Influence of Local Deformations of Transfer Structures on Seismic Design

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ABSTRACT:

The introduction of transfer structures between the high zone and the low zone of a high-rise building has become popular and sometimes even inevitable in modern building developments. Under earthquake actions, concentrated stresses and large lateral displacement may occur at those locations where stiffness changed significantly either on plan or in elevation. In this study, based on the results of the previous shaking table test and numerical analyses, general seismic behavior of transfer structures is identified. The mechanisms for the formation of soft story below the transfer floors, the abrupt change in inter-story drift in the vicinity of transfer story and shear concentration due to local deformation of transfer structures are summarized. This study can improve the general understanding of the seismic response of concrete buildings with transfer structures in low-to-moderate seismicity regions.

1. INTRODUCTION:

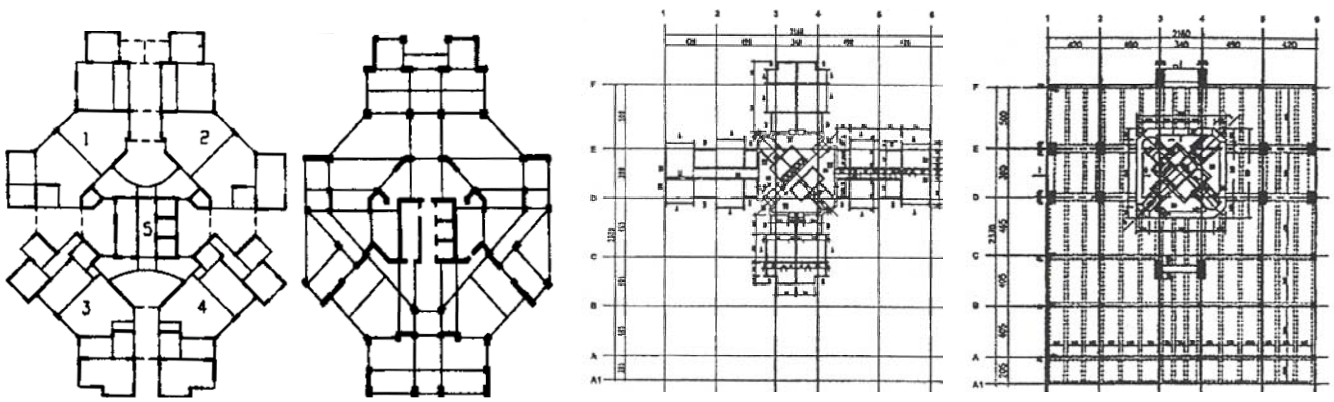
Hong Kong is located in a low-to-moderate seismcity region, however, existing buildings in Hong Kong, following local building design codes, do not provide for seismic resistance. Many modern buildings in Hong Kong have been constructed with various uses and occupancy demands. The lower zones of the buildings are usually used for parking, shopping malls, assembly halls, podium gardens or open spaces for function requirements, while the higher zones generally accommodate apartments or offices. Combined structural systems with moment-resisting frames and core walls in the lower zones together with shear wall systems in higher zones are commonly adopted for these buildings. The use of transfer structures between the high and low zones of a high-rise building has become popular and sometimes even inevitable. Transfer structures can be defined as either flexural or shear structures that transmit heavy loads from columns or walls acting on its top and redistribute them to supporting columns or walls. These transfer structures may be in the form of transfer beams, transfer girders or transfer plates. It is not uncommon for the lateral stiffness of structures above the transfer structure to be significantly greater than that below the transfer structure. For practical usage as well as spatial effects and requirements, transfer structures are usually located about 20 to 30 m above ground level. Under cyclic earthquake loads, concentrated stresses and large lateral displacements (termed soft story) may occur at the transfer plate levels where there are significant structural irregularities either in plan or in elevation. The aims of this study are to (i) review and discuss the findings of some recent shaking table tests, (ii) explain the effects of local deformation of transfer structures on the shear concentrations of walls supported above the transfer structures, and (iii) discuss the effects of rotation of transfer structures under seismic loads on the equivalent lateral stiffness.

2. PREVIOUS EXPERIMENTAL STUDIES OF TRANSFER STRUCTURES

It is well-known that shaking table analyses can investigate not only elastic but also inelastic seismic response and failure mechanism of complex building models. In recent years, many shaking table tests have been conducted in China to study the behavior of buildings with transfer structures under seismic loads. Due to the page limitation, experimental observations of only two most representative shaking table studies (Ye *et al*. 2003 and Li *et al*. 2006) involving transfer structures are summarized in this paper; a more comprehensive review of the experimental studies of building models with transfer structures may be referred to Su (2008). Figure 1

depicts the structural plans above and below the transfer structures of the two studies. Ye *et al*. (2003) used a shaking table test to assess the structural behavior of a 33-story RC residential building located in Guangzhou, China under seismic loads. A series of transfer beams were located in the 4th floor to support the shear walls above. The podium structure below the transfer beams was mainly supported by frame structure. A central core wall was provided above and below the transfer level to achieve lateral stiffness continuity along the height of the building. The length scale of the model was 1:20. Li *et al*. (2006) recently investigated the seismic behavior of a reinforced concrete residential building located in Hong Kong. The building had 34 typical floors above a 2.7m thick transfer plate and a three-level podium. Below the transfer plate, core wall and columns were the major vertical supporting elements, whereas above the transfer plate, the structure changed to shear walls and a core wall supporting system. The length scale of the model was 1:20. Earthquake records of the 1940 EI Centro Earthquake in NS component and/or 1952 Taft earthquake were employed in the tests. All tests assumed the same seismic intensity of VII pursuant to National Standard (2001).
The building models used in the tests was fabricated using microconcrete with steel wires to simulate reinforcement in concrete. As in a real construction, these models were constructed floor-by-floor with microconcrete and steel wires. The similitude laws of length ratio, modulus ratio, equivalent density ratio, time ratio, frequency ratio and acceleration ratio were considered in preparing the model tests. A typical characteristic strength of the microconcrete was 2-3 MPa. Additional mass was required to satisfy the similitude law of equivalent density ratio.

Model by Ye *et al.* (2003) Model by Li *et al.* (2006)



Above the transfer plate Below the transfer plate Above the transfer plate Above the transfer plate

Figure 1. Two studies of shaking table tests involving transfer structures

The shaking table tests indicated that under frequent earthquake attacks, the buildings remained elastic, no cracks were found in the models and the natural frequencies of the models did not decrease. When the models were subjected to occasional (basic design) earthquakes, cracks began to occur at the tops of columns below transfer beams and at the base of 1st floor columns. After rare earthquakes, the models were severely damaged. Tension failure was found on the end shear walls in the vicinity above the transfer plate in study of Li *et al.* (2006). Significant damage to exterior walls and floor slabs occurred above the transfer level (see Figure 2). Furthermore, shear and central core wall structures in the middle and upper floors could be damaged by shear. Floor slabs and beam-wall joints were also cracked in the two models. With strong core walls or shear walls below transfer structures, soft story mechanisms could be avoided, and the frame structures at the podium level had no apparent inelastic deformation.

Damage occurred and both natural frequencies and the damping ratios started to change when the models were subjected to occasional earthquakes. The natural frequencies of the structure in both directions were reduced by 14%. After the rare earthquakes, the responses of the damaged models had considerable inelastic behavior. The natural frequency of the two structural models had decreased by 20-46%.

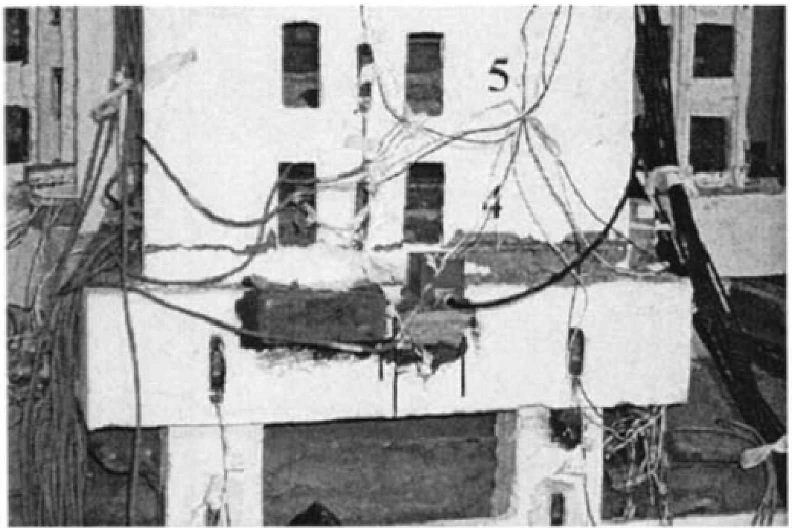


Figure 2. Structural failure on exterior walls at transfer level (Li *et al*., 2006)

3.LOCAL DEFORMATIONS OF TRANSFER STRUCTURES

The shaking table tests as mentioned earlier have revealed that under rare earthquakes, serious damage to shear walls and slabs could occur above transfer structures. Xu *et al*. (2000) conducted an elastic dynamic analysis on a 27-story building with transfer beams at the 7th floor and reported an abrupt change in shear forces of walls above the transfer floor (see Figure 3a). This effect became more acute when the building was subjected to rare earthquakes and the stiffness of the shear walls below the transfer structures was degraded (see Figure 3b). This undesirable shear concentration may be attributed to local deformation of transfer structures.

Transfer structures were usually idealized as deep beams or thick plates. Many engineers and researchers ignore the deformations of transfer structures and adopt rigid plate and rigid diaphragm assumptions in routine structural analyses of buildings with transfer structures. Despite that the flexural stiffness and strength of the transfer structure are much higher than those of the column supports or shear walls of the superstructure above, local flexural deformations of transfer structures do exist and in many cases cannot be ignored (Su 2008). According to the results of a shaking table test on a 12-story building model by the China Academy of Building Research, the actual shear forces in the walls or columns under the transfer structure will be six to eight times greater than those if the transfer structure is assumed to be a rigid diaphragm. Hence, to better predict the interactions between the exterior shear walls, columns and core walls, flexible shell or beam elements instead of rigid floor diaphragms should be used to model transfer structures and slabs in the neighboring floors of the transfer level.

Figure 4 illustrates the detrimental effect of local deformation of a transfer plate on the shear walls supported above. Under earthquake loads, the central core wall deflects as a vertical cantilever. As the plate and core wall are jointed together monolithically, the joint region between the plate and core wall is rotated in a similar manner due to the displacement compatibility. A pair of push-and-pull forces from the columns below the plate causes deflection of the plate. The rotation of the exterior walls θ_{ei} above the transfer plate is therefore different from that of the core wall θ_c, and the difference in rotations (θ_c-θ_{ei}) can be as high as 0.0005 rad. In order to reduce the rotation incompatibility between the core wall and the shear walls above the transfer structure, high in-plane compressive and tensile restraining forces will develop in the slabs just above the transfer floor. These horizontal reactions cause shear force transfer from the core wall to the exterior walls. The effect of transfer floor to the inter-story drift is diminished one to two floors above the transfer structure (Rong & Wang 2004). When the exterior walls take up excessive shear force, shear failure may occur. Likewise, the slabs may also be damaged under high tensile force.

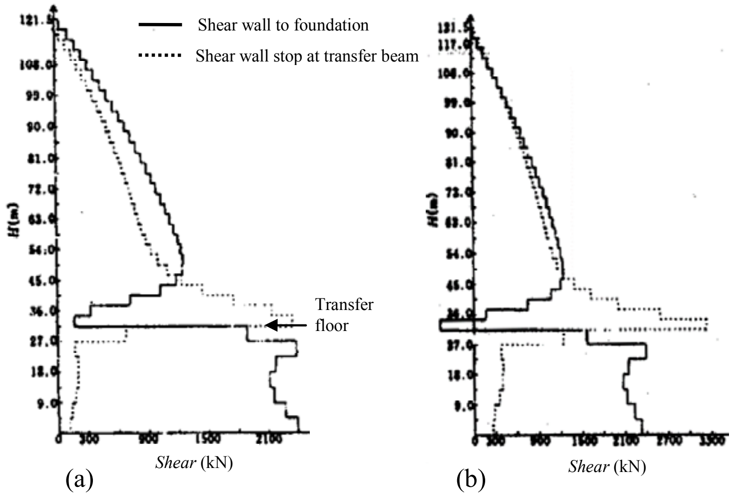


Figure 3. Shear force distributions (a) without stiffness reduction, (b) with 60% stiffness reduction for the shear wall below the transfer floor (Xu et al. 2000)

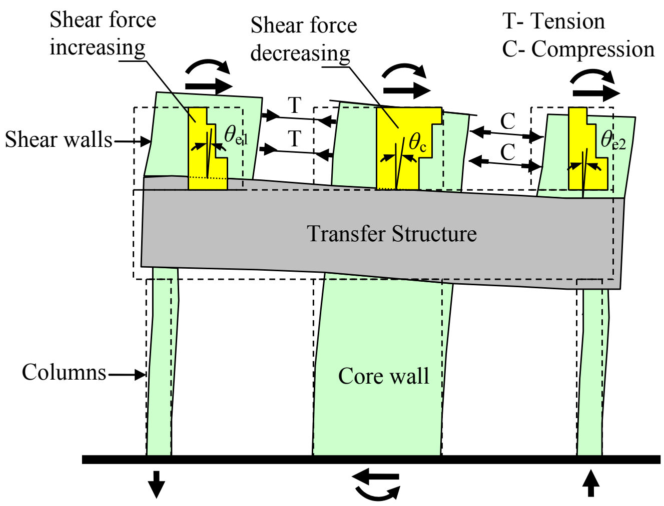


Figure 4. Deformation of transfer structure and shear concentration at the external walls (Su 2008)

To reduce the detrimental effects due to local deformation of transfer structures, the following design principles were suggested by various researchers. First, when the flexural stiffness of exterior shear walls is smaller than that of the transfer structure, a deeper (or stiffer) transfer structure with higher flexural and shear stiffness can help to reduce local deformation of the transfer structure under lateral loads and moderately decrease the abrupt change in shear forces in the exterior walls (Su 2008). The parametric study conducted by Su & Cheng (2008) further revealed that even when a rigid transfer structure was used, shear force concentration in the exterior walls above the transfer structure could still be observed. This demonstrates that the effect of shear concentration is partially due to the intrinsic behavior and interaction of a coupled core wall and shear wall structure on a restraint boundary; this effect cannot be completely eliminated. Second, a stiff core wall below the transfer floor can limit local rotation at the transfer level. By doing so, the inter-story drifts and the difference in rotations between the exterior walls and the core wall can be reduced. The amount of shear force transfer from the core wall to the exterior walls, which is proportional to the difference in rotations, can also be limited. Su & Cheng (2008) pointed out that shear concentration in interior walls is sensitive to an increase of storey height above the transfer level, but is less 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. Furthermore, local rotation of the core wall can be further controlled by arranging the transfer floor located at lower floor (below the 5th floor) so that shear transfer above the transfer structure can be effectively suppressed. Ye *et al.* (2003) reported that providing floor openings above the transfer structure, which could break the essential load path for transferring shear forces, could effectively reduce the shear concentration effect on the shear walls above the transfer structure and hence improve the seismic performance of building.

4.EFFECT OF SOFT STORY BELOW TRANSFER STRUCTURE

Soft story failure is a common failure mechanism for concrete and masonry buildings under earthquake attack. Broadly speaking, a soft story may be associated with a story in which the lateral shear stiffness is much smaller than it is in the neighboring stories. Although not every transfer structure automatically leads to a soft story, many seismic engineers did concern with soft story failure of transfer structures under seismic loads. The definitions of soft story in Chinese codes, which simply compare the elastic lateral stiffness between adjacent levels and ignore the effects of flexural/axial deformation of vertical supporting elements under the transfer structures, may not adequately define an occurrence of a soft story. A thorough discussion on the influence of inelastic deformation of the vertical supporting elements and flexural/axial deformation of vertical supporting elements on the formation of soft story is presented below.

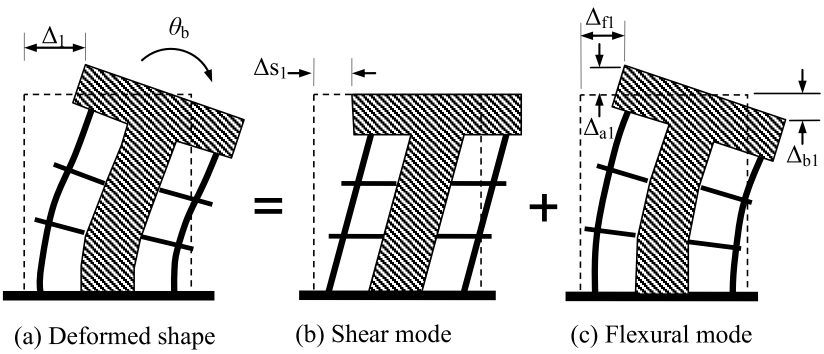


Figure 5. Typical shear and flexural deformations of a substructure below a transfer structure (Su 2008)

Under a seismic attack, a soft story will attract much higher lateral deformations, and in many cases, high torsional deformations. The excessive inter-story drift and the P-delta effect arising from gravity loads may cause plastic hinges to form at the ends of vertical structural elements. If the elements are not ductile enough, failure of individual vertical supports will trigger progressive collapse of the whole story. Since lateral flexural and shear stiffnesses often change abruptly near transfer structures, it is essential to prevent the formation of soft stories in buildings with transfer structures. Typical lateral deformations below a transfer structure can be separated into shear mode and flexural mode (Su 2008), as shown in Figure 5. Obviously, the lateral deformation of the transfer structure is the sum of shear deformation Δ_{s1} and flexural deformation Δ_{f1}; i.e.,

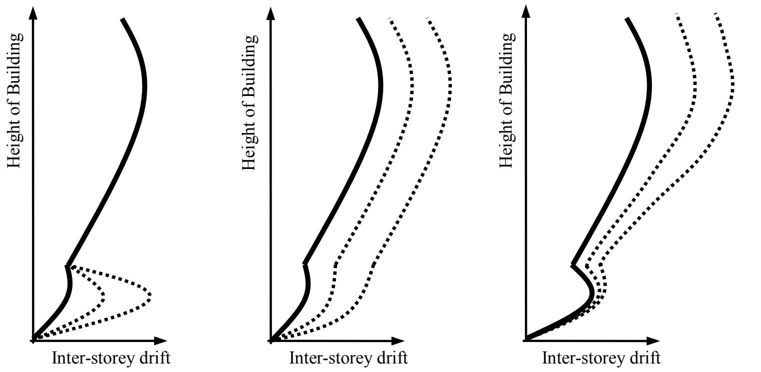
$$\Delta_1 = \Delta_{s1} + \Delta_{f1} \tag{1}$$

The rotation of the transfer structure may be conveniently expressed as:

$$\theta_b = (\Delta_{a1} + \Delta_{b1})/B_1 \tag{2}$$

where Δ_{a1} and Δ_{b1} are the vertical movements at the left and right edges of the transfer structure and B_1 is the width of the substructure below the transfer structure.

Changes in the shear and flexural stiffnesses of the substructures above and below the transfer structure affect the lateral deflection and inter-story drift. Various researchers (Su et al. 2002, Rong et al. 2004, Chen & Fu 2004, Li 2004, Huang & Lu 2003, and Geng & Xu 2002) have studied the effects of changes in lateral stiffness of substructures above and below a transfer structure on the seismic response of buildings. Typical variations in inter-story drift of a multi-story building due to changes in stiffness of substructures were summarized by Su (2008) and are reproduced in Figure 6. From the figure, it is clear that an abrupt change in the inter-story below the transfer structure will be more severe when (i) lateral shear stiffness below the transfer structure is small (Figure 6a), (ii) lateral flexural stiffness below the transfer structure is high (Figure 6b) and (iii) lateral flexural and shear stiffness above the transfer structure are high (Figure 6c).



(a) Decreasing the shear stiffness below the transfer structure

(b) Decreasing the flexural stiffness below the transfer structure

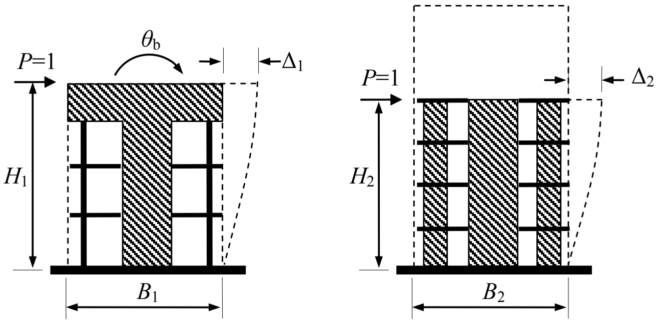
(c) Decreasing the flexural and shear stiffness above the transfer structure

Figure 6. Variations of inter-story drifts due to change in shear and flexural stiffnesses (the dotted lines represent the new inter-story drift profiles after stiffness reductions) (Su 2008)

Despite the importance of flexural stiffness below the transfer structure for controlling the soft story effect, National Specification (2002) and Geng & Xu (2002) only considered the lateral shear stiffness below and above the transfer structure and required the equivalent lateral stiffness ratio $\gamma_e \leq 1.3$ for seismically resistant structures. The concept of equivalent lateral stiffness ratio used in National Specification (2002) was proposed to modify (Su 2008) to take into account the effect of rotation of the structure above the transfer floor due to the flexural rotation θ_b below the transfer structure (see Figure 7) and the inelastic response of structures under a rare earthquake attack. The modified equivalent stiffness ratio was expressed as:

$$\gamma_e' = \frac{\varphi_1\left(\dfrac{\Delta_1}{H_1}\right)}{\varphi_2\left(\dfrac{\Delta_2}{H_2}\right) + \varphi_1\theta_b} \leq 1.3 \tag{3}$$

where φ_1 and φ_2 are the displacement magnification factors due to stiffness degradation for the substructures below and above the transfer structure, which may be taken as $\varphi_1 = 2$ and $\varphi_2 = 1.5$ based on the results from shaking table analyses. This equation naturally reflects the fact that when the lateral drift angle due to flexure ($\varphi_1\theta_b$) is larger than that due to shear ($\varphi_1\left(\dfrac{\Delta_1}{H_1}\right)$), the soft story phenomenon vanishes. In this case, Equation (3) represents a less stringent requirement than that from National Specification (2002). The proposed equation incorporates flexural deformation below the transfer structure, the inelastic response of structures is considered to be more appropriate to define a soft story for buildings with transfer structures. However, further numerical or experimental studies and justifications are required to validate the effectiveness of this equation for controlling the occurrence of soft stories in elastic and inelastic stages.



(a) Model 1- substructure below the transfer structure

(b) Model 2- substructure above the transfer structure

Figure 7. Numerical models for calculating the equivalent stiffness below and above the transfer structure with consideration of the rotation above the transfer structure (Su 2008)

5.CONCLUSIONS

The major findings related to seismic design of transfer structures are summarized as follows:

(1) Shaking table tests indicate that under frequent earthquake attacks, all the buildings with transfer structures remained elastic, no cracks were found in the models and the natural frequencies of the models did not decrease. When the models were subjected to rare earthquakes, extensive cracks occurred in the vicinity of the transfer structure and the models were severely damaged. The natural frequency of the structures decreased by at most 46% and the damping ratio was increased to 4.5-7.5%.
(2) Local flexural deformation of transfer structures was identified as the origin of shear concentration at exterior walls above the transfer floor. A set of measures have been summarized for minimizing the detrimental effect of shear concentration.
(3) To better predict the interaction between exterior shear walls and other structural components, flexible shell or three-dimensional solid elements should be used to model the transfer structures and slabs in the neighboring floors of the transfer level.
(4) The equivalent lateral stiffness ratio might be modified to take into account flexural deformation below transfer structures and inelastic deformation under rare earthquakes. Further studies are suggested to validate the effectiveness of the proposal for controlling transfer structures undergoing soft-story type of failure.

6.ACKNOWLEDGEMENTS

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