INTERNATIONAL SYMPOSIUM

Recent Advances in Structural Design
in Regions of Low-to-Moderate Seismicity

28 June 2019, Hong Kong SAR

Seismic Design of Transfer Structures for Hong Kong Conditions

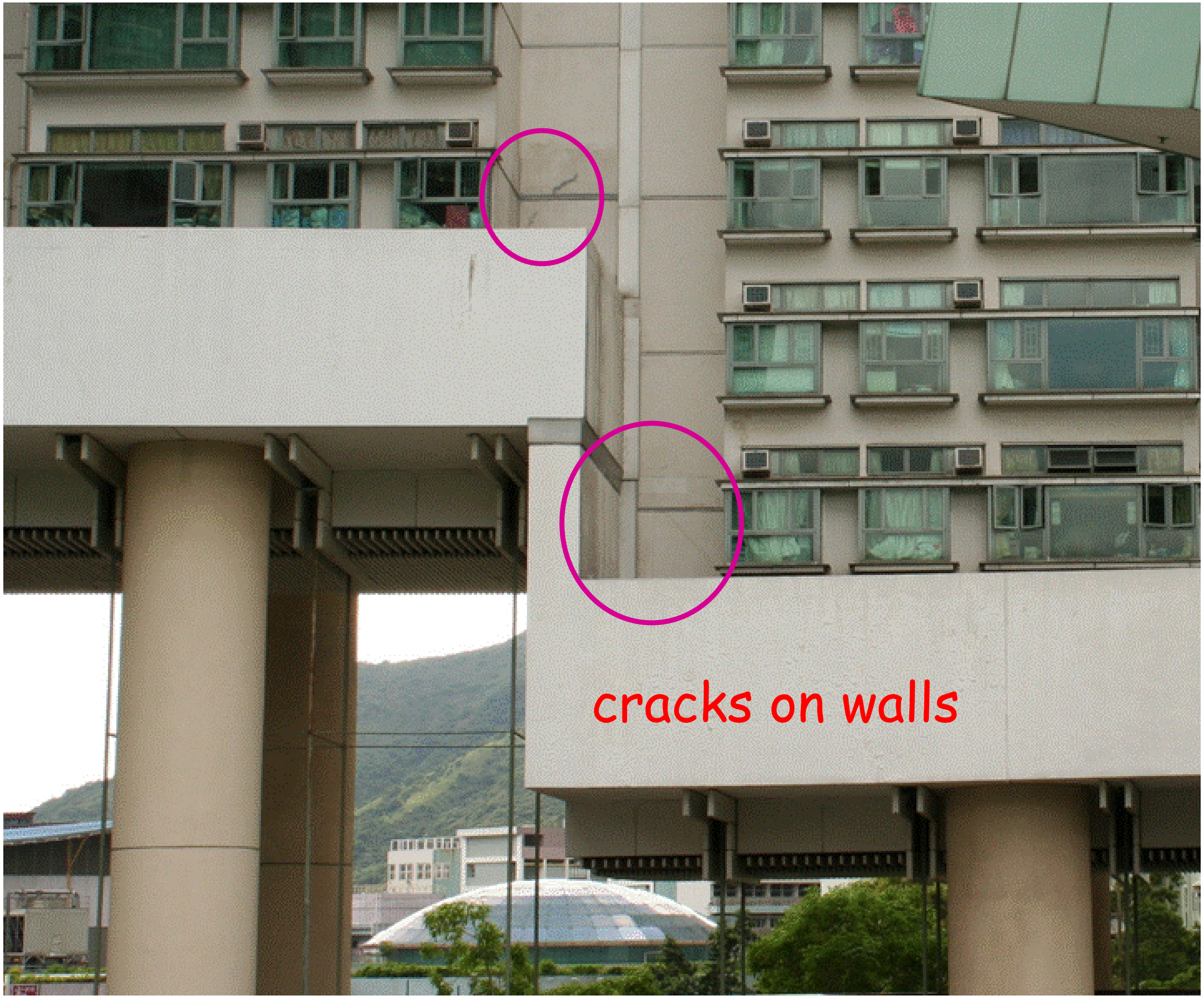
Dr. Ray SU

The University of Hong Kong

Transfer structure (TS) in modern buildings

Transfer structures are commonly used in low-to-moderate seismicity regions. However, their **resilience** to extreme loads, such as earthquake attack, is questionable.

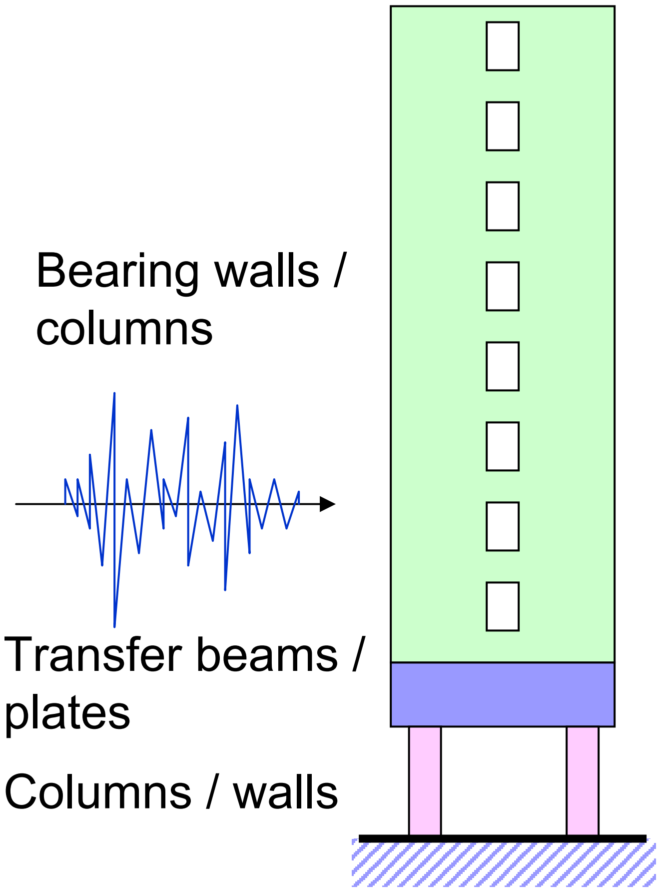
Cracks above TS



Cracks above TS

Seismic vulnerability of transfer structure

Transfer structures are vulnerable under a seismic attack.



Out-of-plane deformation of transfer structure ⇒ Shear concentration at structural walls

⇒ Tensile failure in structural slabs

Structural irregularities
- Lateral stiffness
- Lateral strength
- Mass

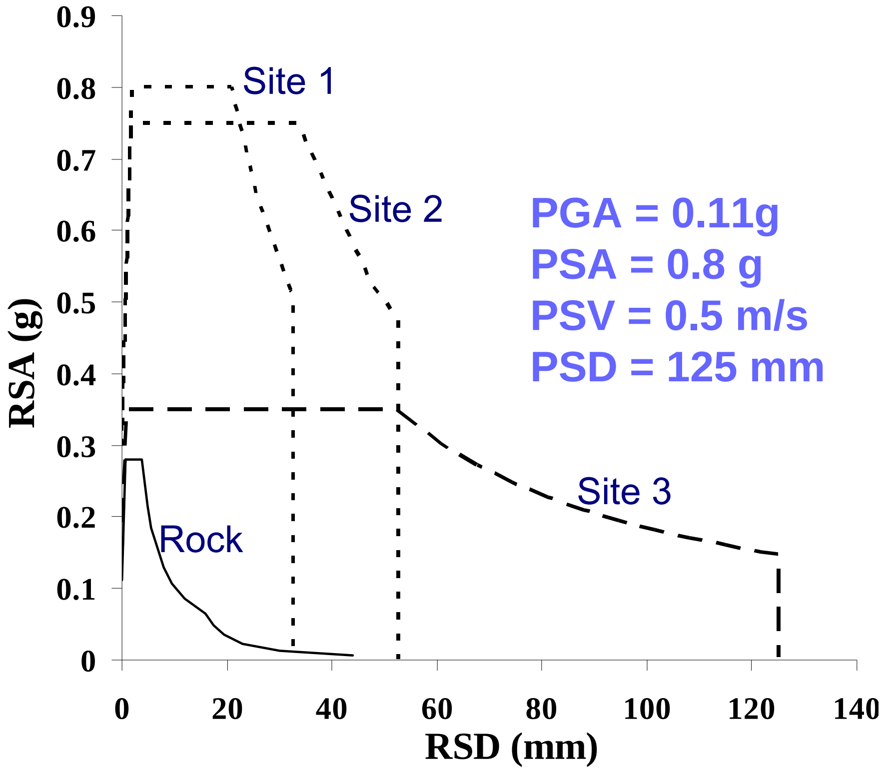
⇒ Soft/weak storey failure

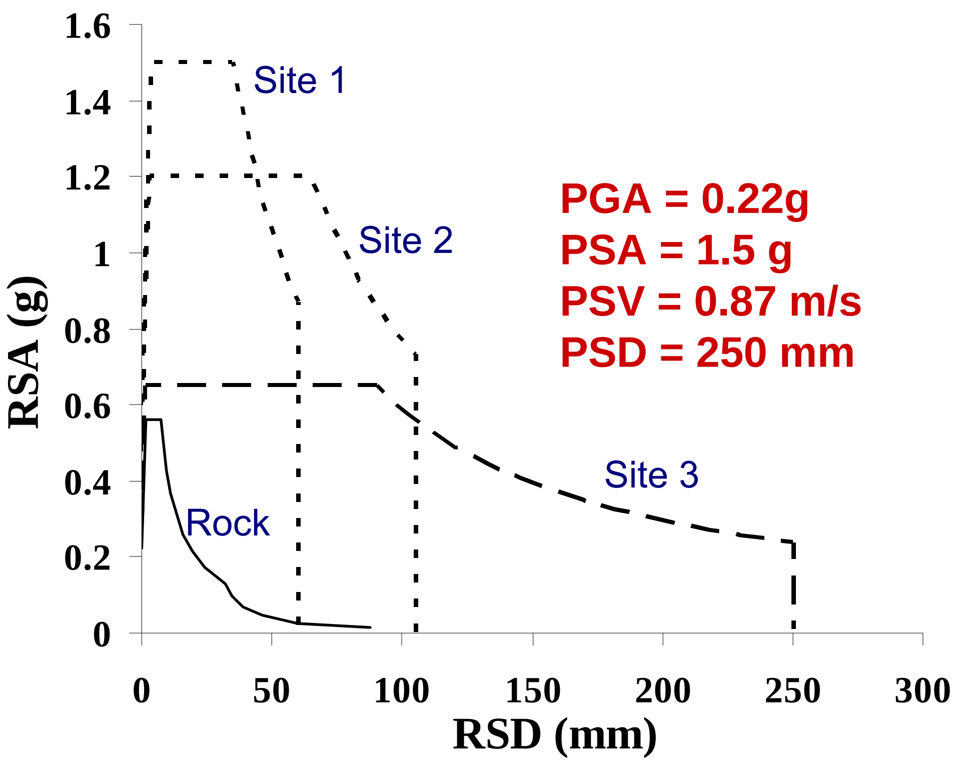
Those failure modes will be examined under the HK design based earthquake (DBE) loads.

Earthquake demands for Hong Kong

Design Based Earthquake (DBE) Spectra
(RP = 475 years)

Rare Earthquake (or MCE) Spectra
(RP = 2475 years)





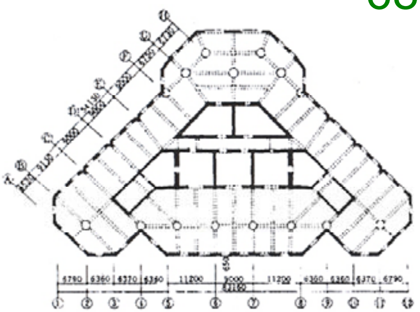
Seismic response is significantly affected by the type of sites and RP considered. Rock sites are better as their seismic response is the lowest.

Shake Table Tests

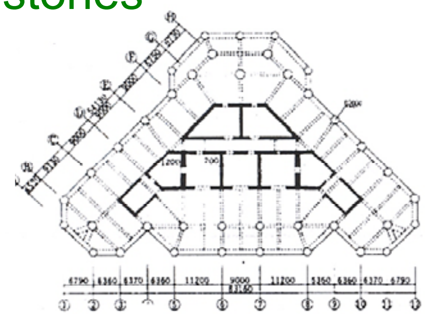
Shake table tests

Case 1 Xu et al 2000

68 stories



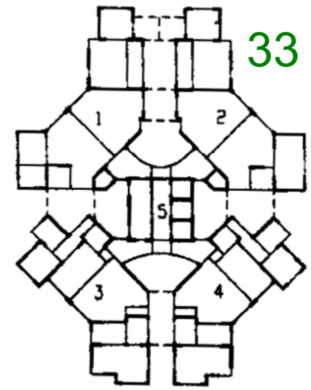
Above the transfer structure



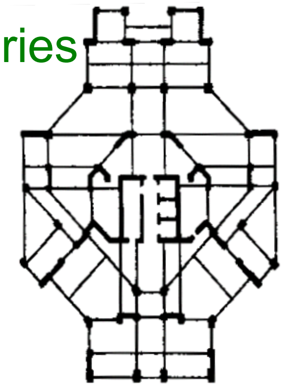
Below the transfer structure

Case 2 Ye et al 2003

33 stories



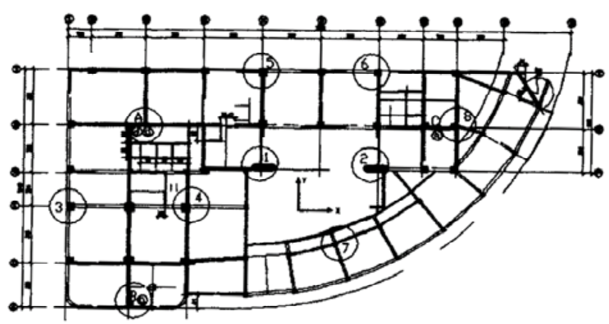
Above the transfer plate



Below the transfer plate

Case 3 Huang et al 2004

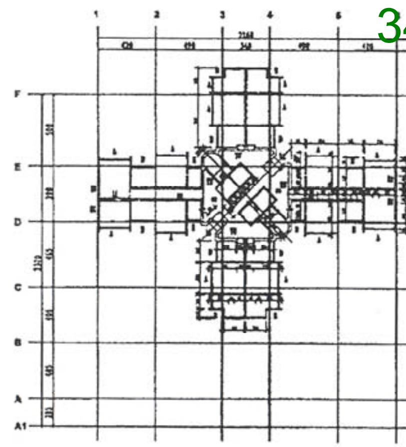
28 stories



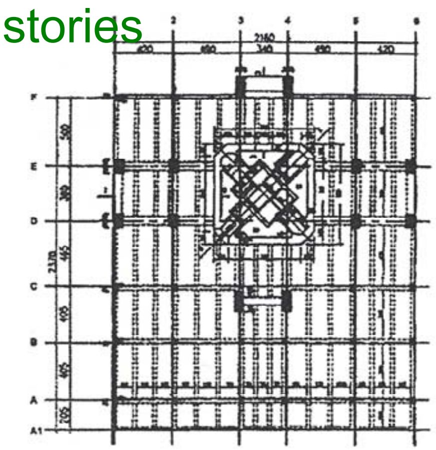
Podium structure

Case 4 Li et al 2006

34 stories



Above the transfer plate

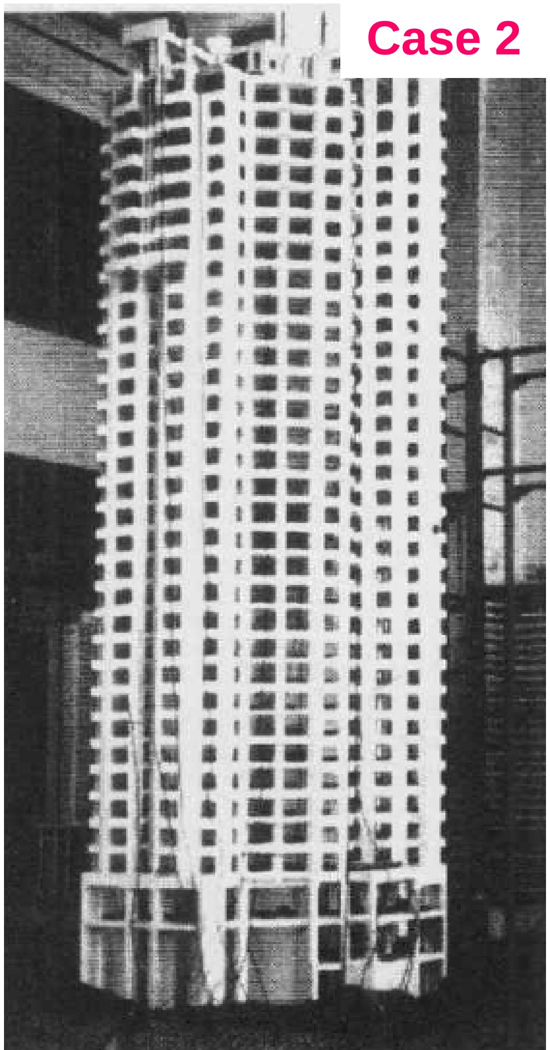


Below the transfer plate

Xu, P., Wang, C., Hao, R. and Xiao, C. (2000) Building Structures 30(1), p38-42.
Ye, Y., Liang, X., Yin, Y., Li, Q., Zhou, Y. and Gao, X. (2003) Structural Engineers 4, p7-12.
Huang, X., Jin J., Zhou, F., Yang, Z. and Luo, X. (2004) Earthquake Engineering and Engineering Vibration 24(3), p73-81.
Li, C.S., Lam, S.S.E., Zhang, M.Z. and Wong, Y.L. (2006) Journal of Structural Engineering ASCE 132(11), p1732-1744.

Shake table tests

Elevation views



Gao et al. 2003

Huang et al. 2004

Li et al. 2006

Shake table tests

Peak ground accelerations (PGA) 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

Note: PGA of Hong Kong ≈ 0.11 g for DBE and 0.22 g for MCE

Su RKL (2008) Electronic Journal of Structural Engineering, 8, p99-109.

Shake table test results

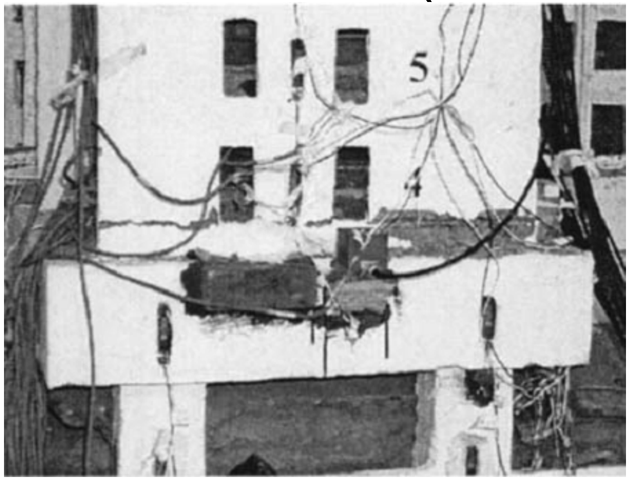
- **Under frequent earthquake attack**, all the building models remained elastic, no cracks were found and no change of the natural frequencies.
- **Under occasional earthquake**, cracks began to occur at the tops of columns below transfer beams and at the base of columns above transfer floor. The natural frequencies dropped by 10 to 20%.
- **After rare earthquake**, all the models were severely damaged. The natural frequency of the structures decreased by 20-46%. The damping ratio was increased from 2% after frequent earthquakes to 4.5-7.5% after a rare earthquake.

Su RKL (2008) Electronic Journal of Structural Engineering, 8, p99-109.

Shake table test results

- **After rare earthquake**, serious damage was found in the peripheral shear walls above the transfer floor (in cases 1 and 3).

- Tension failure was found on the end shear walls above the transfer plate (in case 4).
- 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).
- Most of the damage was caused by shear concentration effects.
- All the buildings survived without collapse



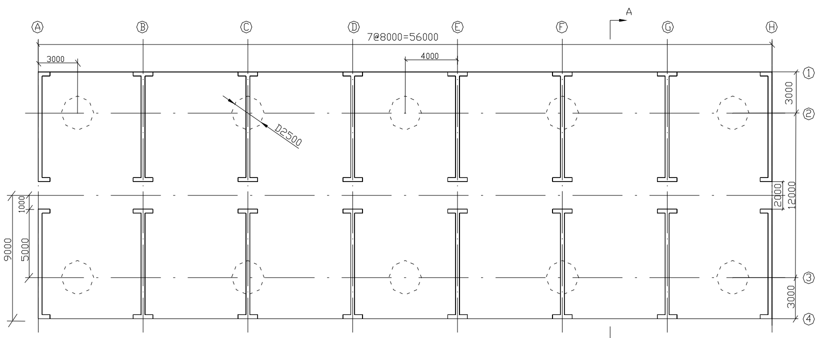
Case 4, after Li et al. 2006

Case 3, after Huang et al. 2004

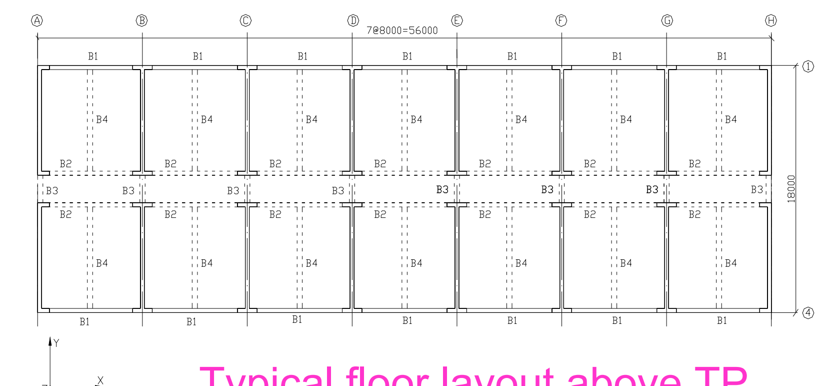
Soft Story Investigation

Soft storey analysis

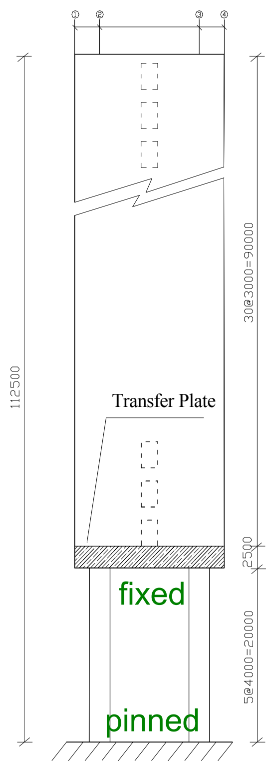
- Seismic analysis was conducted for a 35-storey RC residential building with a transfer plate located at the 6th floor which was designed to the old HK code 2004.



Str. layout at TP level



Typical floor layout above TP



Section A-A

Structural system

Shear walls above TP

Column frame below TP

Basic information

Height: 112.5 m

Plan: 18 m x 56 m

TP level: at 6^{th} floor (20 m above ground)

Plate thickness: 2.5 m

Mega column diameter: 2.5 m

Concrete grade:

$f_{cu,k}$ = 45 MPa below 25/F for columns and walls

Steel grade:

$f_{y,k}$= 460 MPa

Live load = 2.5 kPa

Roof drift ratio under wind loads = 1/677 < 1/500

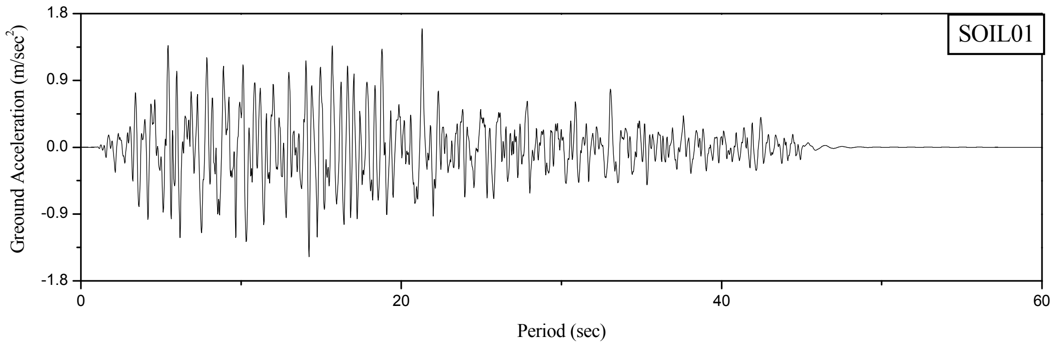
Drift ratio below TP = 1/800 < 1/700

•Su RKL, Chandler AM, Li JH and Lam NTK (2002), Structural Engineering and Mechanics, 14(3), p287-306.

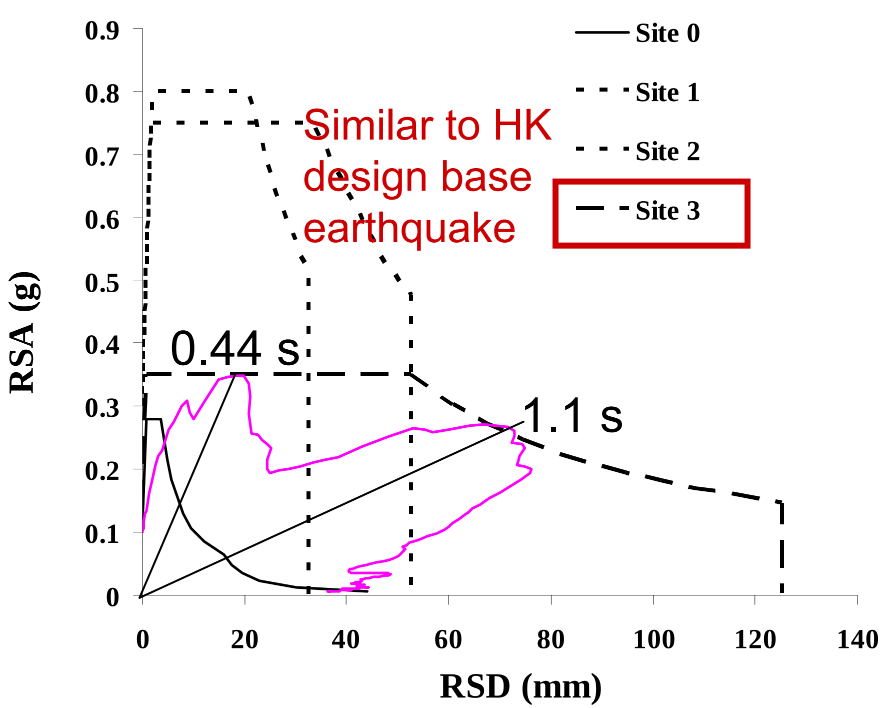
•Li JH, PhD thesis, Seismic Drift Assessment of Buildings in HK with particular application to transfer structures, 2004

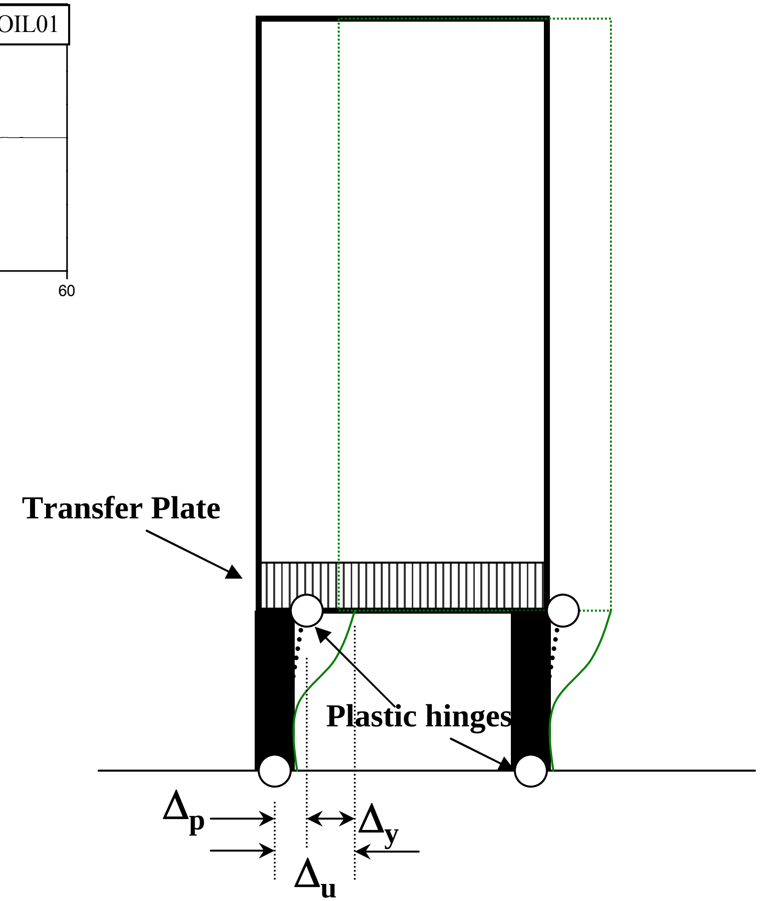
Input seismic loads

5 simulated time-history records at soil sites are considered



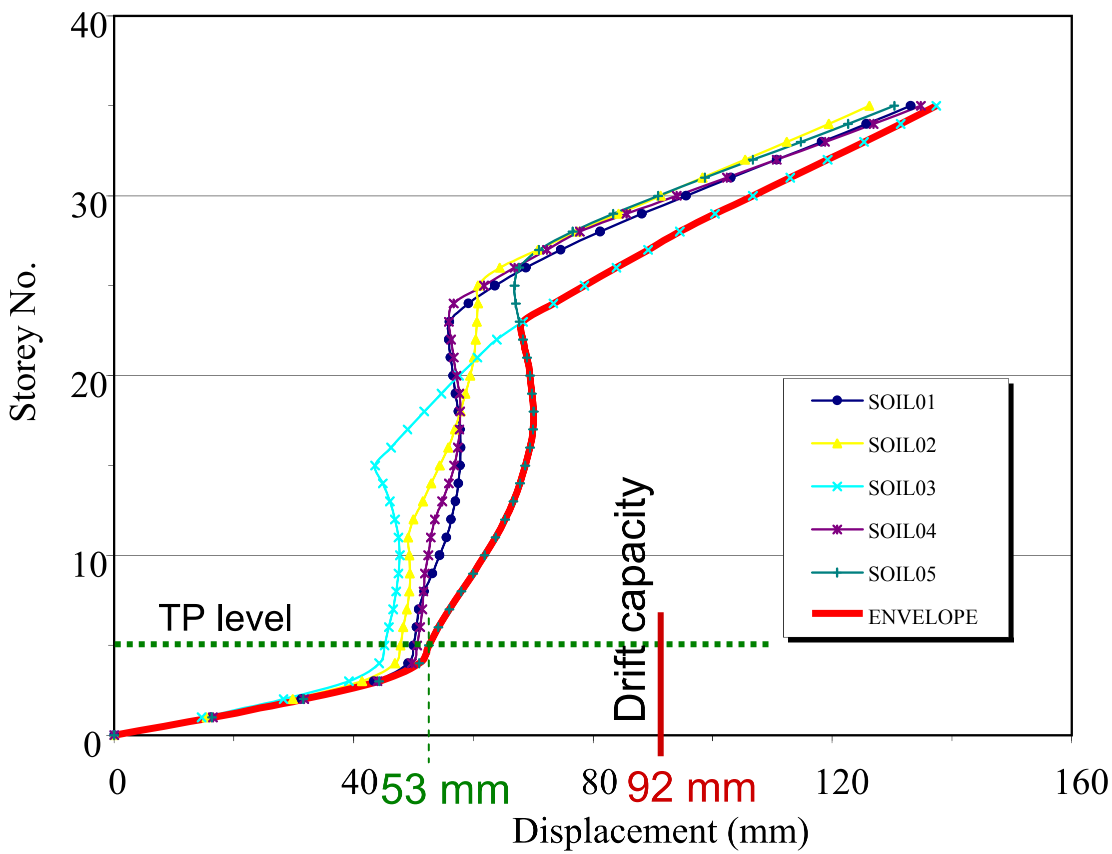
Average acceleration response spectrum





Potential Soft-Storey Failure Mechanism

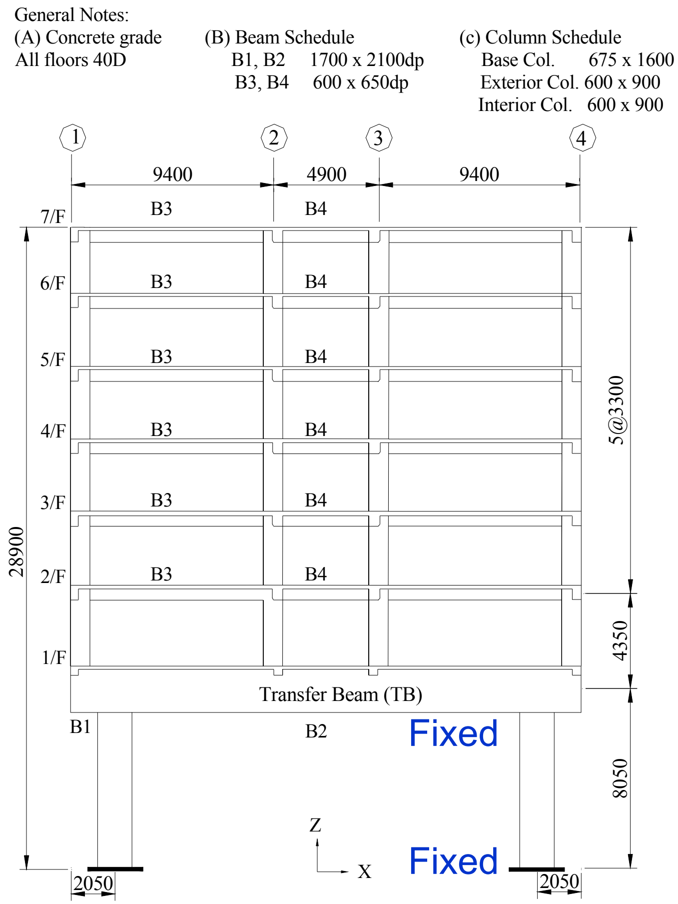
Maximum displacement profiles



- The mega-columns designed to the old HK code can survive under DBE.
- However the seismic demands would be double under rare earthquake attack. The strength of the mega-columns, if designed as force controlled members following PBSD, would be insufficient.
- Higher concrete grade could be used to reduce the ALR and improve the axial strength and lateral deformability of the columns.

Soft storey analysis

- Seismic analysis was conducted for a 7-storey RC building with a transfer beam located at the 1st floor



__Structural system__
Beam-column frame above TB
Column frame below TB

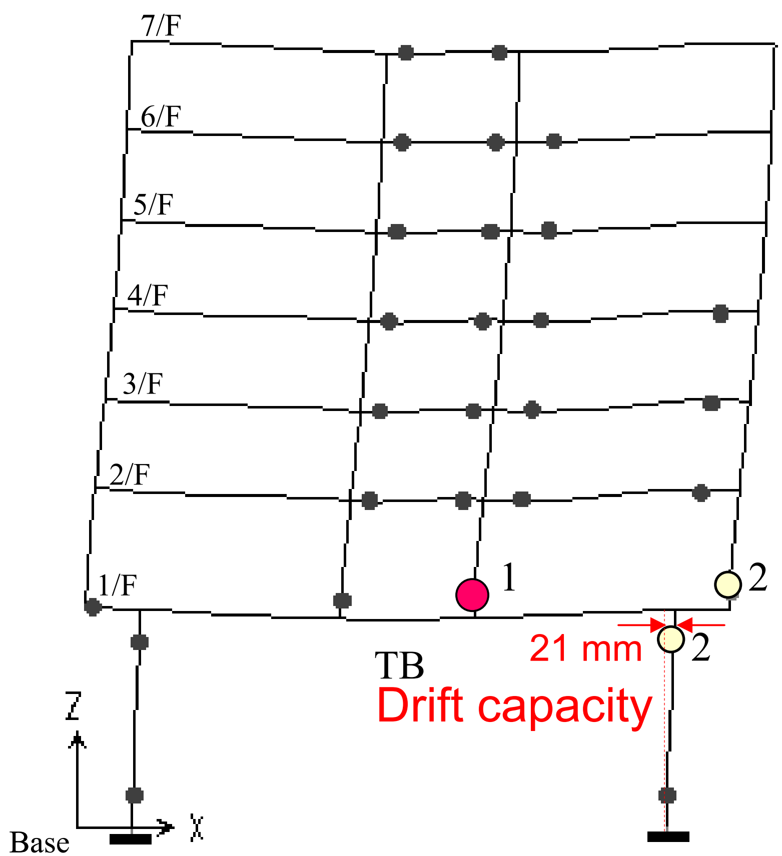
__Basic information__
Height: 28.9 m
Width: 23.7 m
TB level: at 1st floor (7 m above ground)
TB size: 1.7 x 2.1 m (dp)
Base column size: 0.675x1.6 m
Concrete grade:
$f_{cu,k}$ = 40 MPa
Steel grade:
$f_{y,k}$ = 460 MPa
Live load = 2.5 kPa

Gravity load case controlled the RC design

•Li JH, Su RKL and Chandler AM (2003), Engineering Structures, 25(12), p1537-1549.
•Li JH, PhD thesis, 2004

Soft storey analysis

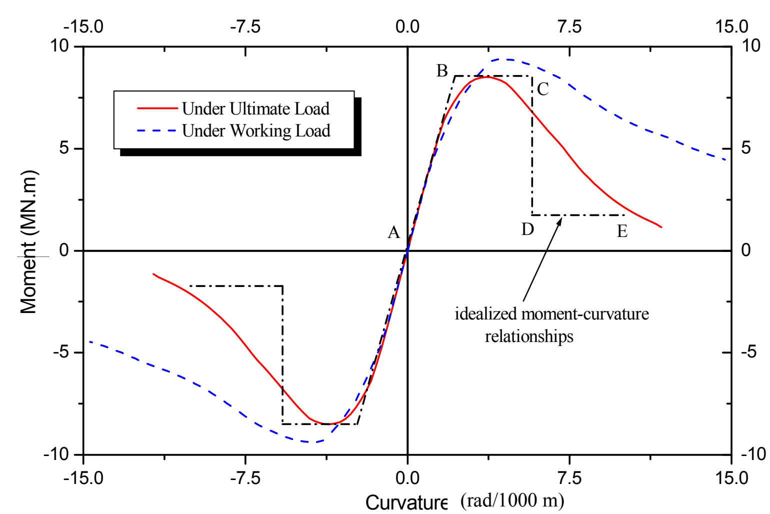
Collapse Mechanism from POA



● reach ultimate capacity (beyond Point C)

○ immediately prior to collapse (just before or at Point C)

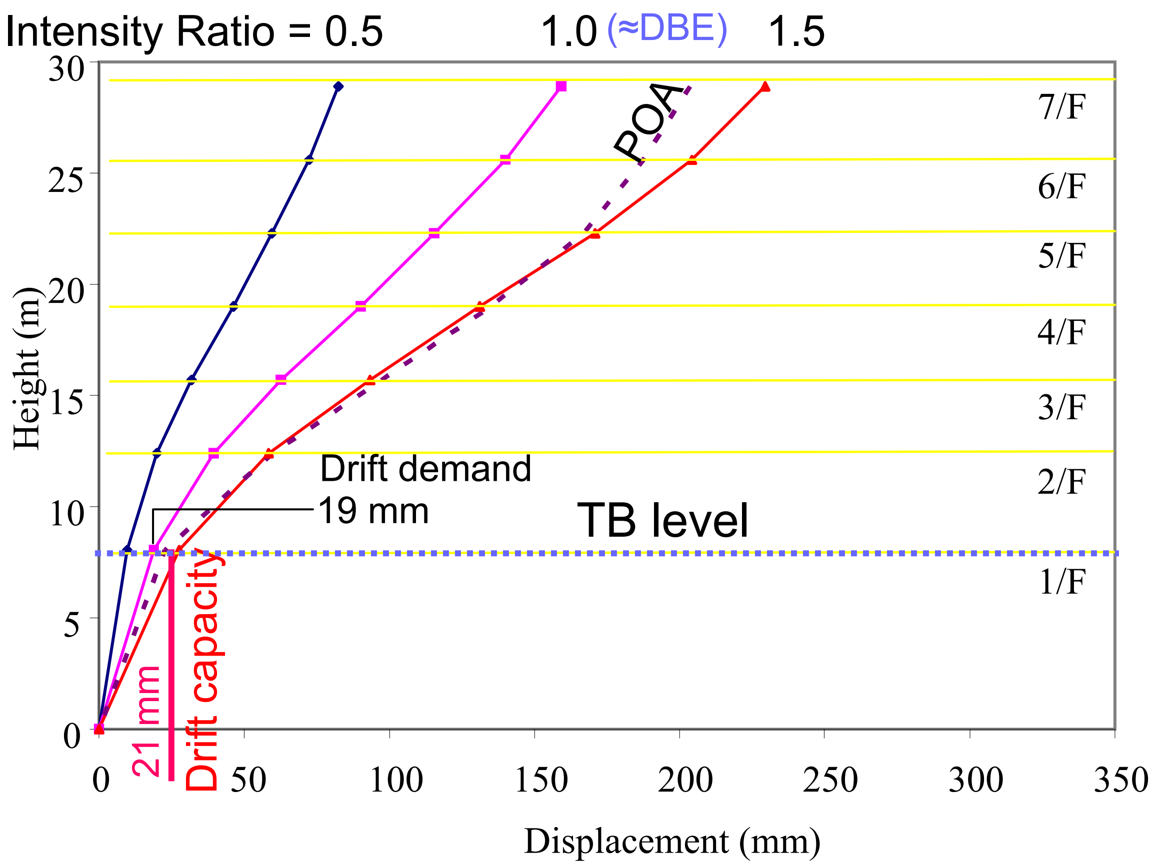
● in the range of the effective yield capacity and the ultimate capacity (in the segment of labels 'B' and 'C')



Moment curvature of base column

Soft storey analysis

Displacement profiles from incremental dynamic analysis

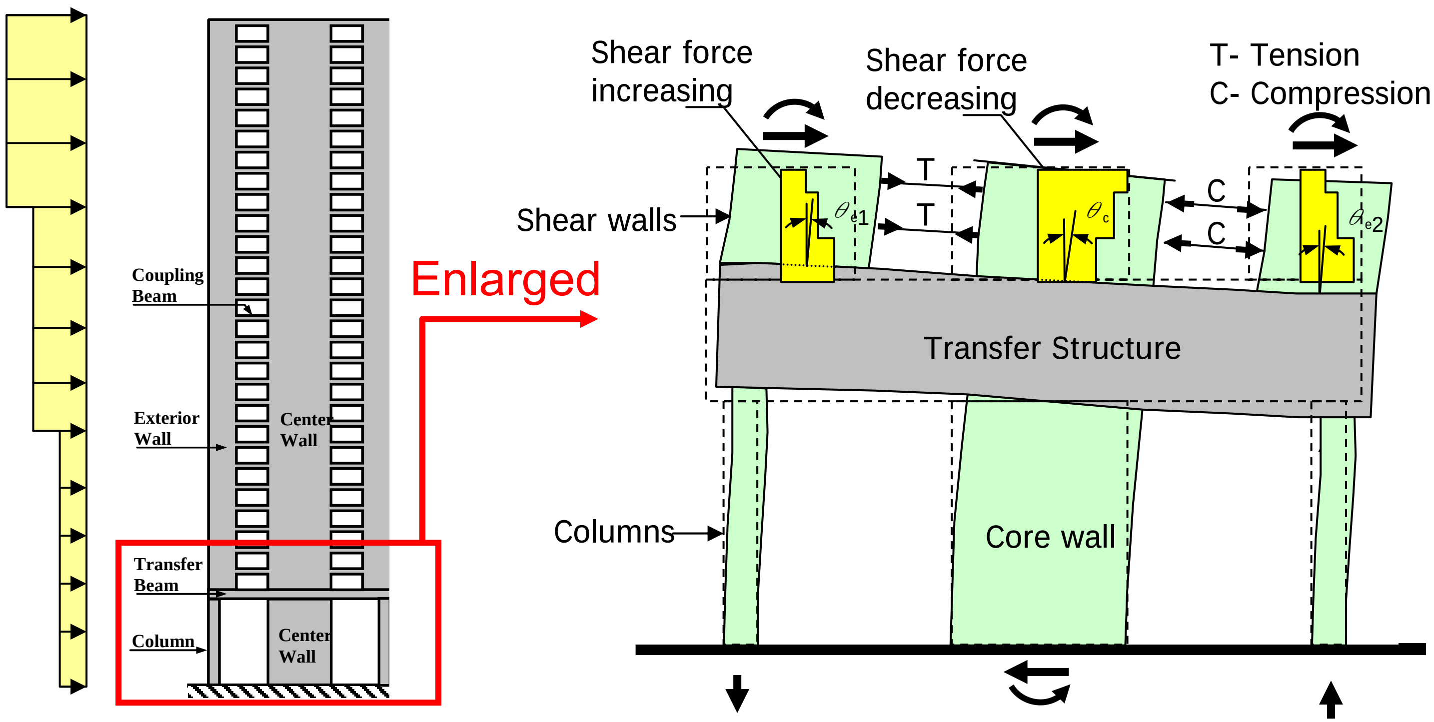


- The base columns could barely satisfy the seismic demand under DBE.
- In general, low rise buildings are more critical than high rise buildings under seismic loads.

Shear Concentration Effect

Shear concentration effects

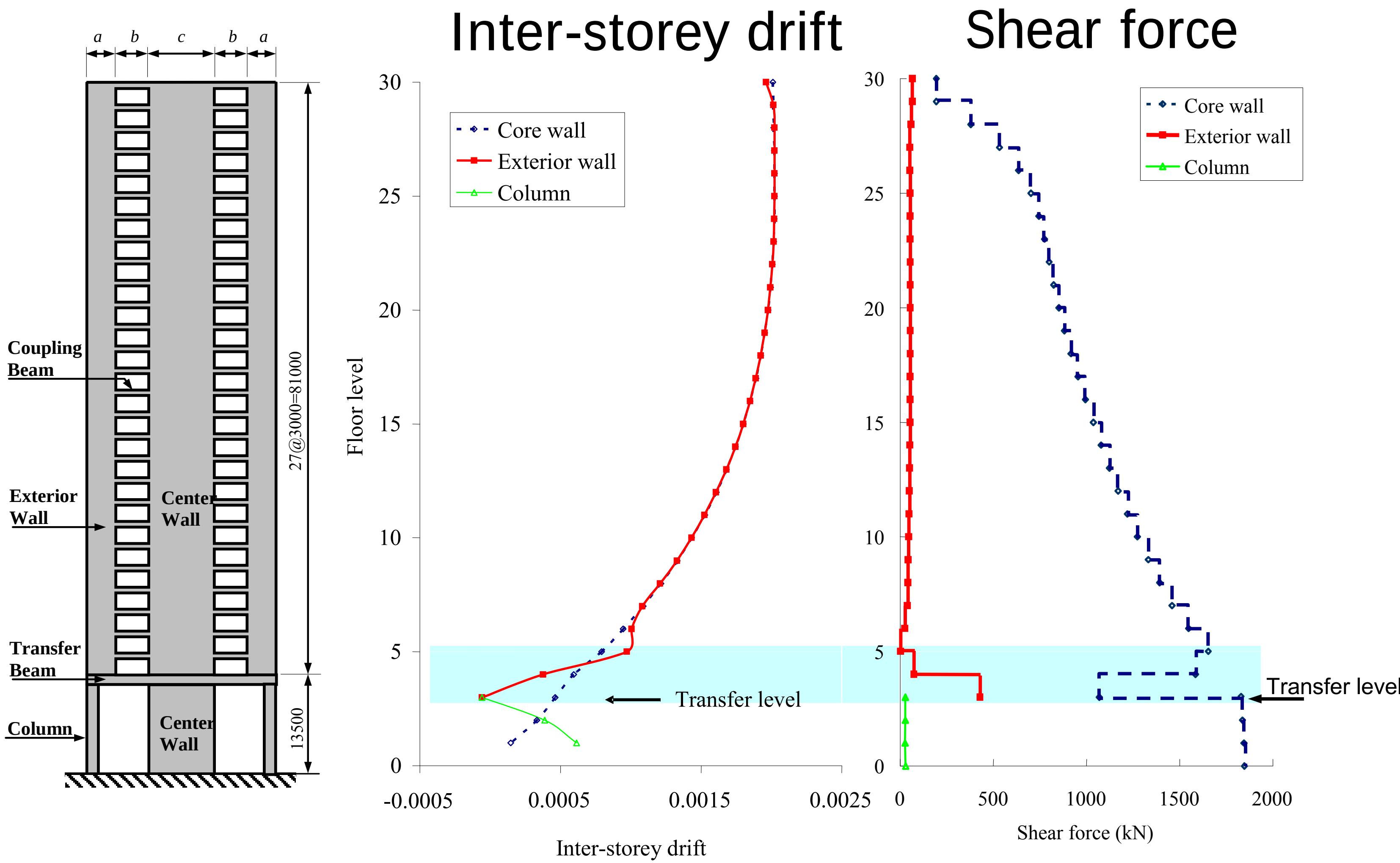
Local out-of-plane deformations of transfer structure under lateral loads



- Very high tension / compression force in slabs and shear force in walls.
- Substantial reduction of the shear span (L_s=M/V) of walls.
- Decrease in deformability / ductility of walls.

•Su RKL and Cheng MH (2009), The Structural Design of Tall and Special Buildings 18(6), p657-671.
•Su RKL (2008), Electronic Journal of Structural Engineering, 8, p99-109.

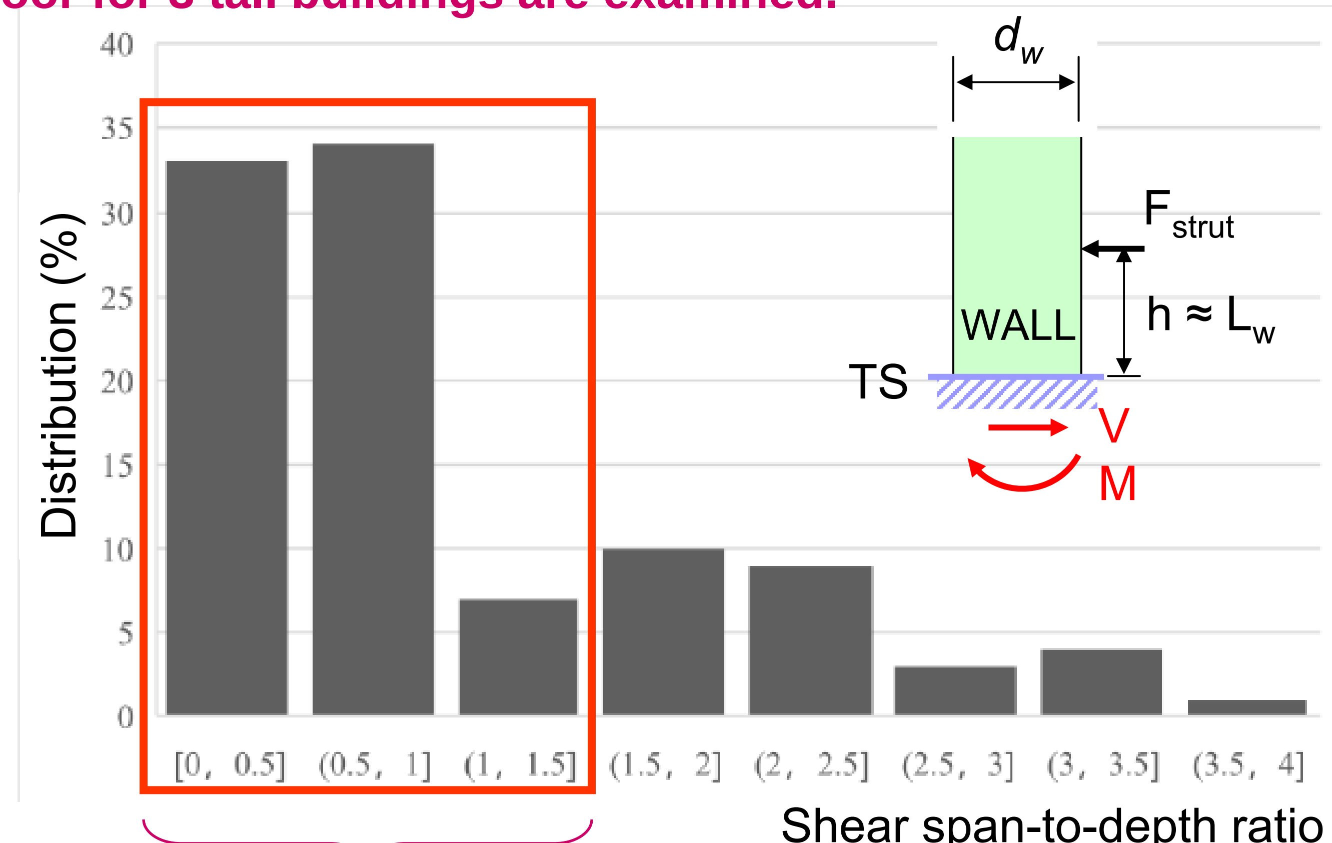
Shear concentration effects



The difference in wall rotations above the transfer structure causes shear concentration in walls.

Shear concentration effects

Shear span-to-depth ratios (SDR) of structural walls above transfer floor for 3 tall buildings are examined.



$SDR = L_w/d_w$

Shear span = L_W= M/V

Wall depth = d_w

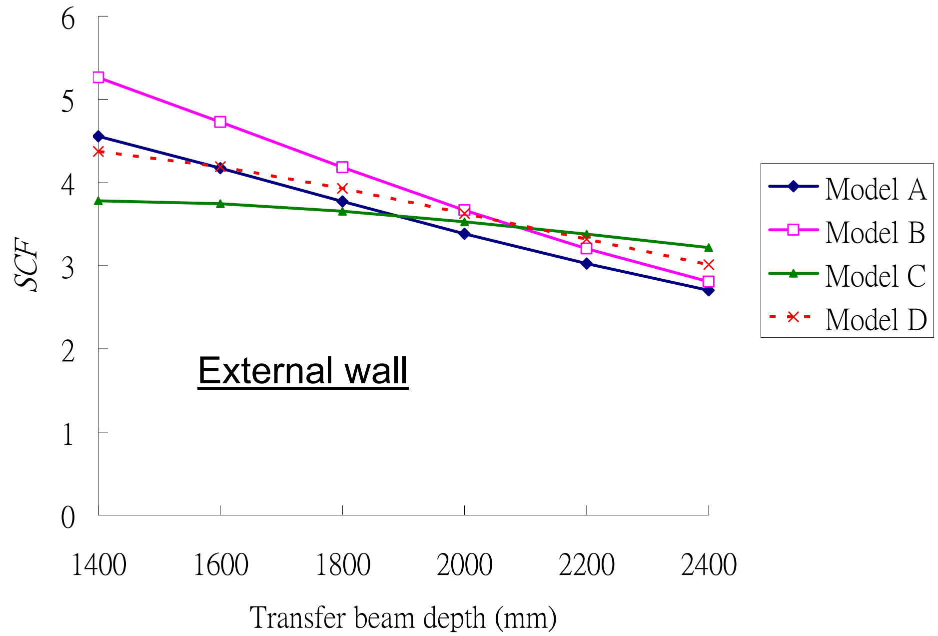
SDR of a big majority of walls (>70%) are less than 1.5.

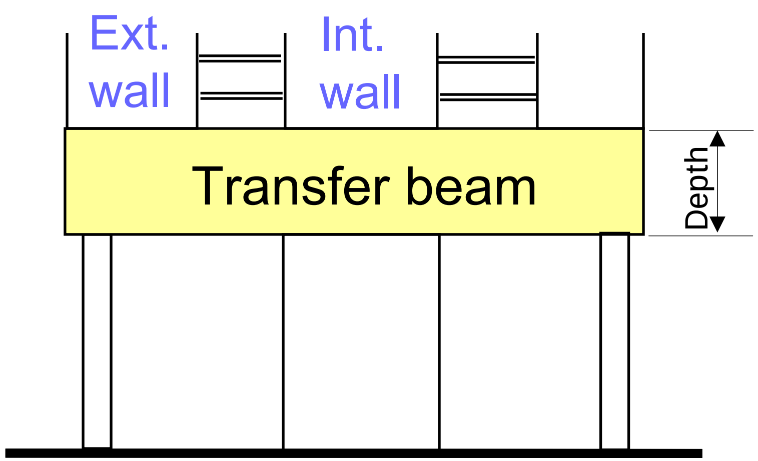
The drift capacity of **squat walls** (SDL $\leq$ 1.5) controls the seismic performance of the structure.

Effect of depth of transfer beam

Under Seismic Loads

Shear concentration factor (SCF) is defined as the shear stress at the wall concerned to the average shear stress of all the walls above the transfer level.



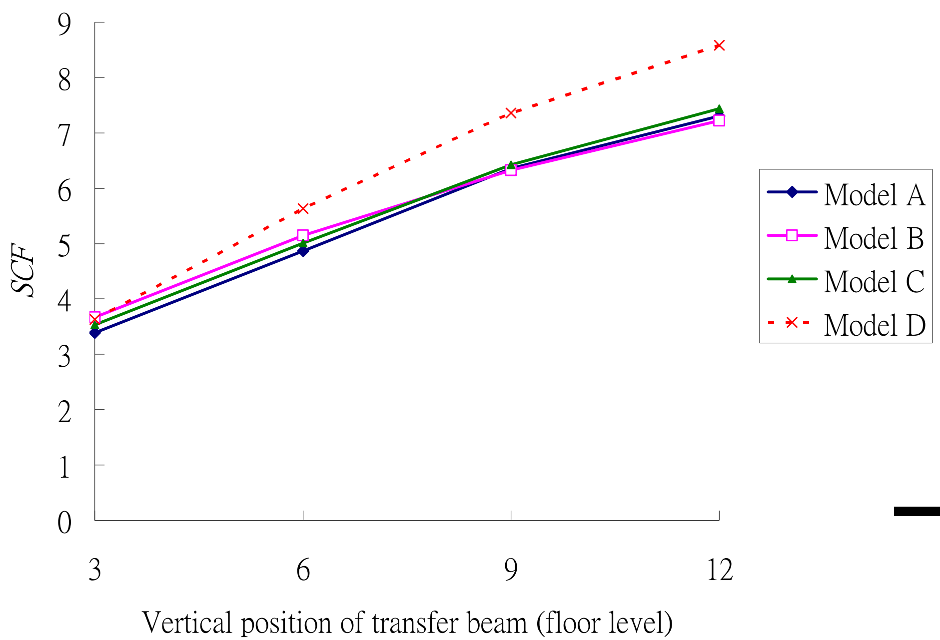


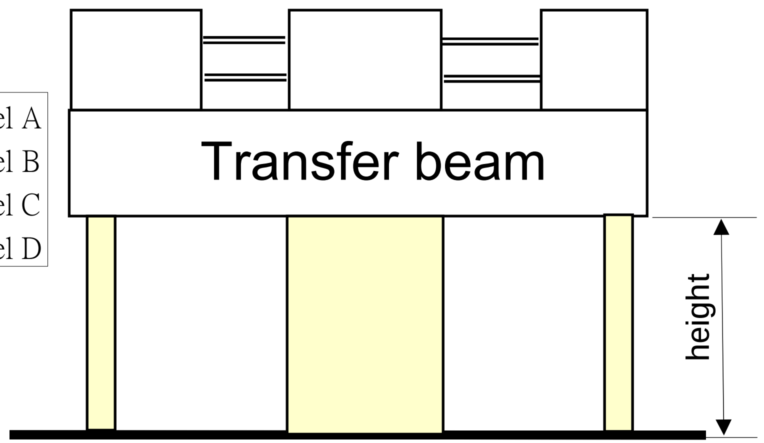
- Stiffening the transfer beams can only moderate the shear concentration effect as the local rotation of TB cannot be eliminated.

•Su RKL and Cheng MH (2009), The Structural Design of Tall and Special Buildings 18(6), p657-671

Effect of vertical positioning of TB

Under Seismic Loads





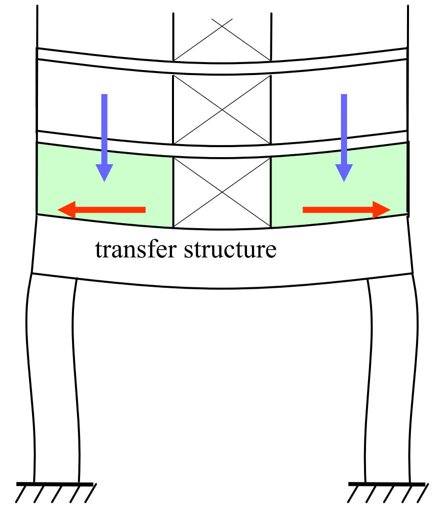
- Placing the transfer structure at a high level can remarkably increase the shear concentration effect. It is because both the global rotation of superstructure and local rotations of transfer structure increase with the level of the transfer structure.
- For seismic design, **the transfer level should be limited to a lower storey, e.g. the bottom level of transfer structure should be less than 20 m above ground** .

•Su RKL and Cheng MH (2009), The Structural Design of Tall and Special Buildings 18(6), p657-671

Effect of gravity loads

Gravity loads can cause out-of-plane deformation of transfer structures and shear concentration.

Such shear forces are self-balance at each floor.



A parametric study by Tang and Su (2015) found that for improperly designed transfer structures, the **induced shear stress** can go up to **around 30%** of the **average vertical stress** above the transfer structure.

For example,

σ_G = 11 MPa, $\tau_w \approx 0.3 \times 11$ MPa = 3.3 MPa.

To mitigate the excessive deflection of the transfer structures under gravity loads, **the maximum sagging deformation** of transfer structure under working gravity loads is recommended to be limited to **L/1000**, where L is the clear span of the transfer structure.

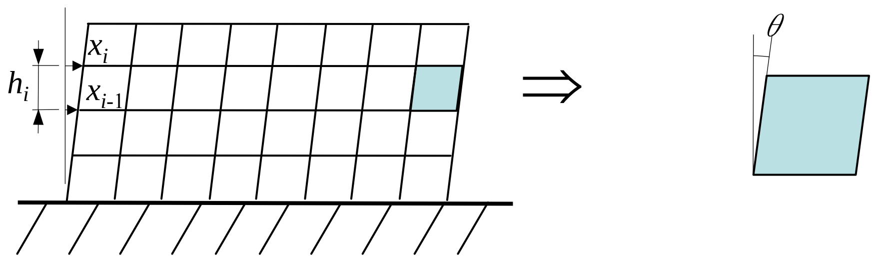
•Tang TO and Su RKL (2015), Proceedings of the ICE Structures & Buildings, 168(1), p40-55.

Deformation limits

Inter-storey Drift Ratio (IDR)

It is defined as the relative horizontal displacement of two adjacent floors to the floor height ratio. It has been widely used for controlling **damage** to structural and non-structural components.

$$IDR_i = (x_{i+1} - x_i)/h_i$$

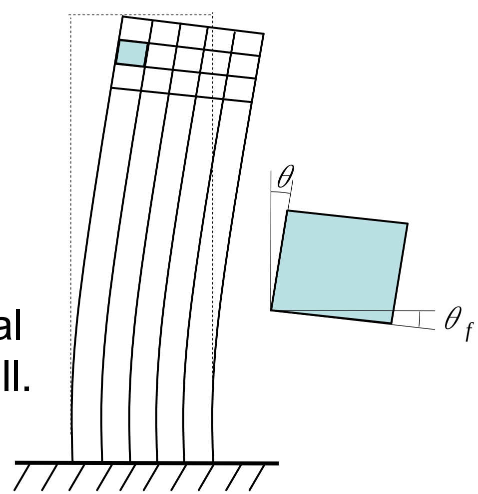


Sway deformation of frame under lateral load

However, it is not applicable for the cases where there is a significant rigid body rotation θ_f. For example:

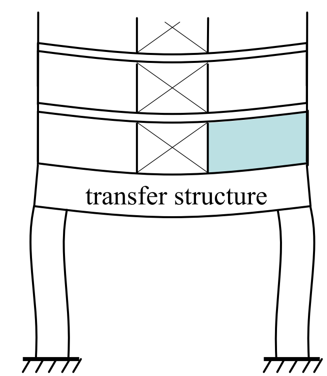
Upper zone of a tall building

$\theta \approx \theta_f$, IDR is high but internal forces are small.



Shear walls above transfer structure

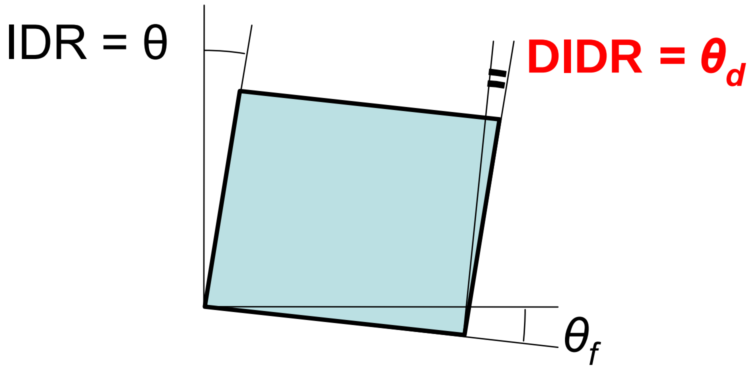
IDR is small but internal forces are high.



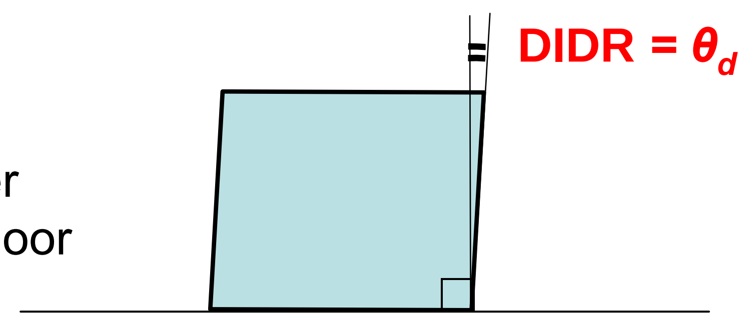
Deformation limits

Distortional Inter-storey Drift Ratio (DIDR)

It is obtained by eliminating the floor rotation (θ_f) from the IDR, is an appropriate measure of the shear deformation of a structural wall. This ratio is particularly suitable for quantifying local distortions and deformations induced by gravity and seismic loads.



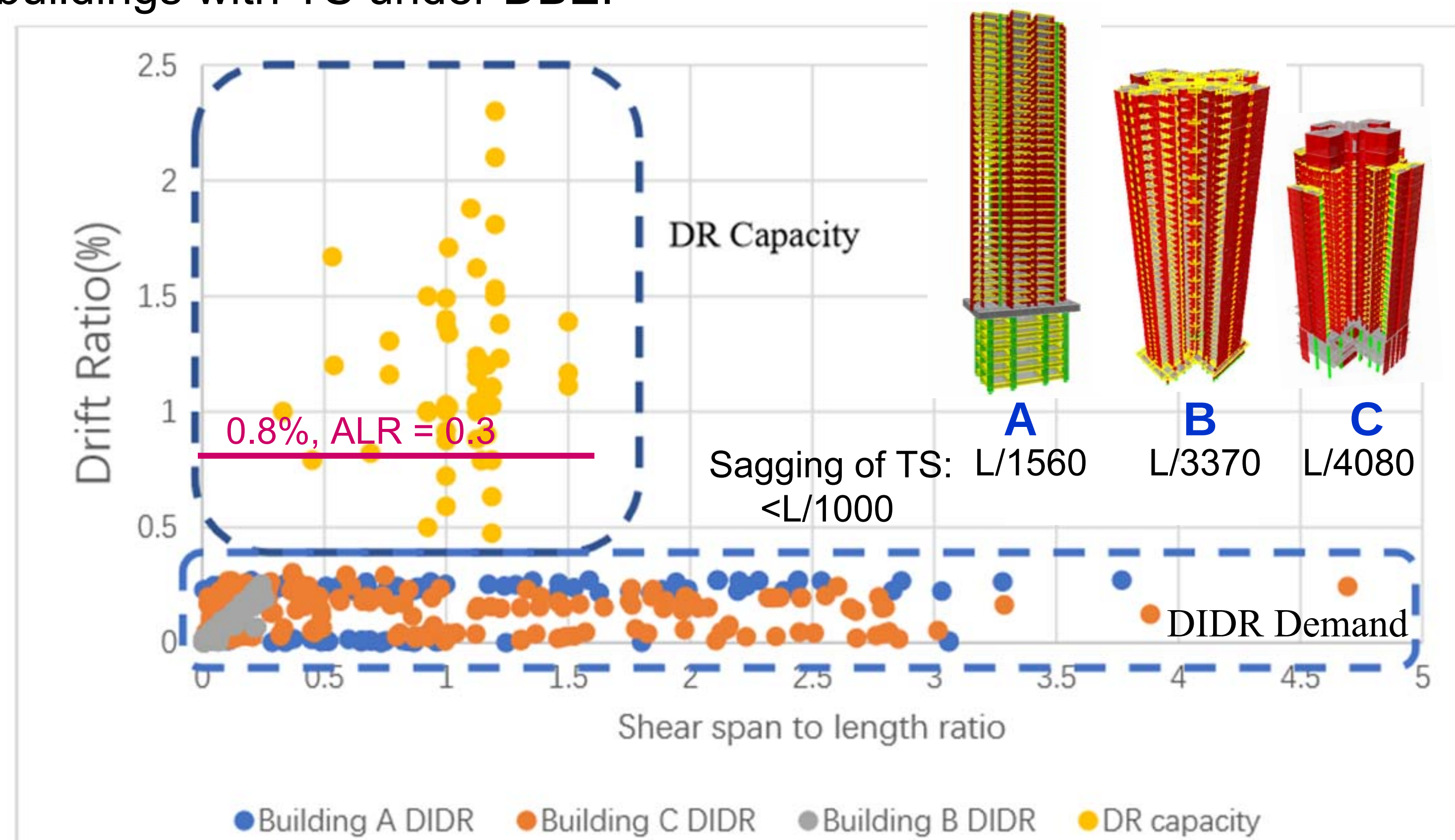
$$\theta_d = \text{IDR} - \theta_f$$



True distortional deformation after eliminating the floor rotation

Comparison of DR demand and capacity

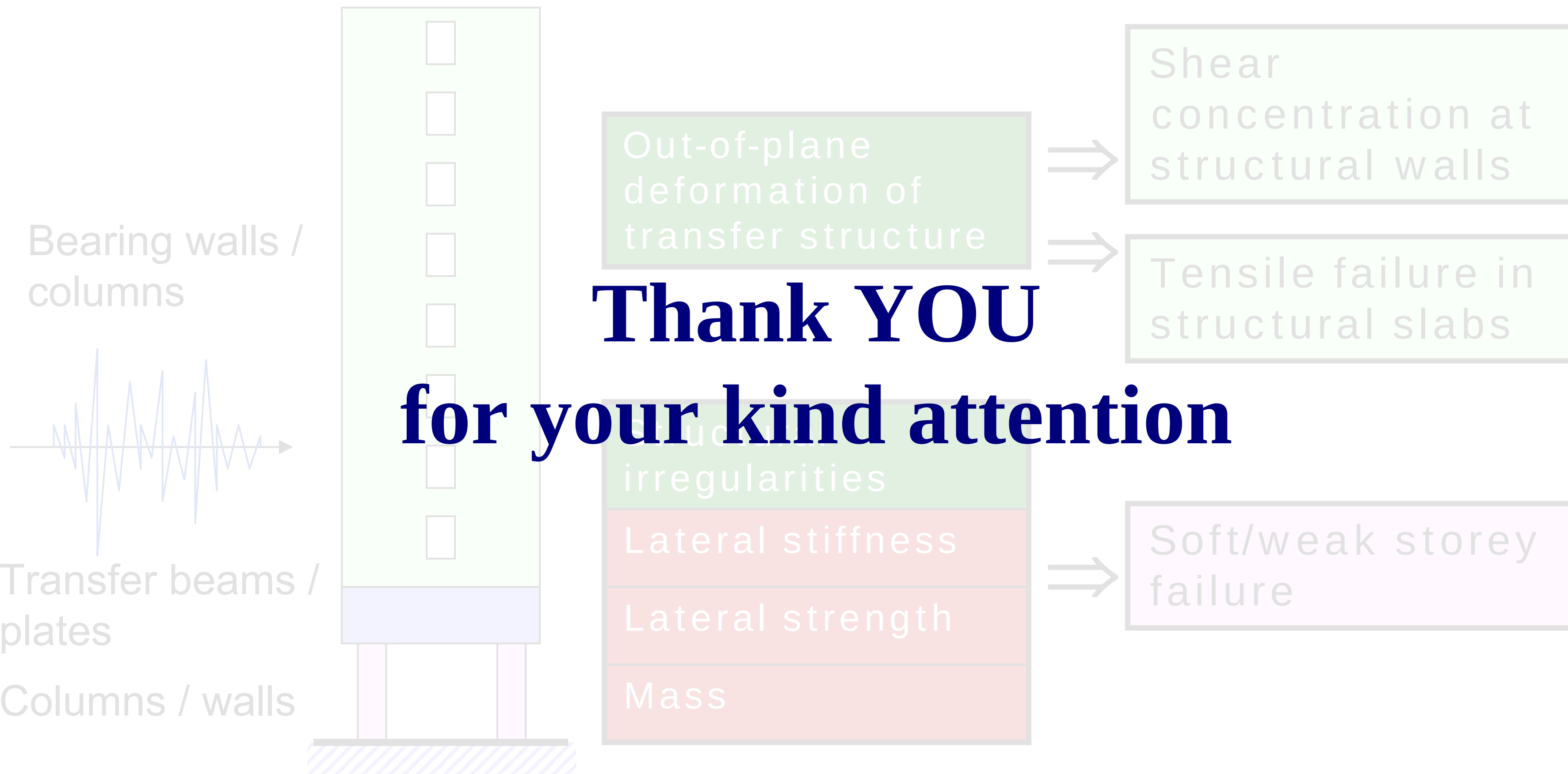
THA was conducted to obtained the seismic drift demands of tall residential buildings with TS under DBE.



- DIDR demands are all less than 0.5% which is much less than the DR capacity of around 0.8% (assuming an ALR of 0.3).
- Thus those shear walls could survive under the DBE.

Conclusions

- **Soft storey failure mode** is more critical for low-rise than high rise buildings.
- **Local deformation of transfer structure** can cause abrupt increase in force demands above the transfer floor and substantial reduction of shear span of structural walls.
- **Drift capacity of squat walls** is around 0.8% (taking the ALR = 0.3).
- **To mitigate the excessive deflection** of the transfer structures under gravity loads, the maximum sagging deformation of transfer structure under gravity loads should be limited (e.g.1/1000 of the clear span).
- **To control the seismic induced deformation demands**, transfer structure should be placed at a lower storey (e.g. $\leq$ 20 m above ground).
- **DIDR** is better than **IDR** for control damage.
- **To increase the drift capacity and shear strength** of structural walls, higher grade concrete (e.g. C60) can be used.
- **Rock sites** are favorable as they induce less seismic response.



Thank YOU for your kind attention

Acknowledgement
I would like to express my gratitude to Mr Lijie Chen and Ms Shuyi Liu for computing the SDR and DIDR results.

Ray Su
Email: klsu@hku.hk

Control of axial load ratio (ALR)

Since the implementation of the new concrete code in 2013, the axial compression stress in shear walls has being controlled. It is very effective in increasing the drift capacity of structural walls.

9.9.3.3 Axial compression ratio N_{cr}

The axial compression ratio N_{cr} of walls is defined as follows

$$N_{cr} = \frac{N}{0.45 f_{cu} A_c}$$

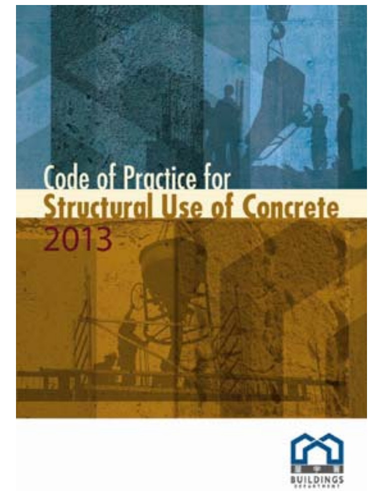
where:

N $= 1.4G_k + 1.6Q_k$

f_{cu} is the characteristic strength of concrete

A_c is the gross area of concrete section

N_{cr} should not be greater than 0.75.



Axial load ratio: $ALR = \frac{P}{f_c' A_c} \le \frac{N}{1.45} \times \frac{1}{1.275 f_{cu} A_c} = \frac{N}{1.85 f_{cu} A_c} = \frac{0.75 \times 0.45}{1.85} = \boxed{0.18}$

Working load: $P = N/1.45$

Expected cylinder strength: $f'_{c,expected} = 0.85 f_{cu,k} \times 1.5$

The drift ratio capacity of RC squat walls designed according to **the current concrete design code** should be more than 0.8% (assuming an ALR of 0.3). Higher grade concrete (e.g. C60) is recommended to be used above TS to increase the shear strength and drift capacity of walls