Original Article

Contribution of typical non-structural components to the performance of high-rise buildings based on field reconnaissance

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ABSTRACT A high-rise building is usually considered as the assemblage of different structural components adopting diverse structural forms in the structural design process. Non-structural components such as facades, infill walls and partition walls, and so on are seldom integrated in the structural analysis. However, based on the information collected from a field reconnaissance in the Asian-Pacific region, along with the analyses of a case-study building, this study observes that the building almost always works as an integrated system, which includes both structural and non-structural components. Thus, non-structural components can make significant contributions to the overall lateral structural stiffness of a building. Because of different design foci in the regions investigated, it is also concluded that different levels of attention should be given to the integration of non-structural components into the structural analysis, especially relating to the geological and hazard conditions in a particular area.

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INTRODUCTION

The current design approach to tall-building design in most of the regions in the world requires the structural skeleton to resist vertical and lateral loads, under both the ultimate and serviceability loading conditions applied to the building. Non-structural components such as infill walls, facades, stairs and so on are considered as non-load bearing components. These components are assumed to be detached from the primary structure in the design of high-rise buildings. However, because of different types of physical connections, interactions between the structural skeleton and the non-structural components do occur. Both structural and non-structural components participate in resisting structure movement. Various researchers (Mahendran and Moor, 1999; Sev, 2001; Hutchinson *et al*, 2006; Li *et al*, 2007, 2008a, b, 2009a, b) have identified that non-structural components make a considerable contribution to the overall structural performance.

Different countries have different design standards for buildings according to their own geographical and geological conditions as well as the local environment. Moreover, the way of approaching building design varies from culture to culture.

Owing to rapid economic development and the increasingly high density of city populations, high-rise structures have become more and more popular in the Asia-Pacific region. Hundreds of fine tall buildings define the skyline of cities. Nevertheless, threatened by different levels of earthquakes and high-gust winds, in various areas tall-building designs may differ considerably.

This study presents findings obtained from a field reconnaissance. In all, 15 buildings were investigated within the Asian-Pacific region in Australia, Taiwan and China. Issues such as structural form, typical design features, non-structural components and design considerations were considered in relation to local geological conditions and the surrounding environment. In-depth understanding of tall-building design in different locations, as well as the performance of overall building systems, was gained from the investigation. It is also noted that because of local constraints and effects, the structure of these tall buildings varies, as does the assemblage of non-structural components.

Communication with local industries in the different countries greatly helped in understanding the current design focus of tall buildings in various locations. Design and construction companies, such as Bovis Lend Lease Pty. Ltd. and Arup (Melbourne office and Beijing office), were contacted during the field reconnaissance. Detailed discussions of the design perspectives of tall buildings relating to the integrated building system were conducted. From these communications, it was confirmed that in practice, non-structural components are seldom considered in the structural design, neither are they included in the advanced design analyses.

AIM AND OBJECTIVES OF THE BUILDING INVESTIGATION

The aim of this investigation is to further understand the performance of tall buildings and the load resisting mechanisms of the tall-building structures by comparing the differences in the design of tall-building structures in different regions.

This study has the following objectives:

- Observation of buildings chosen in different regions;
- Identification of main-design features of the buildings investigated;
- Identification of main non-structural components of each building;
- Discussion with local engineers to understand the design focus of tall buildings in different locations.

Table 1: Buildings and regions included in this paper

<i>Country/Region</i>	<i>City</i>	<i>No. of buildings</i>	<i>Building name</i>
Australia	Melbourne	1	Dock 5
	Sydney	1	World Trade Tower
	Gold Coast	1	Q1 Tower
Taiwan	Taipei	3	1. Taipei 101
			2. Xinyi district commercial building
			3. City Hall subway apartment
P.R. China	Beijing	3	1. China World Trade Center-stage 3
			2. Fortune Plaza
			3. Jingguang Building
	Tianjin	3	1. The New Education Centre, Tianjin University
			2. Jiali commercial building
			3. Tanggu apartment
	Dalian	3	1. Hope Mansion
			2. Xinghai building
			3. Ganjingzi district apartment

The investigated buildings have different structural forms (for example, concrete frame with core and composite structure, and so on) and range from 30 m to more than 509 m, which represent the diversity of tall-building design in different regions. Table 1 is a summary of buildings and regions included in this article.

BUILDINGS IN AUSTRALIA

Australia is recognised as a very diverse country in terms of its climate and environment. A large proportion of the land in Australia is semi-arid or desert and the major cities and its population are principally located along the south-eastern and south-western coastlines (Australian Bureau of Meteorology: <http://www.bom.gov.au/lam/climate/>). The climate of Australia is significantly influenced by the surrounding oceans. Except for the wide area of desert and grassland in central Australia, in major cities hosting most of the population, the climate varies from temperate along the south-eastern coastline to subtropical on south-western coast and tropical and equatorial in the north.

Natural hazards including bushfires, cyclones, earthquakes, floods, landslides, severe weather, tsunami and volcanoes, affect every Australian state and territory (Australian Government Website: <http://www.australia.gov.au/>). However, the likelihood and consequence of each natural hazard varies from place to place. Scientific methods for evaluating these natural hazards in each city or state in Australia are well-developed. Consideration of the consequences brought on by natural hazards for different structures should be assessed by judging the likelihood of hazards in the specific locations during the structural design life. Detailed introduction to hazard quantification will not be provided, as it is beyond the scope of this study. Generally, cyclones are severe in the northern part of the country and only a small area in the south-western part of Australia (near Perth) has potentially high seismic-hazard level. In the cities discussed in this study (Melbourne, Sydney and Gold Coast), even though both types of hazard are rare, they should not be ignored in the design of structures. Thus, in the design of tall buildings in these three cities, wind load almost always governs the lateral stiffness but earthquake and cyclone resistance still needs to be considered carefully.

Dock 5 in Melbourne, Victoria

Dock 5 was constructed by Bovis Lend Lease Pty. Ltd. as the first residential building in the redevelopment of Docklands, Melbourne. The architects of this building are John Wardle Architects and HASSELL-Architects in Association. Structural consultants were

Figure 1: Dock 5, Dockland Melbourne, VIC. (a) Dock 5 in-use; (b) Dock 5 under construction.

Arup and Connell Wagner. In 2008, Dock 5 won the RAIA Best Overend Award for Residential Architecture-Multiple Housing (VIC).

In terms of structural features, the building is located along the eastern seaboard of Melbourne and consists of 32 storeys. The main structure of the building is reinforced concrete, with a concrete core and two sets of shear walls integrated by floor slabs. The floor plans of Dock 5 are very complicated and vary throughout the building height. Figure 1 (a) and (b) shows the building in-use and under construction respectively.

It was confirmed by the structural engineer (Arup Melbourne Office) that owing to its coastal location and the weather conditions in Melbourne, wind load governed the overall design of the lateral resisting system of the building.

The key non-structural components identified in this building are partition walls and glass facades. Based on Australian standards and discussions with the structural engineers, these non-structural components are considered to be isolated from the structural design and are not taken into account in the structural system.

World Tower in Sydney, New South Wales

The World Tower is located in Liverpool Street, Sydney, NSW. It is a 230 m high building, having 73 above ground levels and 10 underground basement levels as shown in Figure 2. This building was constructed by Meriton Apartments Pty. Ltd., and it was the 2004 Bronze recipient of the Emporis Skyscraper Award. The World Tower was once the tallest residential building in Australia. The architect was Nation Fender Katsalidis and the structural engineer was Connell Wagner, Sydney.

High-strength concrete was used in the construction and the lateral resisting system of the building includes (Dean *et al*, 2001): (a) a central core of reinforced concrete shear wall elements; (b) a perimeter 'superframe' of columns, and belt beams located on every third floor; and (c) two pairs of eight-storey high triangulated post-tensioned outriggers between core and perimeter columns centred at the mid-height plant levels.

In terms of the design loads, wind load was assessed as the dominant lateral load in the east-west direction, whereas earthquake load was determined as the governing lateral force along the orthogonal direction (Dean *et al*, 2001) based on detailed computation taking into account the local environment and the geological conditions. Wind tunnel

Figure 2: World Tower, Sydney, NSW.

testing of this building was conducted by MEL Consultants at Monash University and predictions of the building behaviour, such as fundamental frequency and maximum deflections under wind loading, was made through the wind tunnel analysis.

The main non-structural components identified in this building include facades, which appear as curtain walls, partition walls and stairs. Based on observations and a review of the design standards and published research articles using this building as the case-study building (Dean *et al*, 2001), the non-structural components were separately designed, that is non-structural components were excluded in the structural design of the building.

Q1 Tower, Gold Coast, Queensland

The Q1 Tower (Queensland Number One) is located in Surfer's Paradise, Gold Coast, QLD. It is a super tall building, having 78 storeys with a roof height of 275 m. However, including the top spire/antenna, the total building height comes to 323 m, which makes it the tallest residential building in Australia.

Q1 Tower was developed by The Sunland Group and built by Sunland Constructions. The architect of this building was Atelier SDG and the building was the Silver Award winner of the 2005 Emporis Skyscraper Award.

The building is supported by 26 piles, 2 m in diameter that extend 40 m into the soil and then up to a further 4 m into solid rock. The Q1 Tower has Australia's only beachside observation deck: QDeck, which is 230 m above sea level. This building is designed in an oval shape inspired by the Sydney Opera House and the 2000 Sydney Olympic Torch. Apart from its unique shape, Q1 Tower is a typical concrete core with bundled perimeter columns structure. The major construction material is reinforced concrete. Large amounts of glass panels are also used in the construction of glass curtain walls and facades.

Figure 3(a) shows the street view of the Q1 Tower. A three-dimensional computer model of the tower is also obtained from Google Science (Figure 3(b))

Figure 3: QI Tower, Surfers paradise, Gold Coast, QLD (<http://sketchup.google.com/3dwarehouse/>). (a) Street view; (b) three-dimensional model view.

BUILDINGS IN TAIPEI, TAIWAN

Taiwan is a small island surrounded by the East China Sea, South China Sea and Philippine Sea. It is an island located in a complex tectonic area between the Eurasian Plate and the Philippine Plate (The Republic of China Yearbook 2008). The Taipei basin is situated on soft sandy soil sediments with high ground-water table. From the East-Asian Seismic Map (Figure 4), it is seen that the peak ground acceleration in Taiwan is higher than 4.8 m/s^2 , which in descriptive terms represents 'Very High Hazard'. Meanwhile, because of the surrounding seas, Taiwan's climate is marine tropical. Typhoons are common and the northern part, including Taipei, has a long rainy season from January to March. The whole island is dominated by hot and humid weather from July to September. Tall-building design is dominated by earthquakes and typhoon loading.

Three buildings were investigated in Taipei: the Taipei 101 building, the City Hall Subway Apartment Building and the Xinyi District Commercial Building.

Taipei 101 Building

Taipei 101 is a *landmark* in Xinyi District, Taipei (Taiwan Yearbook 2008). The 101-storey building was designed by C.Y. Lee & Partners and constructed primarily by KTRT Joint Venture. At the time of the field reconnaissance, Taipei 101 still officially held the title of 'the world tallest building' authorised by Council on Tall Building and Urban Habitat (CTBUH), the arbiter of tall-building height. Upon its completion, Taipei 101 claimed official records for:

- Ground to highest architectural structure (spire): 509.2 m;
- Ground to roof: 449.2 m;
- Ground to highest occupied floor: 439.2 m;
- Fastest ascending elevator speed: 16.83 m/s (60.6 km/h);
- Largest countdown clock: on display every New Year's Eve;
- Tallest sundial.

Figure 5 shows the view of Taipei 101 building from different directions. In terms of the structural features, Taipei 101 used high-performance steel construction, and massive

Figure 4: East-Asian seismic map.
Source: <http://geology.about.com/library/bl/maps/blaustraliaseismap.htm>.

Figure 5: Taipei 101, Taipei, Taiwan.

Figure 6: Tuned mass damper in Taipei 101, Taipei, Taiwan.

columns and enhanced bracing systems were adopted to achieve both the rigidity and the flexibility aimed at resisting typhoon and earthquake loads. There are 36 columns supporting the building, including 8 ‘mega concrete’ columns. Outrigger belt-trusses connect the columns in the building’s core to those on the exterior every eight stories. This building is a mega-frame structural system with a central braced core connected to perimeter columns on each building face, the total dead and live loads at every floor are transferred to the sloping exterior columns, which enhance the structural capacity to withstand lateral loading (Fan *et al*, 2009). To control the storey drift and vibration caused by lateral loads and to stabilise the building against the excessive movement, a 660-ton tuned mass damper has been installed inside the building on the top levels (Figure 6).

Non-structural double glazed glass curtain walls are used for heat and UV protection. The impact-bearing limit of the glass is 7 tons. Inside the building, there are some partition walls but most of the areas are open to facilitate multi-purpose usage such as retail malls, observation storeys and private clubs.

Analyses and discussions on the seismic performance and the structural system of the Taipei 101 building were provided (Gunel and Ilgin, 2007; Fan *et al*, 2009). However, information shows that little, if any consideration was given to the integration of non-structural components into the structural analysis of the building.

City Hall Subway Apartment

The building shown in Figure 7 is located near the City Hall subway station. It is a concrete framed structure with hybrid bracing bends forming V-bracing together with the zipper columns.

According to Brockenbrough and Merritt (1999), V-bracing is classified as a concentrically braced frame. The bracing members of these concentrically braced frames act as truss systems to resist lateral forces during earthquakes and heavy winds and are subjected primarily to axial forces in the elastic range. In severe earthquakes, significant inelastic deformation may occur in the bracing members, and this may lead the members into a post buckling stage because of the cyclic tension and compression. The concentrically braced frame is designed to avoid the preliminary failure of the overall structure.

V-bracing has the bracing connection at the mid-span of the beam. Under lateral loads, the two bracing elements act as compression and tension elements. However, the tensile

Figure 7: City Hall Subway Apartment, Taipei, Taiwan.

capacity of the bracing element is much higher than the compression capacity and the unbalanced force at the beam intersection may cause beam yielding during severe seismic excitation. Consequently, the energy dissipation can be significantly increased but the damage to the floor system may be severe. If V-bracing is used to help resist lateral loads, strong beams having high flexural capacity to withstand the unbalanced forces are required.

However, working together with the zipper columns, the disadvantages of the V-bracing system can be greatly reduced. The zipper column is an alternative to the strong beams for the V-bracing system. When beams buckle, the zipper columns can transfer the unbalanced forces and distribute the inelastic deformation to other bracing levels so that severe floor damage can be prevented.

In terms of the non-structural components, this building was still under construction with the primary structure completed at the time of the visit, but only part of the glazing system was visible. It is assumed that pre-cast concrete panels would most likely be involved as infill walls. However, considering the feature of the primary structure, tolerances of non-structural components connected to the structure would be a concern for the designers and the builders.

Xinyi District Commercial Building

Figure 8 shows a commercial building which was still under construction at the time of visiting. It is clear that the building is a composite frame structure with heavy bracing. In

Figure 8: Xinyi District Commercial Building, Taipei, Taiwan.

contrast to the building discussed in the previous section, the structural frame of this building is composed of concrete columns and steel beams, and the bracing system is zipper columns.

As discussed above, zipper columns can effectively distribute the beam deformation but they are normally used together with V-bracing or inverse V-bracing system. In this particular building, zipper columns alone are used together with concrete frame and shear cores to resist the lateral movement of the building.

In terms of the non-structural components, since the building was still under construction at the time of the investigation, it was hard to judge the type and material of facades and infill walls.

BUILDINGS IN BEIJING, P.R. CHINA

Beijing, the capital city of People's Republic of China, is an inland city in the northern part of China. Beijing is a city sitting 'at the northern tip of the triangular North China Plain' (MacKerras and Yorke, 1991). It is shielded by mountains to the north, northwest and west. Beijing's climate is a monsoon-influenced humid continental climate, which means humid and hot in summer whereas dry, windy and cold in winter. Moreover, because of the erosion of the desert in northern and north-western parts of China, dust storms happen seasonally in Beijing. The East-Asian seismic map (Figure 4) shows that the hazard level in most of Beijing is 'moderate', with the predicted peak ground acceleration of $0.8\sim 2.4\text{ m/s}^2$. However, some eastern areas of Beijing are categorised into areas with potential 'high to very high' seismic hazard which have peak ground accelerations of $2.4\sim 4.0\text{ m/s}^2$. The geotechnical conditions in Beijing are rather complicated, because of the frequent ground movements in ancient times. However, the investigated buildings are located within the Central Business District (CBD) area, where the ground conditions are stable and adequate for tall-building construction.

From the structural design perspective, both seismic and wind loads should be considered in the design of tall buildings.

The buildings investigated in Beijing were: the China World Trade Center III, the Jing Guang Centre and the Fortune Plaza Tower.

China World Trade Center III

The China World Trade Center III is a 330 m high, 80-storey building located in Beijing CBD. The architect of this building is Skidmore Owings & Merrill LLP, and the structural and geotechnical design was carried out by Arup Beijing.

In the design of this building, the width of the building decreases with the increase of the building height (Figure 9). Hence the column numbers need to be reduced up the building and the seismic performance needs to be carefully analysed. The designer finally chose composite steel walls as a core, composite columns and steel beams for the framing system working together with the bracing.

As far as non-structural components, the building has glass facades over its entire surface and it uses pre-cast concrete panels as partition walls. At the top levels, there are also truss-shaped concrete facades for decorative purposes.

According to the designer, even though the top facades of the building (truss-type facades) were originally considered as decoration, they were identified to have negative effects on the main structure under thermal loads. In the detailed design of the building, finite element modelling analyses were involved because of the complexity of the structure. The finite element models were developed and analysed for different loading conditions. The results revealed that under thermal loads, the movements of the top facades caused by the expansion and shrinkage of different parts can significantly affect the structural performance, especially the stress distribution in the adjacent components. Thus, the whole structure was re-analysed, giving serious consideration to the top facades, that is, integrating them into the structural design of the building.

Jing Guang Centre

Jing Guang Centre was built in 1990. It has 3 underground levels and 57 above ground. Its height is 208 m and it had been the tallest building in Beijing for a long time.

The Jing Guang Centre is a steel framed structure, with reinforced concrete shear walls. The bottom levels of this building use the steel re-inforced concrete (SRC) to form the structural frame, making full use of the advantages of SRC structures, that is, the high efficiency of concrete, low cost, outstanding seismic and fire resisting performance and easy construction.

Figure 9: The China World Trade Center III, Beijing, P.R. China.

Figure 10: Jing Guang Centre, Beijing, P.R. China.

In terms of non-structural components, pre-cast concrete panels are used as partition walls. The building also has elegant curved-shape double-glazed glass curtain walls from the base to the top (Figure 10). This subsequently increases the cost and the difficulty of manufacturing and installation of the curtain walls, and thus in turn, increases the vulnerability of the facades under different loading conditions, especially when these glass curtain walls are connected to the main structure and work together with the primary structure as a system (as they do in this case). However, based on the discussion with the structural engineers, as the design of tall buildings in Beijing is dominated by high gust winds and earthquake loads, rigorous design criteria on the serviceability of the building (typically a stiffer structure) is adopted by the Chinese Standards. This to a large extent limits the chance of those glass panels being exposed to large deflection introduced by the structural movement, and thus lowered the possibility of damage to these non-structural components. However, even these non-structural components are excluded from the design of the structure.

Fortune Plaza Tower

As shown in Figure 11, the Fortune Plaza Tower in Beijing is a building with a traditional square shape. It is 260m high and has 63 storeys. It is a typical re-inforced concrete-framed structure, with central cores and shear walls, as well as perimeter columns working together as its lateral resisting system (a bundled core system). It has floor to ceiling windows around the four sides, which means most of the outside walls are glass curtain walls. Pre-cast concrete panels are used as partition walls inside the building, but the

Figure 11: Fortune Plaza Tower, Beijing, P.R. China.

greater portion of areas are open because of the commercial use of the building. Similar to Jinguang Centre, the glass facades are the key non-structural components of this building and are vulnerable to different loads because of the large covering area and the very limited gap between them.

This, again, together with the findings from Jing Guang Centre, raises the question of whether these non-structural components should be integrated into the structural analysis to assess their vulnerability and/or to evaluate their structural contributions and the related cost savings.

BUILDINGS IN TIANJIN, P.R. CHINA

Three buildings were investigated in Tianjin, the New Education Centre in Tianjin University, an anonymous residential building and Tianjin Jiali Center Office Building.

Tianjin is the third largest city in China, ranked only after Shanghai and Beijing (<http://www.tj.gov.cn/english>). The climate and seismic hazard levels in Tianjin are similar to that in Beijing, for they are located close to each other. However, great differences exist in the geological conditions in these two cities. Beijing has rock (granite) beneath it in most areas whilst Tianjin typically has soft clay. In Tianjin, it becomes a challenge and can significantly influence the structural design and construction. Even though analyses of foundations is not within the scope of this study, the difference in the underground conditions in these two cities will directly lead to the variations in the design of buildings and thus variations of structural expressions despite using the same design code.

The New Education Centre in Tianjin University, Tianjin

The New Education Centre in Tianjin University was built for teaching and learning purposes (Figure 12). Driven by its functions, it has large open spaces, high storey

Figure 12: The New Education Centre in Tianjin University, Tianjin, P.R. China.

heights, large door and window openings and an efficient evacuation system. To achieve its function, the building consists of a traditional concrete frame with shear cores as its primary structural system. The concrete frame allows for large open spaces as classrooms and multifunctional teaching spaces, providing a most effective way of quickly evacuating people during rush hours and emergencies. The service cores are an integrated part of the lateral resisting system.

Glass facades are used on the outside of the building, similar to most modern tall buildings in China. The infill walls are built from pre-cast concrete panels and masonry.

Seismic design is also an important factor in the design of tall buildings in Tianjin. However, unlike Taipei where the city has a very high likelihood of severe earthquakes and typhoons, buildings in Tianjin normally do not adopt heavy bracing systems. Shear cores and strong frames are the commonly used lateral resisting systems.

Non-structural components such as infill walls and facades are widely included in tall buildings in Tianjin. Pre-cast concrete panels and masonry walls are the norm for infill walls and glass and aluminium frames compose the typical facade system for most of the tall buildings.

Jiali Center Office Building, Tianjin

This building is a commercial building designed by Arup Beijing Office (2008). It is a 72 level building, with the height of 333 m (Figure 13). The main lateral resisting system of the building is the braced steel frame with a concrete shear core. The designed maximum storey drift is approximately 450 mm.

After the discussion with the structural engineers, it was noted that the construction of infill walls in China is different to that in Australia and other places. In Australia, gaps between infill walls and the frame are specified in the structural design and are filled using elastic materials. This, to some extent, reduces the chance of direct contact between infill walls and the structural frame, and thus provides a margin to accommodate the actual movement of the infill wall. In China, the masonry infill walls are built to fill the frame, with the very top layer of bricks being oriented along an in-plane 45-degree diagonal line (approximately) (Figure 14). In this way, the energy transferred from the frame to the infill walls (introduced by frame movements) can be effectively dispelled by scarifying the top layer bricks.

Figure 13: Jiali Center Office Building, Tianjin, P.R. China.

Figure 14: Demonstration of the practice used for dissipating the load transferred from the frame to infill walls in China.

Moreover, out-of-plane behaviour of the infill panels (such as buckling) are not covered in this study. It is understandable that with a high slenderness ratio (in this study around 30:1), the infill walls will tend to buckle under the combination of gravity loads and the out-of-plane loads. Under these circumstances, the contribution of infill walls to the structural stiffness will be diminished and the algorithm of the analysis needs to be revised. However, this study only focuses on the serviceability of the structure and the in-plane behaviour of infill walls rather than its out-of-plane behaviour. Moreover, taking

into account the practices adopted above in different countries, the opportunity for the infill wall to buckle under these circumstances is slim.

Tanggu Apartment, Tanggu District, Tianjin

The Tanggu Apartment building shown in Figure 15 is a typical residential tall building in China. It consists of square-shaped reinforced concrete frames with cores as its primary structure. Pre-cast concrete panels and masonry are used for infill walls, whereas cladding is to be found on the surface of the outside walls. Floor plans for this type of building are normally regular throughout the building. Because of the location of the building, near the harbour, strong wind loading is expected. Also, because of the special soft clay ground conditions and high seismic hazard, the design of the building is focused on the stability and the strength of the structure.

Further, the foundation design of tall buildings in Tianjin is often a bottle-neck in most structural designs. Deep pile foundation or pile foundation with underground aligning walls and plates are widely adopted in current construction in Tianjin. These types of foundations can efficiently solve problems such as uneven settlement caused by the soft clay ground conditions and the seepage of underground aligning walls caused by the high underground water table.

BUILDINGS IN DALIAN, P.R. CHINA

Dalian is a coastal city lying in the northern part of China and it is neither within a high seismic-hazard region nor in a high wind region. Hence, the design emphasis differs from that in Beijing and Tianjin. The buildings investigated in this city include: The Hope Mansion, Ganjingzi District Apartment and the Xinghai Guobao Residential Buildings. The construction sites of Dalian city mainly have solid rock foundations with very limited ground water, hence providing better ground conditions than Tianjin.

The Hope Mansion

The Hope Mansion building is a 170m high building, with 41 floors including 3 basement levels (Figure 16). It is a re-inforced concrete structure and includes a great proportion of pre-stressed components. The lateral resisting system of this building is a concrete core and frame with main supporting columns at the four corners of the building and a narrow base at the bottom as shown in Figure 16.

Figure 15: Tanggu apartment, Tanggu District, Tianjin, P.R. China.

Figure 16: The Hope Mansion, Dalian, P.R. China.

As Dalian is not a city with severe seismic hazard or wind hazard, the requirements for the rigidity and ductility of the structure are not as great as that of buildings in other cities such as Taipei and Beijing. From Figure 4, the seismic-hazard level of Dalian is shown as low, which means the peak ground acceleration would be $0.2\sim 0.8\text{ m/s}^2$. The seismic-resistance level of this building was designed at level 8 specified in the Chinese design standards.

Non-structural components involved in this building include pre-cast concrete panels as partition walls and glass panels, vertically meshed by surface concrete frames, as facades.

Ganjingzi District Apartment Building

The apartment building located in Ganjingzi District in Dalian was still under construction at the time of the visit. As shown in Figure 17, it is clear that the building has a concrete frame structure with shear walls as its main lateral resisting system, similar to the Tanggu Apartment in Tianjin. The structural forms of these two buildings are typical of most residential buildings in China. However, as Dalian has better ground conditions and lower seismic-hazard levels than Tianjin, the overall strength and stiffness requirement of this apartment building would be less than those of equivalent residential buildings in Tianjin.

Figure 17: Ganjingzi district apartment building, Dalian, P.R. China.

Xinghai Guobao (National Treasure) Residential Buildings

The Xinghai Guobao residential buildings are located on the edge of Xinghai Square, Dalian. Xinghai Square sits at the north of Xinghai bay, and takes a shape like a giant star. As shown in Figure 18, modern characteristics and traditional Chinese cultural elements are combined in the architectural design of these buildings, making them elegant and outstanding.

These buildings are designed especially as high-class accommodation and are spacious, comfortable and secure. Their primary structural systems consist of concrete frames, shear walls and concrete cores. For the secondary structural elements of these buildings, claddings, infill walls and floor-to-ceiling windows are all widely adopted.

DISCUSSION AND COMPARISON

It can be seen that buildings investigated in different cities in Australia, Taiwan and Mainland China have characteristic design features. These are determined by complicated factors, such as local culture, climate, geographical condition and particular requirements. A brief summary of the features of buildings investigated is presented in Table 2.

In Australia, because of the low probability of seismic hazard in most of the areas, especially in the three cities investigated, wind force governs the lateral design of high-rise buildings in most cases. Concrete and steel frame structures are commonly utilised in Australia, having large amounts of glass facades and partition walls in both commercial and residential buildings. Discussions with structural engineers in Australia indicated that even though the individual non-structural components are designed in detail according to specific standards, they are considered isolated from the primary structure and are not integrated in to the structural design analysis.

Dominated by seismic loading and wind loading, the design of tall buildings in Taiwan and Mainland China mainly focuses on the primary structure. No matter what type of structural

Figure 18: Xinghai Guobao residential building, Dalian, P.R. China.

form is adopted, the core strategy of design is to assure the stability and ductility of the primary structure, that is the structural frame, the core and the whole lateral resisting system, to make sure the primary structure of a building will not be damaged during severe earthquakes and/or high winds. In terms of the secondary elements, although infill walls and facades are widely used in tall buildings in these cities, they are seldom included in the holistic design. There seem to be several reasons why the integrated inclusion of the secondary elements in the structural designs in Taiwan and Mainland China is not considered:

- during severe earthquakes and high wind attack, damage to non-structural components is inevitable. To be more cost-effective, both the designer and the client would not spend time and money developing/integrating the secondary elements into the structural analysis, even though it might be beneficial from the long term point of view;
- extra rigidity and ductility have been designed into the primary structure for the worst load cases. Thus, when under service load, the overall movement of the structure will be much less than that of a building designed in non-hazard areas. This directly leads to diminished interaction between the primary and secondary structural elements thereby eliminating the damage/influence of the secondary elements;
- different approaches are used in the construction of the secondary elements. For example, as discussed under the heading 'Buildings in Beijing', in China, masonry infill walls are built with the top-layer brick lying on a 45-degree gradient. This can effectively eliminate the pressure transferred from the frame deformation, which to some extent isolates the non-structural components from the primary structure.

Overall, for the 15 buildings in 7 cities, it is hard to conduct a systematic comparison, but some salient points are summarised in the following sections.

Buildings in Australia

The three buildings investigated in Australia, as well as observations and communications with local industry indicate that the following features can be summarised for high-rise buildings in Australia:

- steel and re-inforced concrete structures with structural frames, concrete cores and shear walls as the lateral resisting systems are widely adopted in the design of high-rise buildings;

Table 2: Summary of structural features of buildings investigated

Location	Name	Storey	Height (m)	Dominant lateral load	Structural form	Main material	Typical non-structural components
Melbourne, Australia	Dock 5 building	32	96	Wind	Core + shear wall; flat slab	Re-inforced concrete	Glass facades; partition walls; and infill walls
Sydney, Australia	World Tower	73	230	Earthquake and wind	Core + shear wall + outrigger frame	Re-inforced concrete	Facades (appears as curtain walls); partition walls; and stairs
Gold Coast, Australia	Q1 Tower	78	323	Earthquake and wind	Core + bundled columns	Re-inforced concrete	Glass curtain walls
Taipei, Taiwan	Taipei 101	101	509.2	Earthquake and typhoon	Braced core + mega columns + mega frame	Re-inforced concrete and steel	Double glazed glass curtain walls and partition walls
Taipei, Taiwan	City Hall subway apartment	30 +	90 +	Earthquake and typhoon	Frame + V-bracing + zipper columns	Re-inforced concrete and steel	Facades and infill walls (estimated)
Taipei, Taiwan	Xinyi District Commercial Building	—	—	Earthquake and typhoon	Composite frame + zipper columns	Re-inforced concrete and steel	Unknown
Beijing, China	China World Trade Center III	80	330	Earthquake and wind	Core + composite frame + bracing	Re-inforced concrete and steel	Glass facade; truss-shaped concrete facade; and partition walls
Beijing, China	Jing Guang Centre	53	208	Earthquake and wind	Frame + shear walls	Re-inforced concrete and steel	Glass curtain walls and partition walls
Beijing, China	Fortune Plaza Tower	63	260	Earthquake and wind	Core + frame + shear walls	Re-inforced concrete	Glass curtain walls and partition walls
Tianjin, China	The New Education Centre in Tianjin University	10 +	30 +	Earthquake and wind	Core + frame	Re-inforced concrete	Glass curtain walls; partition walls; and infill walls
Tianjin, China	Jiali Center Office Building	72	333	Earthquake and wind	Core + frame	Re-inforced concrete	Glass curtain walls; partition walls; and infill walls
Tianjin, China	Tangu Apartment Building	30 +	90 +	Earthquake and wind	Core + frame + shear walls	Re-inforced concrete	Infill walls and partition walls
Dalian, China	The Hope Mansion	41	170	Wind and earthquake	Core + frame + corner columns	Re-inforced concrete	Partition walls and Glass curtain walls
Dalian, China	Ganjiangzi Apartment Building	20	60	Wind and earthquake	Frame + core	Re-inforced concrete	Infill walls
Dalian, China	Xinghai Guobao residential building	40 +	120 +	Wind and earthquake	Frame + core	Re-inforced concrete	Infill walls; Partition walls; and facades

- in the design of high-rise buildings, wind load normally governs in terms of the stability and serviceability of the structure owing to the low seismic-hazard level in most parts of Australia;
- glass facades are involved in most commercial buildings and the facade system is designed separately by facade engineers and is considered detached from the main structure in the structural design;
- pre-cast concrete panels and masonry walls are used as partition walls/infill walls for buildings and they are considered as non-load bearing components which are isolated from the primary structure.

Buildings in Taipei, Taiwan

From the investigation of the three buildings in Taipei, it can be concluded that tall buildings in Taipei have the following common characteristics:

- regardless of the different structural forms, all the tall buildings are designed mainly to resist the seismic and typhoon loads;
- both concrete and high-performance steel structures are common in Taipei; braced frames are the most widely used structural form for tall buildings in Taipei. Even though different types are chosen according to the specific requirements of different buildings, bracing is very popular in tall-building design because of its capacity to provide extra ductility and extra stability to the structural frame;
- modern glass facade/curtain walls, pre-cast concrete infill panels are the commonly used secondary elements for decoration and thermal purposes.

Buildings in Mainland China

Compared with other cities, the three cities in China have many more very tall buildings. However, in terms of the structural features, a lot of similarities can be found. The structural features of tall buildings in Mainland China can be summarised as follows:

- the dominant lateral loads in tall building design in China are earthquake load and wind load;
- framed structures with concrete cores are the most common structural form used in tall buildings in China, whereas bracing systems are also readily identified in many buildings;
- pre-cast concrete panels are normally used as wall panels, and masonry infill walls are also widely used in tall buildings;
- claddings in various materials such as glass and ceramics, are common elements of tall buildings;
- many commercial buildings in China have modern facade systems on the outside of the buildings. Glass panels with aluminium frames are the most common type of facades;
- the facade systems in China are mainly considered for thermal purposes, that is the main load-bearing considerations for the facade design are thermal loads if relevant;
- the diversity of foundation conditions makes the design of tall buildings even more challenging in China.

CONCLUSIONS

The structural design of high-rise buildings is greatly influenced by their environment, the local geological conditions and the local culture.

It can be concluded that even though the structural form of tall buildings is more or less similar in different regions, subtle variations of the design features exist because of the complex influence of local conditions.

Considerable non-structural components are involved in the buildings in each city studied. Glass facades, pre-cast concrete partition walls, and masonry infill walls make up a proportion of the components of a building. Moreover, these non-structural components are all designed according to various standards as individual components separate to the structural design.

Few of the non-structural components are considered in a holistic structural analysis. However, all of them are physically connected to the primary structures by various connections.

It is clear that current design analysis of tall buildings in different regions does not show close correlation with construction practice in terms of interaction between the primary structure and non-structural components.

In Australia and countries having similar geological conditions, where there is very low likelihood of earthquakes and cyclones in most parts of the country, the design of high-rise buildings is mainly governed by wind load. Moreover, to a great extent, the serviceability (for example, the lateral drift) of the building dominates the behaviour and the design of tall buildings. It appears that the evaluation of the influence of integrating non-structural components into the structural design is important to local design practice.

In Taiwan, Mainland China and countries having similar geological conditions, seismic-hazard levels and other extreme loading conditions (for example, typhoon), the design of tall buildings is governed by these extreme loading conditions and the strength and stability of the structure are the dominant factors in building design. Hence, the potential advantage of integrating non-structural components into the structural analysis of the overall building performance may not be of interest in tall-building design in these regions. This is because the contribution of non-structural components to the building performance are minimised because of the consideration of extreme loadings. However, the potential for damage to the non-structural components caused by the interactions between the primary structure and non-structural components during the service life of the building remains a risk and is worthy of further investigation.

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