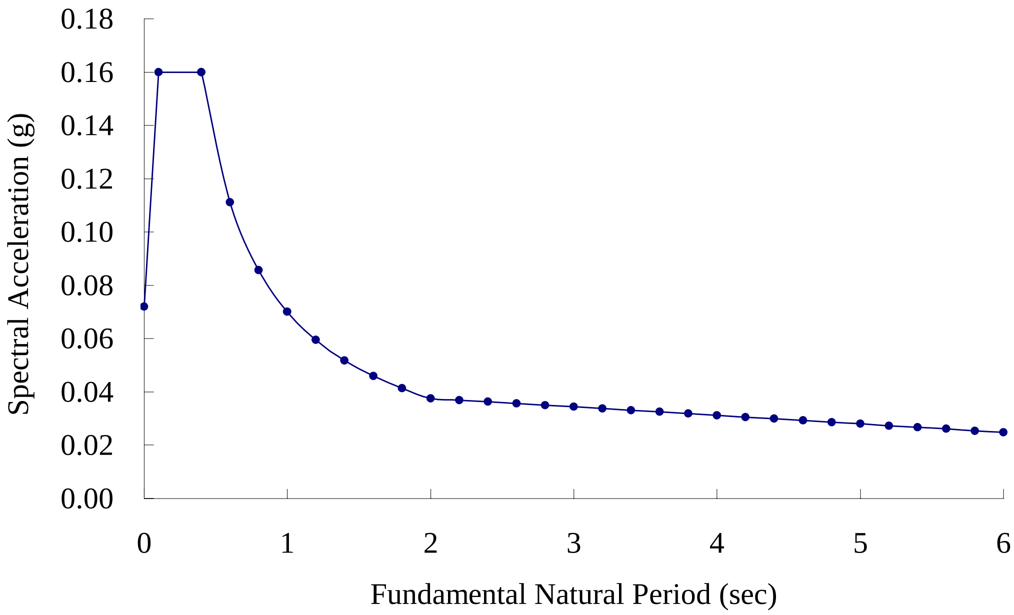

Figure 7. Chinese response spectrum for a moderate earthquake of intensity VII

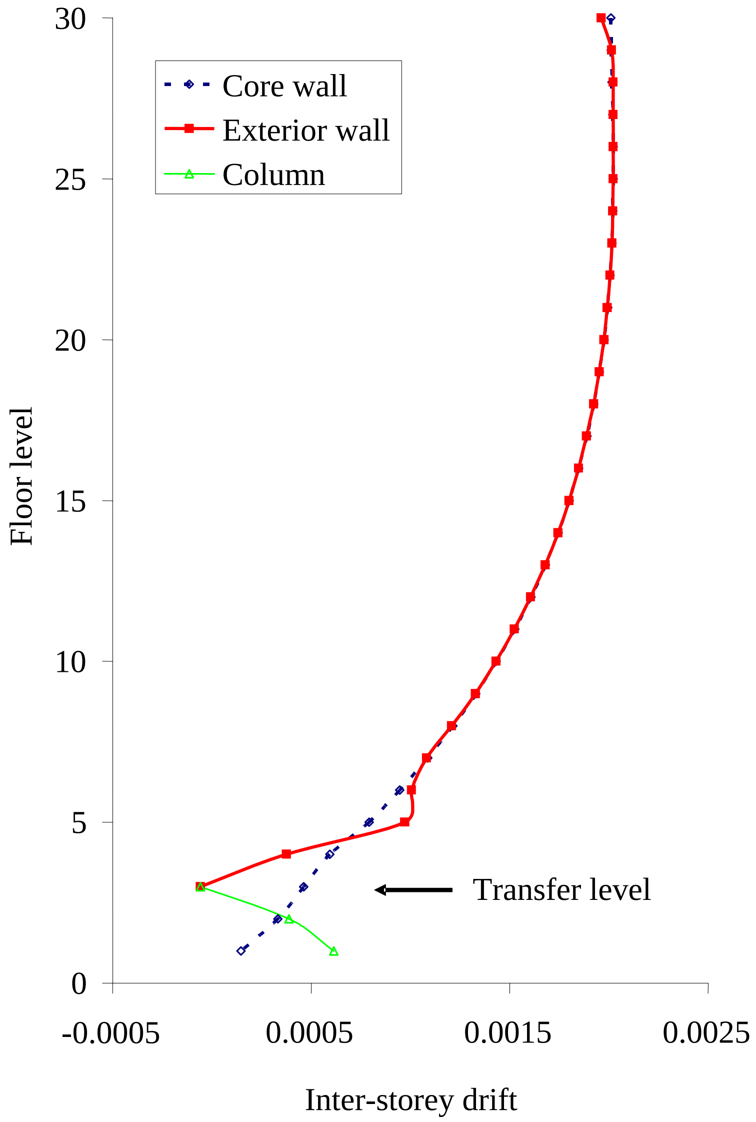

Figure 8. Inter-storey drift in Model A

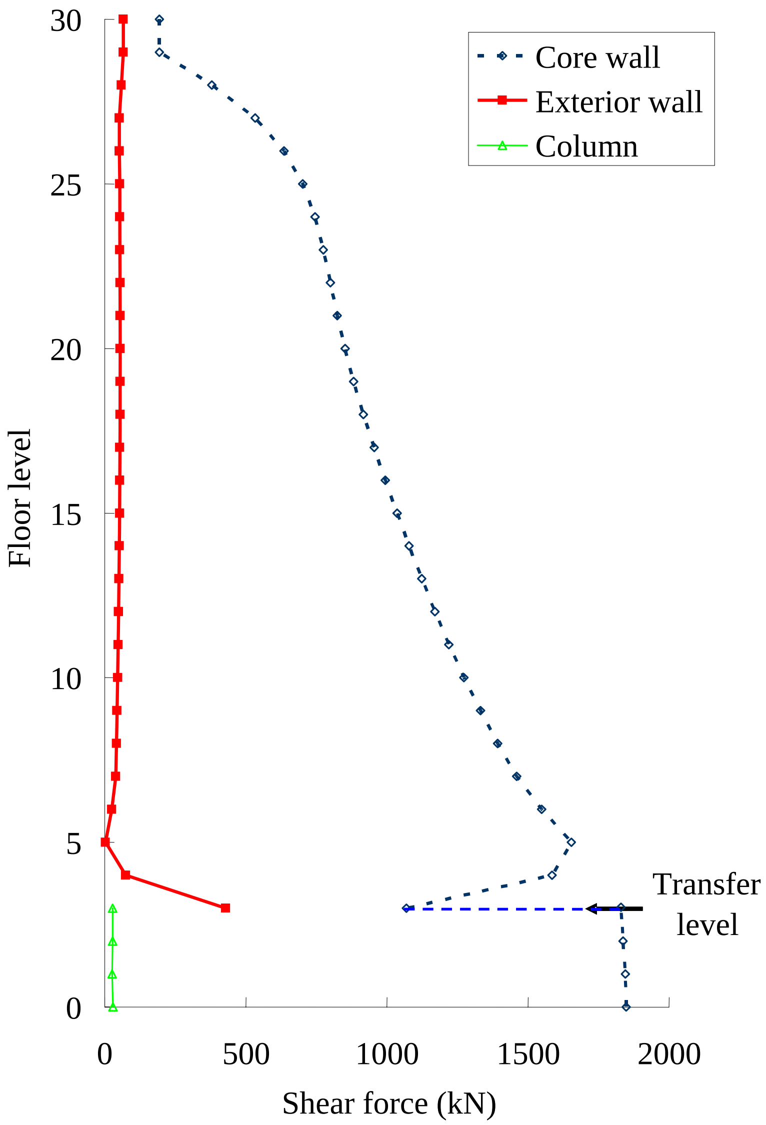

Figure 9. Shear force distribution in Model A

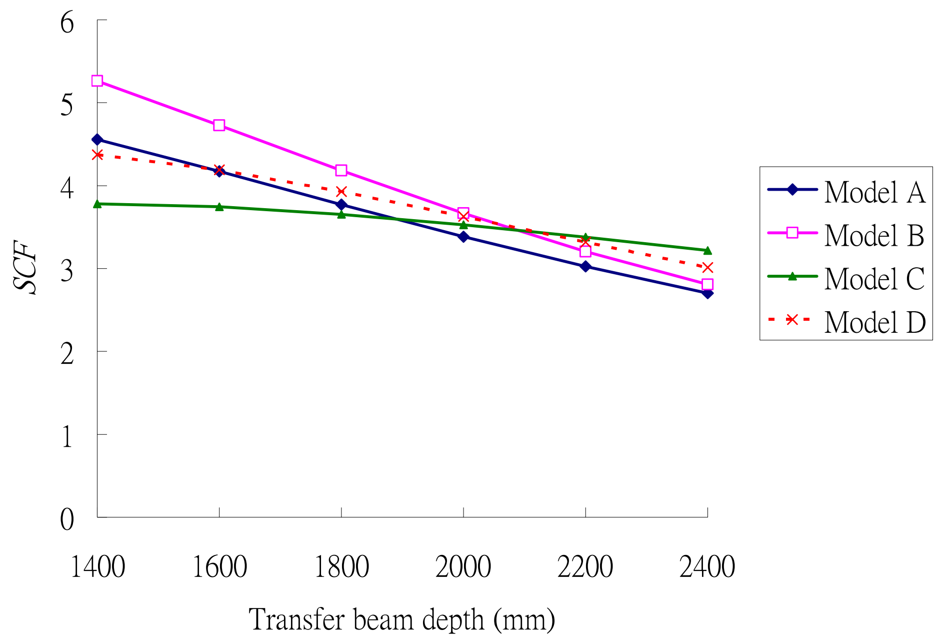

Figure 10. Variation of *SCF* against the depth of transfer beam

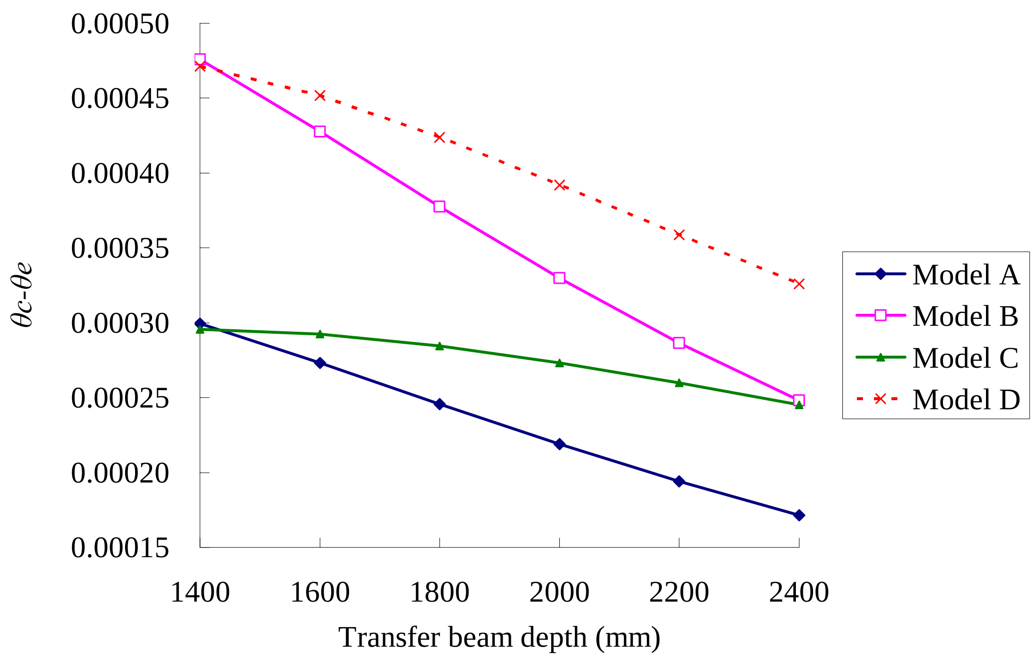

Figure 11. Difference in wall rotations against the depth of transfer beam

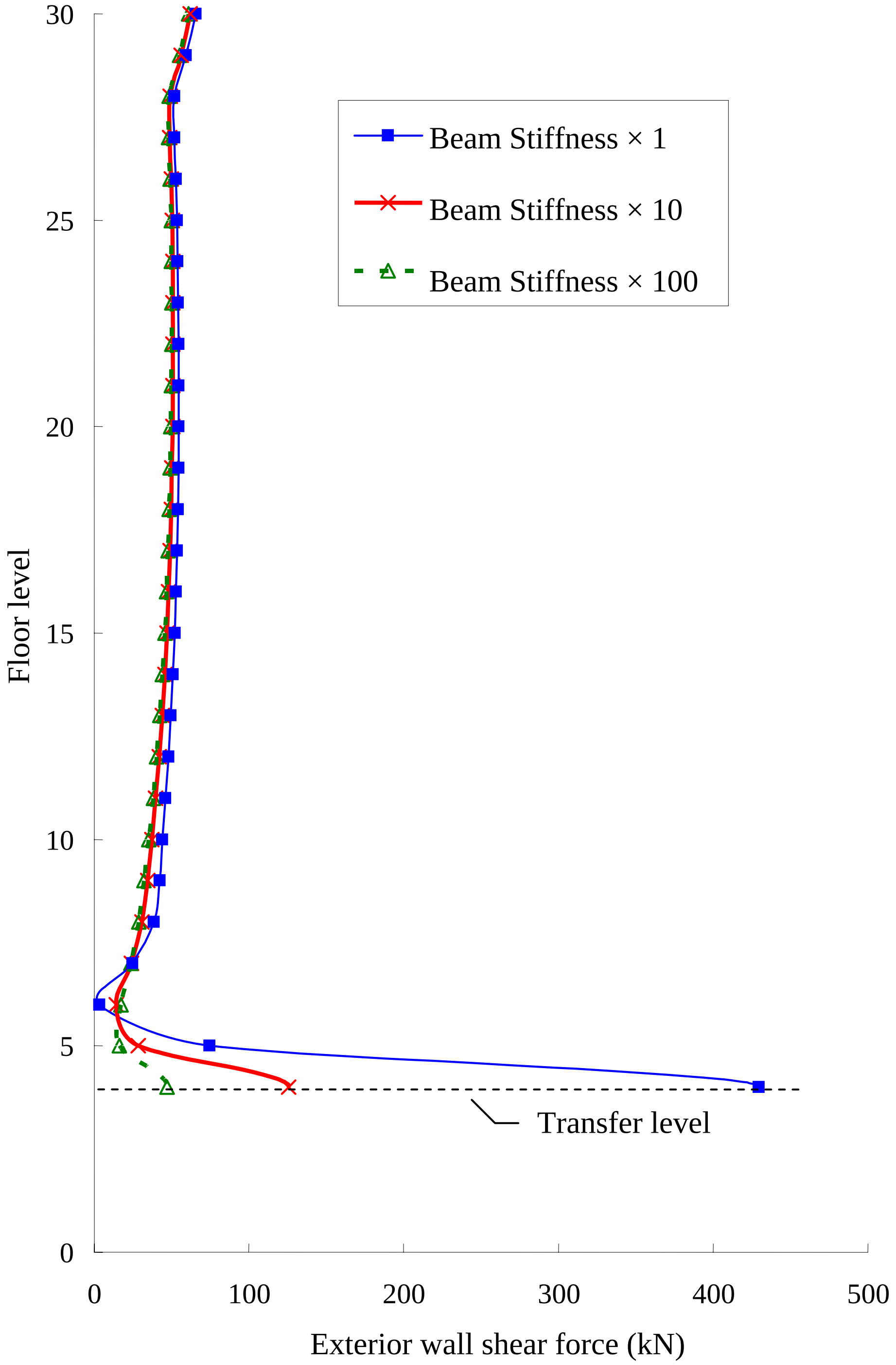

Figure 12. Shear force distributions in the exterior wall of Model A with different stiffness of transfer beams

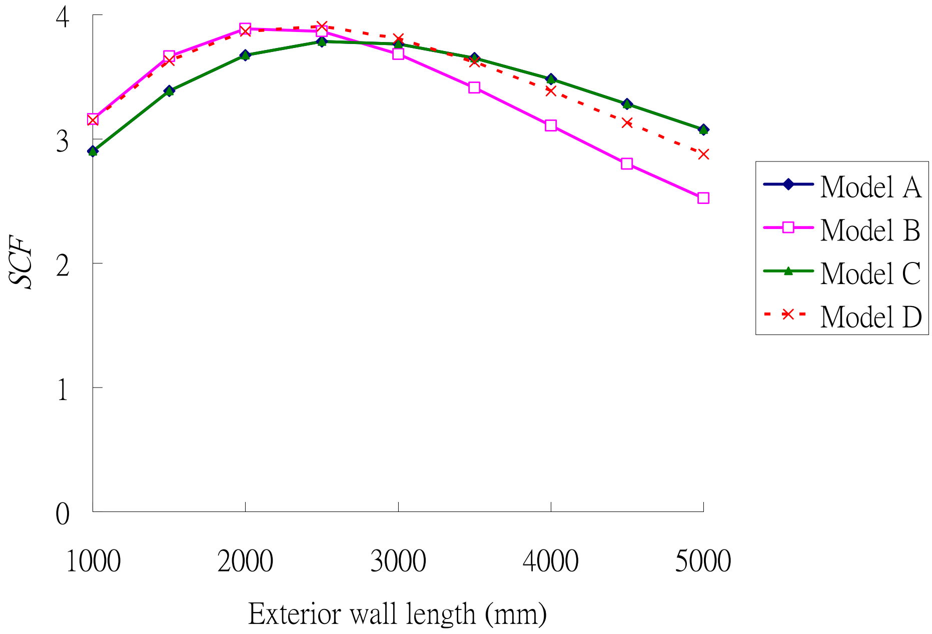

Figure 13. The variations of *SCF* against the length of exterior walls

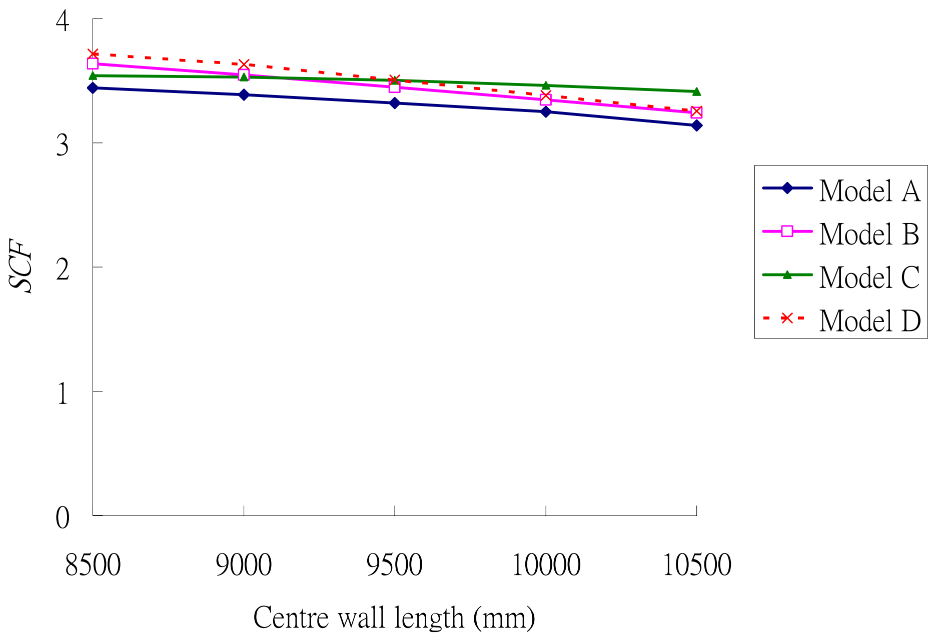

Figure 14. The variations of *SCF* against the length of centre walls

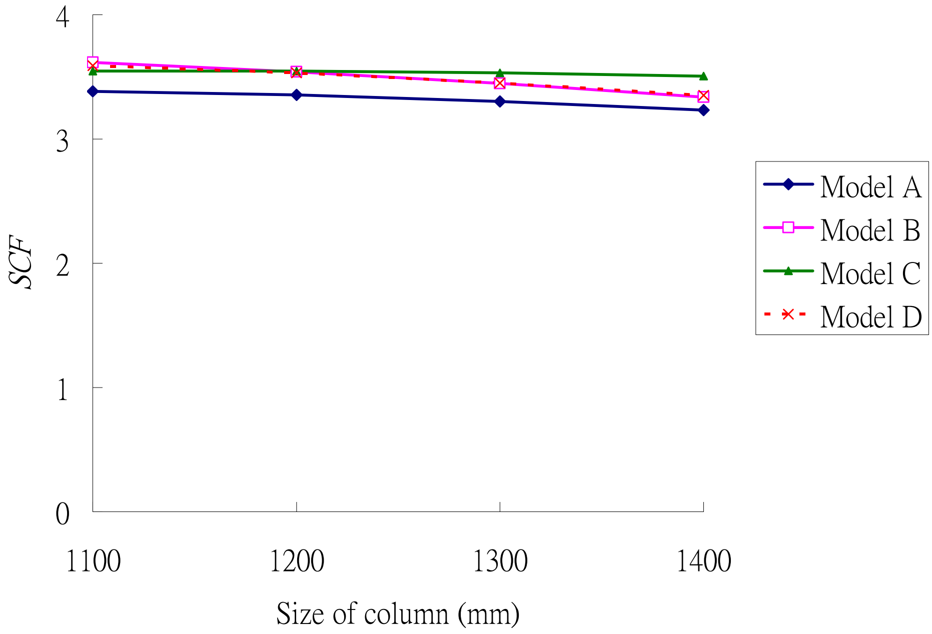

Figure 15. The variations of *SCF* against the size of columns

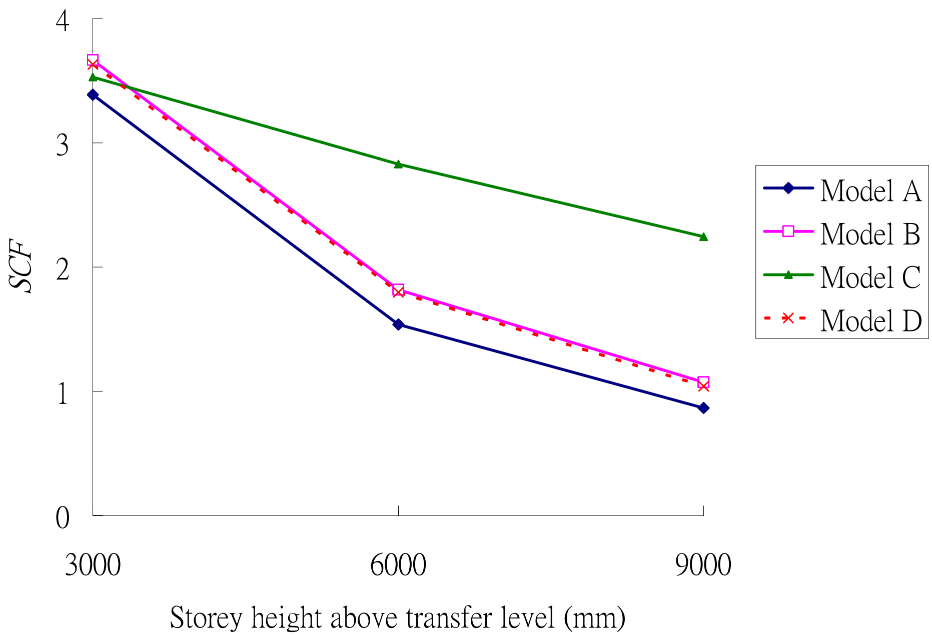

Figure 16. The variations of *SCF* against the storey height above the transfer level

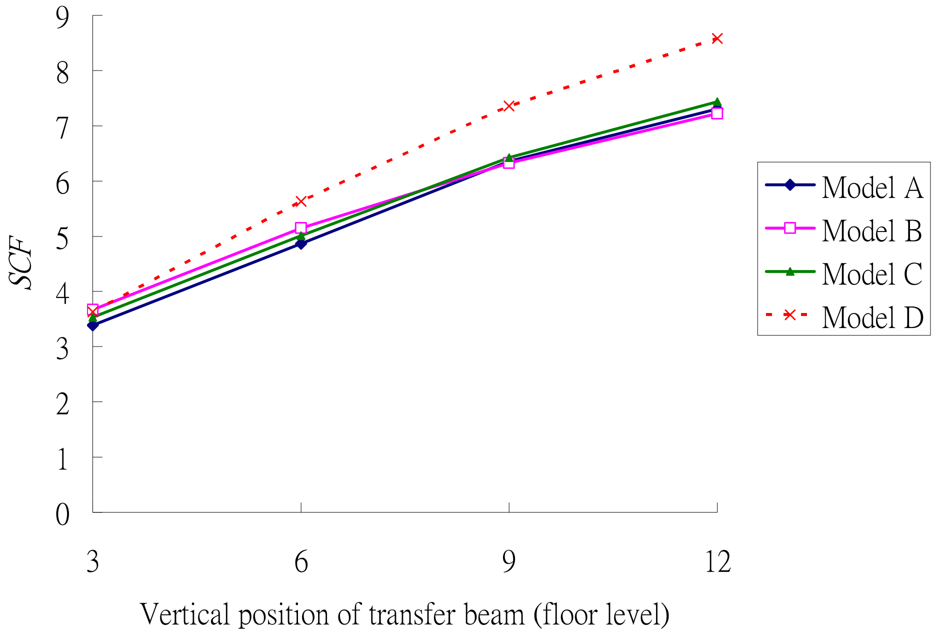

Figure 17. The variations of *SCF* against the vertical position of transfer beam

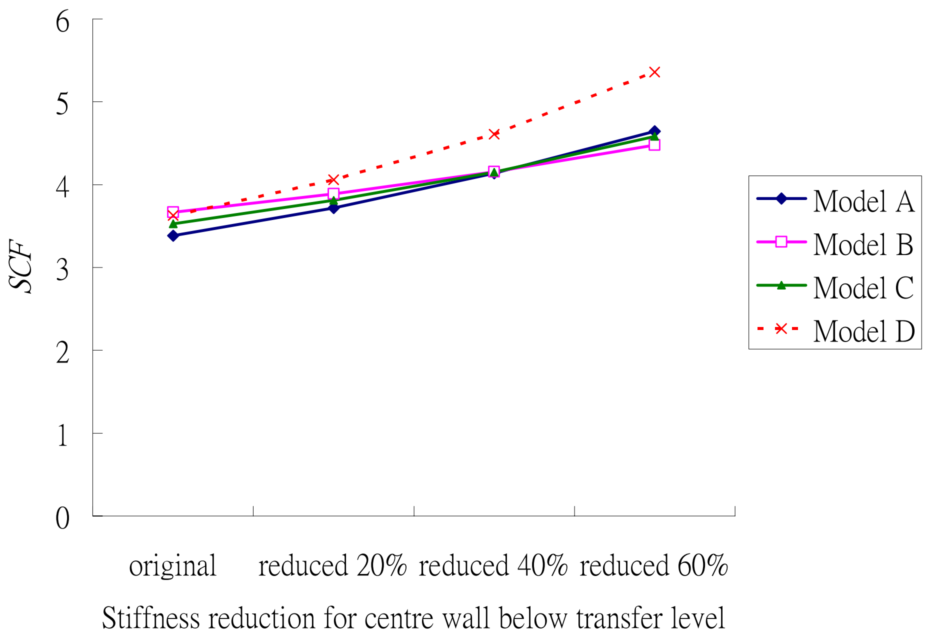

Figure 18. The variations of *SCF* against the reduction of centre wall stiffness