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Seismic Behaviour of Buildings with Transfer Structures in Low-to-Moderate Seismicity Regions

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ABSTRACT: A literature review has been conducted aimed at improving the general understanding of the seismic response of concrete buildings with transfer structures in low-to-moderate seismicity regions. This paper summarizes and discusses the existing codified requirements for transfer structure design under seismic conditions. Based on the previous shaking table test results and numerical findings, the seismic effects on the inelastic behaviours of transfer structures are investigated. The mechanisms for the formation of a soft storey below transfer floors, the abrupt change in inter-storey drift near transfer storeys and shear concentration due to local deformation of transfer structures are developed. Design principles have been established for controlling soft-storey type failure and minimizing shear concentration in exterior walls supported by transfer structures. The influence of the vertical positioning of transfer floors on the seismic response of buildings has also been reviewed.

KEYWORDS: Transfer structures, soft storey, shear concentration, equivalent lateral stiffness

1 INTRODUCTION

Due to mountainous topography within the territory, modern developments in Hong Kong have constructed many buildings 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 (see Figure 1).

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. One of the major characteristics of buildings with transfer structures is that the spacing of vertical supporting elements above a transfer structure (typical floor) is comparatively closer than below it (podium) for easy and flexible architectural planning purposes. It is not uncommon for the lateral stiffness of structures above the transfer structure to be significantly greater than that below the transfer structure. Moreover, for practical usage as well as spatial effects and requirements, transfer structures are usually located about 20 to 30 m above ground level so that the lateral stiffness ratio of structures above and below the structures is further increased.

Figure 1. Combined structural system with transfer plate

Hong Kong is located in a low-to-moderate seismicity region. The peak ground earthquake acceleration of Hong Kong, which ranges from 0.1 to 0.15 g over a 475-year return period (according to GB18306 2001), is well within the typical limit of 0.05 to 0.25 g for low-to-moderate regions. However, existing buildings in Hong Kong, following local building design codes, do not provide for seismic resistance. Under cyclic earthquake loads, concentrated stresses and large lateral displacements (termed soft storeys) may occur at locations where there are significant structural irregularities either in plan or in elevation. These irregularities include asymmetrical building shapes, building set-backs, large building openings, staggered floor levels, and building weight irregularities, as well as uneven or abrupt changes in structural stiffness. The aims of this paper are to (i) review the definitions of structural irregularity in relation to abrupt changes in lateral stiffness along building height by the adoption of transfer structures, (ii) highlight and discuss the findings of some recent shaking table tests, (iii) explain the effects of local deformation of transfer structures on the shear concentrations of walls supported above the transfer structures, and (iv) discuss the effects of rotation of transfer structures under seismic loads on the equivalent lateral stiffness.

2 EFFECT OF THE EARTHQUAKE SPECTRUM

According to the Chinese National Standard (2001), the use of transfer structures in concrete buildings is allowed only in low-to-moderate seismic zones (maximum seismic intensity of VII). Ground motions of minor (frequent), moderate (occasional) and major (rare) earthquakes based on 63%, 10% and 2% probabilities of exceedence in a 50-year return period are adopted in the standard; the corresponding return period, peak ground acceleration and peak spectral acceleration (PSA) are listed in Table 1.

Table 1. PGA and PSA of earthquake intensity VII (site II)

Earthquake intensity	Return period	PGA	PSA
Minor	50 years	0.055g	0.120g
Moderate	475 years	0.150g	0.330g
Major	2475 years	0.310g	0.720g

Of all earthquake records, the 1940 EI Centro (NS component) and the 1952 Taft earthquakes (N21E component) have been widely adopted in China for various earthquake simulations (Zhang *et al.* 2000, Xu *et al.* 2000, Geng & Xu 2002, Zhang *et al.* 2003, Gao *et al.* 2003, Rong & Wang 2004, Rong *et al.* 2004) and shaking table tests (Zhao & Hao 1996, Huang *et al.* 2004, Ye *et al.* 2003, Li *et al.* 2006). Both seismic events belong to near field strong motion events with earthquake magnitude between 6.9 and 7.7 on the Richter scale. The near field event is characterised by abundant high frequency content. As the array stations for recording these earthquake histories were located above alluvium sites, the seismic waves measured were significantly amplified due to the soft soil site effect, in particular in the long period range (T>2 sec). Figures 2 and 3 present the spectra of the EI Centro and Taft earthquakes, adjusted such that the peak ground acceleration is equal to 0.31 g and is consistent with the rare earthquake events of intensity VII (site II) specified in the National Standard (2001).

When a near field earthquake acts on a deep soil site, such as the 1940 El Centro earthquake, the seismic waves are substantially amplified in the long period range (T>2 sec) due to the soil site effect; the response spectral displacement increases almost linearly with respect to the natural period of the structure. The increasing displacement demand due to the period lengthening effect accelerates the degradation of buildings. As the displacement demand in the long period range can be much higher than 250 mm, which a soft-storey building cannot tolerate, engineers in high seismicity conditions normally aim to prevent strength degradation (or else the building could collapse). In contrast, in relatively low seismicity regions such as Hong Kong, designers can allow some degradation without building collapse. Shaking table analyses (Huang *et al.* 2004, Ye *et al.* 2003 and Li *et al.* 2006) show that the natural period and lateral displacement demand of damaged buildings after a rare earthquake may be doubled compared with intact buildings. The substantial increase in displacement demand would significantly amplify the soft storey effect. In a rare earthquake, buildings would deform inelastically, and the displacement demands for the structures below and above the transfer structure need to be magnified by approximately 2 and 1.5 times, respectively.

On the contrary, Hong Kong is situated in the coastal region of south China and is a few hundred kilometres from the nearest active faults. Hence, Hong Kong is unlikely to be threatened by near field strong earthquakes. However, risks from far field earthquakes cannot be neglected. Due to a shortage of land, a significant portion of land has been gained by reclamation. Such reclaimed lands generally comprise fill over a variety of substrates, including marine deposits, alluvium, completely decomposed granite, moderately decomposed granite or slightly decomposed granite (Chandler & Su 2000). The two most adverse soil sites in Hong Kong with a soft soil depth of 45 m at Tsuen Kwan O Site and 77 m at Central Site were adopted to generate seismic response spectra by the uniform hazard method (Tsang 2006). Comparisons of acceleration and displacement response spectra for the El Centro and Taft earthquakes and uniform hazard spectra are presented in Figures 2 and 3 respectively. The earthquake-induced accelerations and displacements from the El Centro and Taft earthquakes, which combine the effects of strong near field earthquakes and soil site amplification, are considerably higher than those from the simulated spectra of Hong Kong. The use of these earthquake records in seismic analyses of buildings in Hong Kong can cause over-conservative predictions of seismic responses.

Based on the site-specific response spectral displacement for the Hong Kong region, the maximum response spectral displacement (RSD) of a rare earthquake event was around 140 mm in the most unfavourable soil site (Tsang 2006). This value would be constant for a fundamental structural period (T) over 1.7 sec (see Figure 3). As the maximum response spectral displacement is saturated and will not increase with the natural period for T>1.7 sec, the inelastic displacement demand and soft storey effect determined with Hong Kong site-specific spectra (Figure 2) are less pronounced than those due to a strong near field earthquake on a deep soil site such as the El Centro record, which is widely used by other researchers or engineers. It is therefore not necessary to account for the increase in seismic displacement demand when the fundamental periods of buildings are higher than 1.7 sec (equivalent to a building taller than 100 m, Su *et al*. 2003).

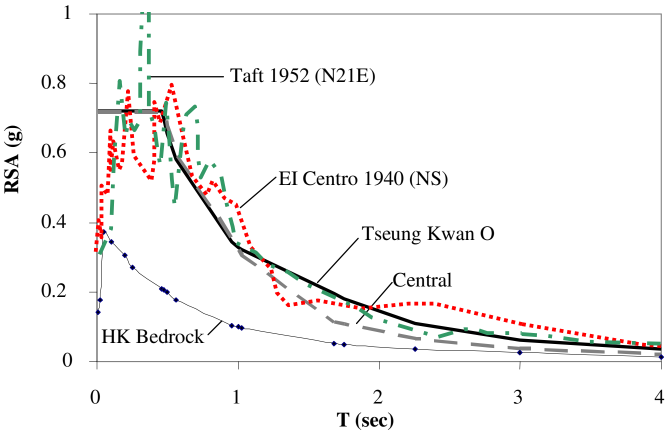


Figure 2. Response spectral accelerations with a 2% exceedance in 50 years (damping ratio=5%)

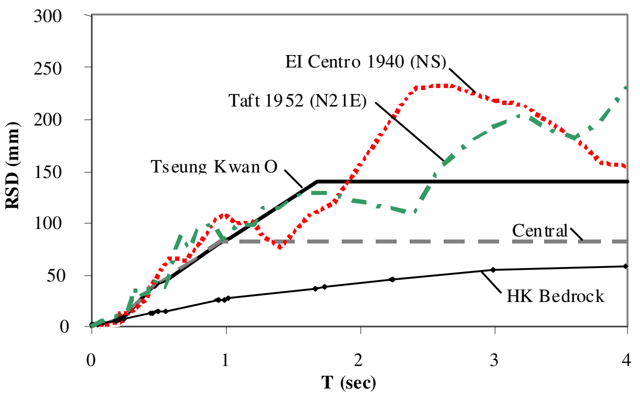


Figure 3. Response spectral displacements with a 2% exceedance in 50 years (damping ratio=5%)

3 EXPERIMENTAL STUDIES OF TRANSFER STRUCTURES

In the recent years, shaking table tests have been conducted to study the behaviour of buildings with transfer structures under seismic loads (Zhao & Hao 1996, Ye *et al*. 2003, Huang *et al*. 2004, Li *et al*. 2006 and Wu *et al*. 2007). Most of the building models used in the tests, except that from Wu *et al*. (2007), were fabricated using microconcrete with steel wires to simulate reinforcement in concrete.

Fabrication of delicate scaled models is complicated and time consuming. As in a real construction, the 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 fully considered in preparing the model tests. A typical characteristic strength of the microconcrete was 2-3 MPa. Additional mass was often required to satisfy the similitude law of equivalent density ratio. Four shaking table test case studies involving transfer structures are described herein; the corresponding structural plans above and below the transfer structures are depicted in Figure 4.

Case Study 1

Zhao & Hao (1996) studied a 68-storey commercial building; their work was later cited by Xu *et al.* (2000). The building is situated in Nanjing and has two transfer structures located in the 6th and 38th floors of the building. From ground level to the 6th floor, the building structure has a central core wall with a peripheral frame. From the 6th to 38th floors, there are core wall, peripheral frames and shear walls, whereas above the 38th floor, it is a pure shear wall structure. The scaled model used was 1:35.

Case Study 2

Ye *et al*. (2003) used a shaking table test to assess the structural behaviour of a 33-storey RC residential building located in Guangzhou, China under seismic loads. A series of transfer beams are located in the 4th floor to support the shear walls above. The podium structure below the transfer beams is mainly supported by frame structure. A central core wall is provided above and below the transfer level to achieve lateral stiffness continuity along the height of the building. The length scale of the model is 1:20.

Case Study 3

Huang *et al.* (2004) conducted a shaking table analysis for a high-rise building with a transfer floor located at a high level. The building is located in Shenzhen, China and has 28 storeys with a transfer beam structure at the 9th floor. The scaled model was designed to 1:25.

Case Study 4

Li *et al.* (2006) recently investigated the seismic behaviour of a reinforced concrete residential building located in Hong Kong. The building has 34 typical floors above a 2.7 m thick transfer plate and a three-level podium. Below the transfer plate, core wall and columns are the major vertical supporting elements, whereas above the transfer plate, the structure changes to shear walls and a core wall supporting system. The length scale of the model is 1:20.

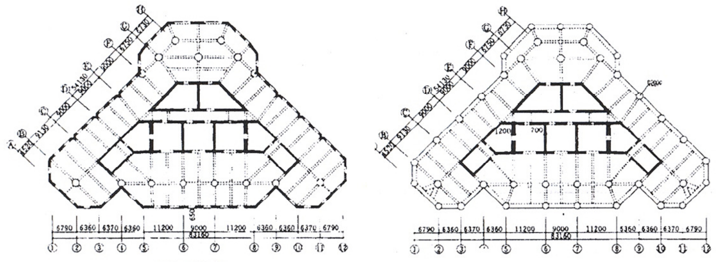
Earthquake records of the 1940 El Centro Earthquake in NS component and/or 1952 Taft earthquake were employed in the tests. All tests assumed the same seismic intensity of VII pursuant to National Standard (2001). There were only minor differences in the peak ground accelerations (g) of the prototypes (see Table 2).

Table 2. Peak ground accelerations of the prototypes adopted in shaking table tests

Earthquake Intensity	Ye *et al.* (2003)	Huang *et al.* (2004)	Li *et al.* (2006)
Minor	0.02-0.03g	0.035-0.04g	0.02-0.06g
Moderate	0.07-0.16g	0.07-0.12g	0.08-0.14g
Major	0.12-0.30g	0.16g	0.15-0.34g

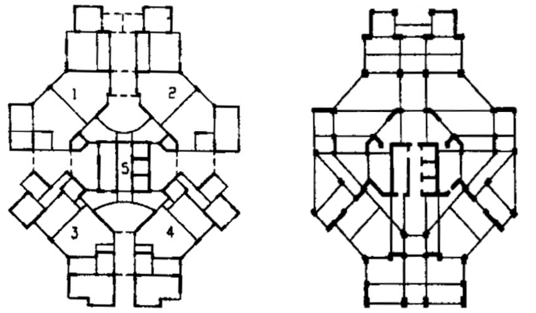
The shaking table tests indicated that under frequent (minor) earthquake attacks, all the buildings remained elastic, no cracks were found in the models and the natural frequencies of the models did not decrease. When the models were subjected to occasional (moderate) earthquakes, cracks began to occur at the tops of columns below transfer beams and at the base of 1st floor columns. After rare (major) earthquakes, all the models were severely damaged. Serious damage was found in the peripheral shear walls above the transfer floor (in cases 1 and 3).

Case 1: by Xu *et al.* 2000


Above the transfer structure

Below the transfer structure

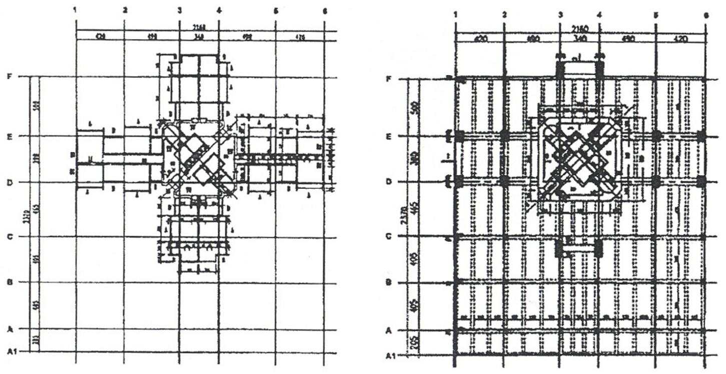
Case 2: by Ye *et al.* 2003



Above the transfer plate

Below the transfer plate

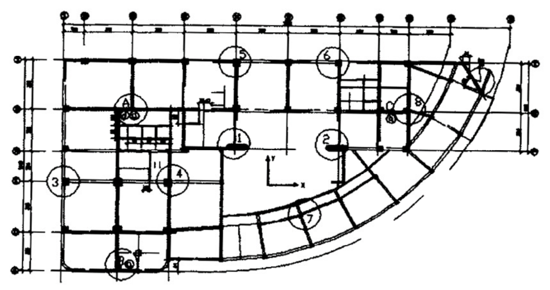
Case 4: by Li *et al.* 2006



Above the transfer plate

Below the transfer plate

Case 3: by Huang *et al.* 2004



Podium structure

Figure 4. Four case studies of shaking table tests involving transfer structures

Tension failure was found on the end shear walls in the vicinity above the transfer plate (in case 4). 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 cases 2 and 4). A weak floor formed at the floor above the transfer structure in case 3.

However, the seismic behaviour of the structures below transfer floor can vary significantly. With strong core walls or shear walls below transfer structures, soft storey mechanisms could be avoided in cases 2 and 4, and the frame structures at the podium level had no apparent inelastic deformation. However, in case 1, the shear wall structure above the transfer floor was supported by a peripheral frame that was relatively weak in lateral and torsional stiffness; extensive cracks were found in the peripheral frame below the transfer floor. However, only minor cracks were observed in the core walls just above and below the transfer floor.

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 different directions dropped by 10 to 20% in case 3 and that in both directions was reduced by 14% in cases 2 and 4. After the rare earthquakes, the responses of the damaged models had considerable inelastic behaviour. The natural frequency of the structures decreased by 20-46% in cases 2 to 4. The damping ratio was increased from 2% after frequent earthquakes to 4.5-7.5% after a rare earthquake, as demonstrated in case 3.

3D computer models were constructed to compare with the results obtained from the shaking table tests. Ye *et al.* (2003) performed a 3D elastic analysis of the model (shown in case 3 of Figure 4) and reported that the difference in natural frequencies of the first and second modes between the tests and the computer models were within 10% for frequent earthquakes. They observed that the ratios of maximum acceleration responses at the top floor to peak ground accelerations were 2.60 for the EI Centro and 2.34 for Taft, whereas the corresponding ratios of the computer results were 2.56 and 2.37, respectively. The displacements of the top floor obtained from the tests and the computer results under different seismic intensities were all within 3 to 7%. Huang *et al.* (2004) and Wu *et al.* (2007) used the SAP2000 program to construct 3D computer models to compare the structural responses of buildings with transfer structures under frequent earthquake loads. The comparisons showed that the test and the computer results of accelerations and inter-storey drift ratios of bare frame models were similar, and the results generally agreed with each other for the first few vibration modes. Although their numerical studies could satisfactorily reflect the real dynamic response of buildings under frequent earthquakes, seismic responses of buildings under rare earthquakes could not be accurately simulated as the effects of stiffness and strength degradations of concrete elements were not considered.

4 LOCAL DEFORMATIONS OF TRANSFER STRUCTURES

Transfer structures were usually idealized as deep beams or thick plates. Normally, 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. Many engineers and researchers (Zhang *et al.* 2003 and 2005) ignore the deformations of transfer structures and adopt rigid plate and rigid diaphragm assumptions in routine structural analyses of buildings with transfer structures. However, local flexural rotations of transfer structures as illustrated in Figure 5 do exist and in many cases cannot be ignored.

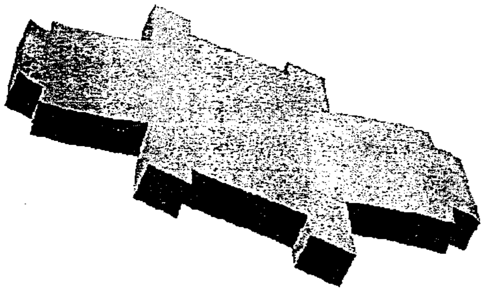
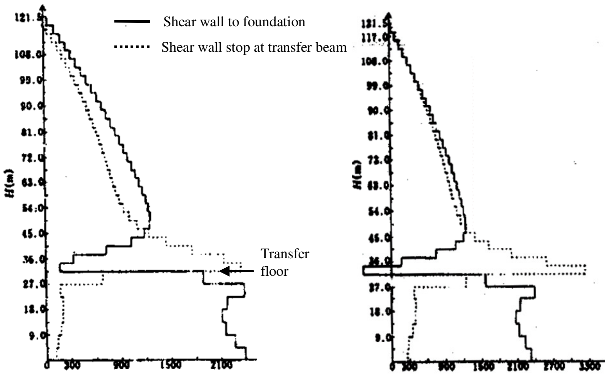


Figure 5. Local deformation of a transfer plate under lateral load (after Li 2005)



(a) (b)

Figure 6. Shear force distributions (a) without stiffness reduction, (b) with 60% stiffness reduction for the shear wall below the transfer floor

Extensive 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-storey building with transfer beams at the 7th floor and reported an abrupt change in shear forces of walls above the transfer floor (see Figure 6a). 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 6b). This undesirable shear concentration may be attributed to local deformation of transfer structures. According to the results of a shaking table test on a 12-storey building model by the China Academy of Building Research (subsequently cited by the technical specification JGJ 3 – 2002 and the numerical analysis of a 29-storey building conducted by Wu *et al.*, 2007), 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 neighbouring floors of the transfer level.

Figure 7 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-storey 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.

To reduce the detrimental effects due to local deformation of transfer structures, the following design principles are suggested. 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 reduce local deformation of the transfer structure under lateral loads and thus decrease the abrupt change in shear forces in the exterior walls.

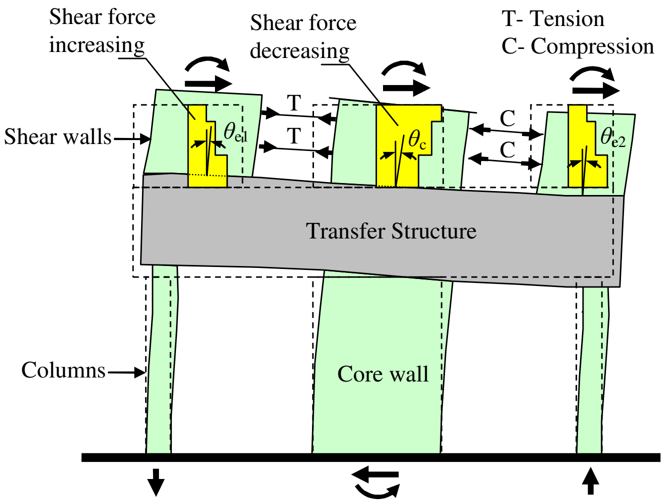
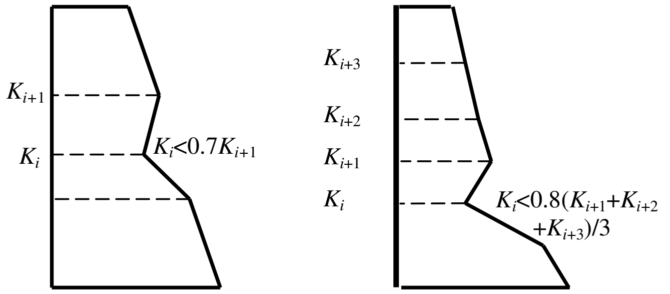


Figure 7. Deformation of transfer structure and shear concentration at the external walls

A preliminary numerical analysis conducted by the author revealed that in some cases even when a rigid transfer structure is used, shear force concentration in the exterior walls above the transfer structure can still be observed. This demonstrates that the effect of shear concentration is partially due to the intrinsic behaviour 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 slightly limit local rotations at the transfer level. By doing so, the inter-storey drifts and the difference in rotations between the exterior walls and the core wall can be slightly 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. Similarly, 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. Incidentally, Chen & Fu (2004) suggested that when the flexural stiffness of shear walls above the transfer floor is much higher than that of the transfer beam, reducing the flexural stiffness of the transfer beam can also decrease shear force transfer from the centre wall to the edge walls. Furthermore, 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. Lastly, Rong & Wang (2004) suggested increasing the shear load at the shear walls above the transfer structure by more than 20% to take into account the shear concentration effect. It is important to note that, in addition to the strength requirement of the whole building structure, appropriate stiffness allocation between the transfer structure and the structure supported above will greatly enhance the overall structural behaviour under seismic loads.

5 CURRENT SEISMIC DESIGN CRITERIA OF TRANSFER STRUCTURES IN CHINESE BUILDING CODES

Soft storey failure is a common failure mechanism for concrete and masonry buildings under earthquake attack (Booth 1986, EFFIT 1987, Dolsek & Fajfar 2001). Broadly speaking, a soft storey may be associated with a storey in which the lateral shear stiffness is much smaller than it is in the neighbouring storeys. Although not every transfer structure automatically leads to a soft storey, seismic engineers (e.g., Scott et al. 1994) are concerned with soft storey failure of transfer structures under seismic loads. In line with international building codes (ICC 2006, ICBO 1997, EC8 2005), the Chinese National Standard (2001) and the Chinese National Specification (2002) have quantitatively defined structural irregularities and soft storeys in building structures. Three codified definitions of soft storey in Chinese design codes are presented here.

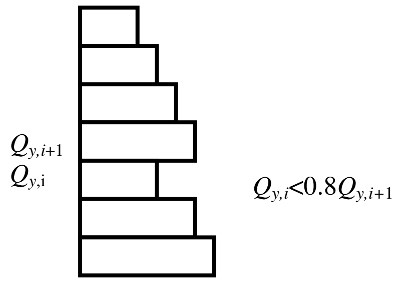


where:
$K_i=V_i/u_i$
V_i=shear force of the ith-storey
u_i=displacement of the ith-storey

Figure 8. Irregularity of lateral stiffness (soft storey)

According to the National Specification, a soft storey (irregularity in lateral stiffness) is defined as a storey in which the lateral stiffness is less than 70% of that of the storey above or less than 80% of the average stiffness of the three storeys above (see Figure 8).

Moreover, a discontinuity in vertical elements in a lateral load resisting system and the requirements of transfer of internal forces in these elements through horizontal structural elements (like a transfer truss/plate) as well as the case of abrupt change in shear capacity (Q_y) of a lateral load resisting system between two adjacent storeys (that is $Q_{y,i}<0.8Q_{y,i+1}$) are also classified as vertical irregularities (see Figure 9).



where:
$Q_{y,i}$=shear capacity of the ith-storey along building height

Figure 9. Irregularity of shear capacity along building height (weak storey)

For a transfer structure used in a building located at a relatively high level (see Figure 10a), the abrupt change in inter-storey drift above and below the transfer structure becomes more serious. There is an additional guideline in the National Specification (2002) for the situation based on the equivalent lateral stiffness ratio γ_e as defined in Equation (1). In this guideline, two models simulating the structures above and below the transfer structures as shown in Figures 10b and c are built, and the bases of the models are fixed. The height of the substructure below the transfer structure (as shown in model 1 in Figure 10b) is H_1, while that of the substructure above the transfer structure (similar to but not taller than H_1; see model 2 in Figure 10c) is H_2. By applying a unit horizontal load to each model, the elastic lateral deflections Δ_1 and Δ_2 of models 1 and 2 are calculated, and the equivalent lateral stiffness ratio γ_e can be evaluated accordingly.

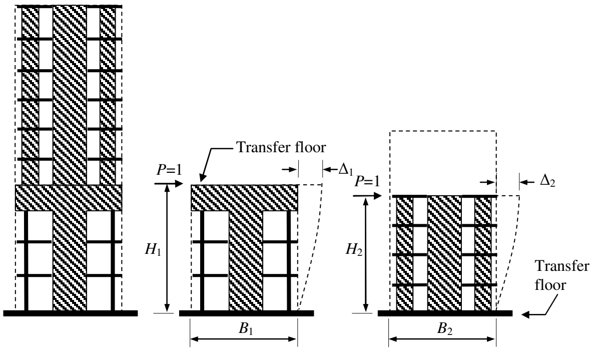
$$\gamma_e = \frac{\Delta_1}{H_1}\Big/\frac{\Delta_2}{H_2} = \frac{\Delta_1 H_2}{\Delta_2 H_1} \qquad (1)$$

For non-seismically designed low rise buildings with soft storeys, the amount of drift in the upper part of the buildings above the ground floor is usually negligible when compared with the lower storeys, in which case the denominator on the right hand side of Equation (1) tends to be small; as a result, γ_e approaches a high value. According to the National Specification (2002), when the structures below the transfer structure are more than one storey, the ratio of the equivalent lateral stiffness ratio γ_e should not be greater than 1.3 for seismically resistant design.

The aforementioned definitions of soft storey, 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 storey. 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 storey is provided in next section.

6 EFFECT OF SOFT STOREY BELOW TRANSFER STRUCTURE

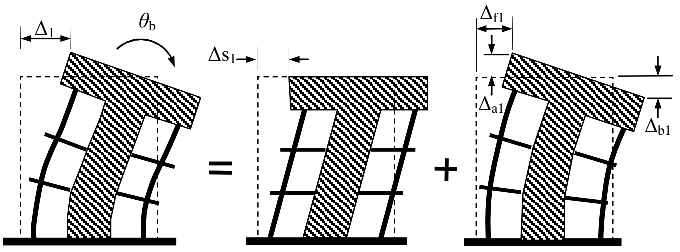
Under a seismic attack, a soft storey will attract much higher lateral deformations, and in many cases, high torsional deformations. The excessive inter-storey drift and the P-delta effect arising from gravity loads may cause plastic hinges to form at the ends of vertical structural elements. If the elements are not ductile enough, failure of individual vertical supports will trigger progressive collapse of the whole storey.



(a) Full model (b) Model 1- substructure below the transfer structure (c) Model 2- substructure above the transfer structure

Figure 10. Numerical models for calculating the equivalent stiffness below and above the transfer structure

Since lateral flexural and shear stiffnesses often change abruptly near transfer structures, it is essential to prevent the formation of soft storeys in buildings with transfer structures. Typical lateral deformations below a transfer structure can be separated into shear mode and flexural mode, as shown in Figure 11.



(a) Deformed shape (b) Shear mode (c) Flexural mode

Figure 11. Typical shear and flexural deformations of a substructure below a transfer structure

Obviously, the lateral deformation of the transfer structure is the sum of shear deformation Δ_{s1} and flexural deformation Δ_{f1}; i.e.,

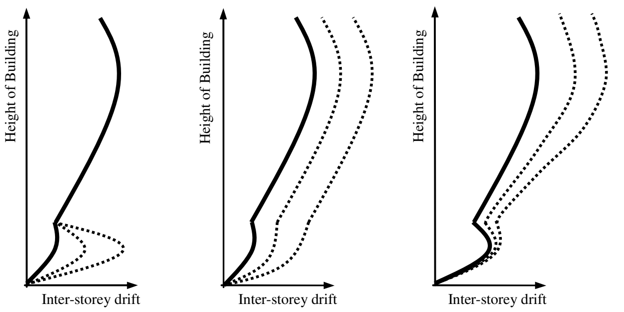
$$\Delta_1 = \Delta_{s1} + \Delta_{f1} \tag{2}$$

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

$$\theta_b = (\Delta_{a1} + \Delta_{b1})/B_1 \tag{3}$$

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-storey 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-storey drift of a multi-storey building due to changes in stiffness of substructures are summarized and presented in Figure 12. From the figure, it is clear that an abrupt change in the inter-storey below the transfer structure will be more severe when (i) lateral shear stiffness below the transfer structure is small (Figure 12a), (ii) lateral flexural stiffness below the transfer structure is high (Figure 12b) and (iii) lateral flexural and shear stiffness above the transfer structure are high (Figure 12c).



(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 12. Variations of inter-storey drifts due to change in shear and flexural stiffnesses (the dotted lines represent the new inter-storey drift profiles after stiffness reductions)

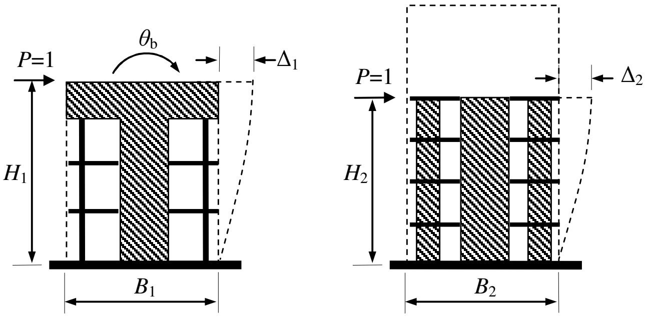
Despite the importance of flexural stiffness below the transfer structure for controlling the soft storey effect, National Specification (2002) and Geng & Xu (2002) only considered the lateral shear stiffness below and above the transfer structure and required the equivalent lateral stiffness ratio $\gamma_e \leq 1.3$ for seismically resistant structures. The concept of equivalent lateral stiffness ratio used in National Specification (2002) is modified 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 13) and the inelastic response of structures under a rare earthquake attack.

The modified equivalent stiffness ratio is expressed as:

$$\gamma_e' = \frac{\varphi_1\left(\dfrac{\Delta_1}{H_1}\right)}{\varphi_2\left(\dfrac{\Delta_2}{H_2}\right)+\varphi_1\theta_b} \leq 1.3 \qquad (4)$$

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 storey phenomenon vanishes. In this case, Equation (4) represents a less stringent requirement than Equation (1). Alternatively, when the flexural mode does not exist, for example for a pure shear frame, and elastic deformation is considered (φ1 = φ2 = 1), Equation (1) would be recovered from Equation (4). Furthermore, for a pure shear frame with a transfer structure, φ1 = 2, φ2 = 1.5 and θb=0, Equation (4) imposes a more stringent requirement than Equation (1) for controlling the formation of a soft storey. Despite the fact that 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 storey for buildings with transfer structures. Further numerical or experimental studies and justifications are required to validate the effectiveness of this equation for controlling the occurrence of soft storeys in elastic and inelastic stages.

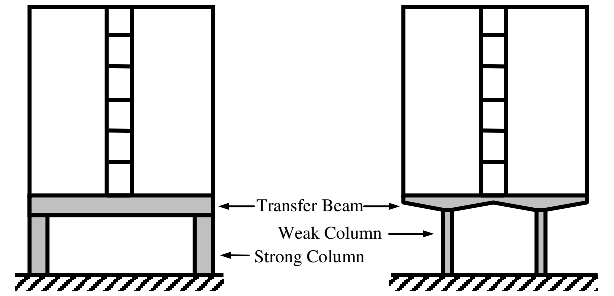
Li *et al*. (2003) revealed that for low-rise buildings with edge columns supporting the long transfer beam (see Figure 14a), gravity load usually controls the design of the buildings. Even though the structural walls do not extend below the transfer structure, the column frame structure alone below the transfer structure designed to resist the gravity load is strong and stiff enough to resist the seismic load. However, when set back columns are used to support the transfer beam (see Figure 14b), less unbalanced end moment due to gravity load is induced in the columns supporting the transfer structure. Hence, the columns designed to resist gravity load may not be strong enough to resist the additional seismic load. A soft storey mechanism could be realised below the transfer storey under seismic conditions. Special attention must be paid to design low-rise buildings with this type of transfer structure.



(a) Model 1- substructure below the transfer structure

(b) Model 2- substructure above the transfer structure

Figure 13. Numerical models for calculating the equivalent stiffness below and above the transfer structure with consideration of the rotation above the transfer structure



(a) Transfer beam supported by edge columns

(b) Transfer beam supported by set back columns

Figure 14. Low-rise buildings with columns supporting the transfer beam

7 VERTICAL POSITIONING OF TRANSFER STRUCTURES

Xu *et al*. (2000) and Zhang & Li (2003) investigated the effects of the vertical positioning of the transfer structure on the seismic response behaviour of the frame-supported shear wall structures. They found that the degree of abrupt change in the inter-storey drifts and shear concentration of the frame-supported shear walls increased with increasing height of the transfer structure. For a high-level transfer storey supported by frame with a full elevation centre core wall, more cracks and damage appeared on the exterior shear walls above the transfer structure. Abrupt changes in the inter-storey drift for the storeys adjacent to the transfer floor level (i.e. the soft-storey behaviour phenomenon) could be moderated with decreasing height of the transfer floor level. Similar moderation trends are expected as the difference in the equivalent lateral stiffnesses (defined in Section 5) between the substructures above and below the transfer floor decreases. The most onerous soft-storey behaviour phenomenon is expected when the transfer floor is located at a level close to 40% of the height of the building, in which case the maximum inter-storey drift is expected at the transfer floor level. The shear concentration effect is partially attributed to local deformation of transfer structures and can be reduced but not completely eliminated as mentioned in Section 4. Geng & Xu (2002), Wu *et al*. (2007), Wang & Wei (2002) and Rong & Wang (2004) studied hypothetical tube structures and real coupled shear wall-core wall buildings with transfer storeys at various levels under earthquake loads. The soft-storey phenomenon (i.e. abrupt changes in inter-storey drift) was found to be more dominant with increasing difference in the equivalent lateral stiffness between the substructures above and below the transfer floor. Inter-storey drift demands at the neighbouring floors of a transfer storey and high mode effects were generally higher as the transfer floor is positioned at a higher level. More vibration modes are recommended in response spectrum analysis to improve the accuracy of the estimates.

8 CONCLUSIONS

Previous shaking table tests and numerical analyses of buildings with transfer structure under simulated seismic loads were comprehensively reviewed. The major findings from the study are summarized as follows:

1. El Centro and Taft earthquake records have been widely used in shaking table tests. The spectral displacements and accelerations of these records are considerably higher than those from site specific spectra of Hong Kong. Using these earthquake records in seismic analyses of buildings can lead to over-conservative predictions of seismic response for buildings in Hong Kong.
2. The maximum response spectral displacement of Hong Kong is saturated when the natural period is higher than 1.7 sec. The inelastic displacement demand and soft storey effect are less pronounced than those due to a strong near field earthquake on a deep soil site, e.g. the 1940 EI-Centro earthquake. In relatively low seismicity regions such as Hong Kong, designers can allow some strength degradation to occur without building collapse.
3. Shaking table tests indicate that under frequent earthquake attacks, all the buildings remained elastic, no cracks were found in the models and the natural frequencies of the models did not decrease. Conventional elastic analyses satisfactorily reflected the real dynamic behaviour of buildings under frequent (minor) earthquakes.
4. When the models were subjected to major (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%. As the effects of stiffness and strength degradations of concrete elements were not considered in elastic analyses, the calculated seismic responses of buildings under rare earthquakes were not accurate. Pushover analyses or non-linear time-history analyses should be adopted.
5. 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 (e.g. using deeper transfer structure, stiffer core wall and lower level transfer structure) have been suggested for minimizing the detrimental effect of shear concentration.
6. 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 neighbouring floors of the transfer level.
7. The equivalent lateral stiffness ratio was 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-storey type of failure.

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