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# The Evolution of Outrigger System in Tall Buildings

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**Abstract**

The structural efficiency of tall buildings heavily depends on the lateral stiffness and resistance capacity. Among those structural systems for tall buildings, outrigger system is one of the most common and efficient systems especially for those with relatively regular floor plan. The use of outriggers in building structures can be traced back from early 50 from the concept of deep beams. With the rise of building height, deep beams become concrete walls or now in a form of at least one story high steel truss type of outriggers. Because of the widened choice in material to be adopted in outriggers, the form and even the objective of using outrigger system is also changing. In the past, outrigger systems is only used to provide additional stiffness to reduce drift and deflection. New applications for outrigger systems now move to provide additional damping to reduce wind load and acceleration, and also could be used as structural fuse to protect the building under a severe earthquake condition. Besides analysis and member design, construction issue of outrigger systems is somehow cannot be separated. Axial shortening effect between core and perimeter structure is unavoidable. This paper presents a state-of-the-art review on the outrigger system in tall buildings including development history and applications of outrigger systems in tall buildings. The concept of outrigger system, optimum topology, and design and construction consideration will also be discussed and presented.

**Keywords:** Tall buildings, Outrigger system, Structural design, Construction, Damped outrigger system, Fused outrigger system

## 1. Introduction

The race to the sky started from the time of the Tower of Babel once people found the ways in making bricks. Nowadays, engineers use reinforced concrete, steel or composite material of steel and concrete to build high - rise buildings. Furthermore, various lateral structural systems such as shear wall, core plus perimeter frame, tube-in-tube, core plus outriggers with or without belt truss and mega frame etc. were developed. Ali and Moon (2007) had a comprehensive review on the development of structural systems for tall buildings. Among the systems adopted by Ali and Moon (2007) "outrigger structures" is the category with efficient height limit up to 150 storeys. Hong Kong Cheung Kong Center (290 m), Hong Kong IFC2 (380 m), Hong Kong ICC (450 m), Taipei 101 (509 m), Guangzhou CTF Tower (520 m) are typical well known tall building examples using outrigger system.

The first building with elevators was the Equitable Life Assurance Building in New York completed in 1870. This 40 m tall building was named as the world first tall building. The structural system is just simply framed building. With the height of buildings increasing, the design will be controlled by stiffness and displacement. By simple engineering principle as shown in Fig. 1, the lateral resistance increases if the perimeter can be coupled with the core (Fig. 1a). Furthermore, the deeper the beams (Fig. 1b) which stretch out from the core to the extreme perimeter, the stiffer the structure will be. Therefore, engineers started considering using stiff beams to connect both the core and the perimeter tube. It is obvious that the stiffer the beam, the further increase in lateral stiffness. Once the building height increases, it is very difficult to adopt the "stiff" beam concept as the depth of the "stiff" beam will be like a wall. Outrigger systems were therefore developed. Shankar Nair (1998) proposed the concept of the "Virtual Outrigger" but engineers must make sure that the stiffened coupled floors and the vertical perimeter structures can provide sufficient stiffness to behave as outriggers.

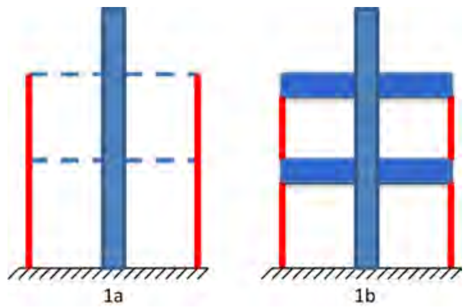


**Figure 1.** Model showing building with and without deep beam.

After World War II, the use of steel in tall buildings become popular because of the speed of construction and

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reduction in labour cost etc. With buildings with typical slenderness ratio and taller than 40 storeys, the "stiff" beam become very deep or to be replaced by concrete wall or by means of single or double story high steel truss. Although the use of the outrigger system is getting more widespread, research in outrigger is still very limited. Taranath, B. S (1998). , Stafford Smith (1991), Gerasimidis et al. (2009) and Fawiza et al. (2011) studies were focused on the overall efficiency of outrigger systems in tall buildings in controlling drifts and optimum locations of outriggers. Nevertheless, the possible locations which allow the designers to install the outrigger system are limited by the usage and the layout of the building. In practice, outriggers are limited to be installed in mechanical or refugee floors instead of "optimum" locations. In some countries the refugee floors are in fixed numbers (e.g., China refugee floors are required for every 15 floors), the locations for installation of outriggers are not determined by engineer but the program of the tall building. It is an ideal situation that outriggers should be as deep as possible and therefore engineers will try to request to have double story height space for outriggers. However, in some buildings, the floor spaces which can allow for outriggers to be installed are limited to be single story height. Therefore, study on optimum topology of outriggers layout rather than the optimum locations of outriggers is more practical. Ho (2016) presented a series of study of commonly used topology of outrigger system and comparison on their stiffness and strength etc were listed.

Besides that, engineers believe the performance of tall buildings against drift is a linear function of outrigger stiffness. Hence, there is a tendency of providing oversize and overstiff outriggers in tall buildings. However, wind loading is not the only lateral loads for tall buildings; seismic resistance is also an important factor for considerations in some area. Therefore, a balance for the stiffness, strength and ductility of the outriggers should be an area which engineers should pay special attention.

Outriggers increase the stiffness of buildings by means of converting the lateral forces into push (compression) and pull (tension) forces in the perimeter structures. Hence, outriggers are required to resist reverse and cyclic loading. From engineering principle, the topology for outrigger system should be symmetric to both upward and downward load such that it provides similar performance in all load cases. If symmetric topology cannot be used, the designer must be aware of the behaviour of outriggers under cyclic load.

## 2. Concept of Outriggers Structural System

The idea of outriggers in building structures is to couple the perimeter and the internal structure as a whole to resist lateral load. Considering the structure as shown in Fig. 2, both the internal core and the perimeter frame (or tube) are uncoupled. Therefore, the core and perimeter frame resist the lateral load by means of pure cantilever action only. In theory, if the internal beams between core and perimeter are getting deeper and stiffer, the core and perimeter frame can work together to resist lateral forces. However, as the typical span between core and the perimeter frame is in the range of 9 m to 15 m, it is very difficult to provide beams which are stiff or deep enough to couple the core and the perimeter frame especially when the building is slender.

All tall buildings have refugee floor(s) and some buildings with mechanical floors at intermediate levels. This provides the opportunity for engineers in fully utilizes these spaces (sometimes from single to triple stories high) to stiffen-up the structures. For ease of presentation, the outriggers are draw as a deep beam as in Fig. 3. Assuming the outriggers are strong enough to generate restraining moment M1 and M2, the moment at the base, oMbase will be reduced by (M1+M2), i.e.,

$$\text{Mbase} = \text{oMbase} + \text{M1} + \text{M2} \qquad (1)$$

Eq. (1) can be rewritten in the following form:

$$\text{oMbase} = \text{Mbase} - \text{S Mi} \qquad (2)$$

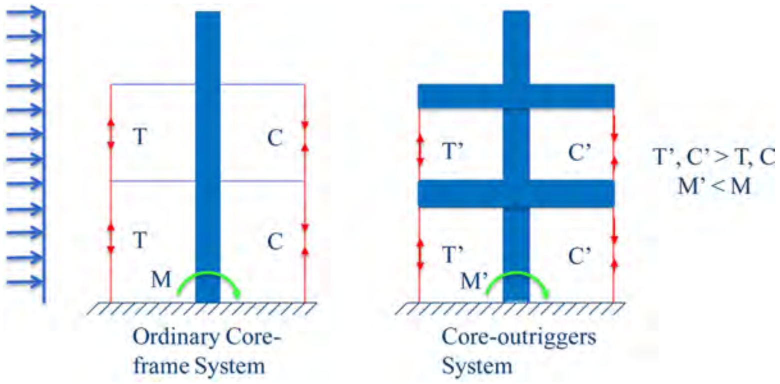



**Figure 2.** Difference between ordinary core-frame and core-outriggers system.

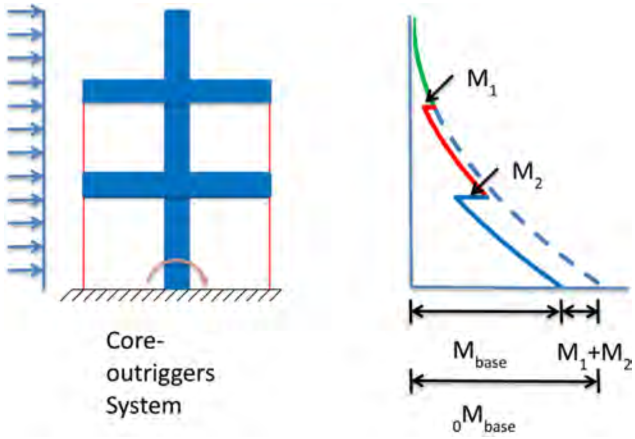



**Figure 3.** Difference of Moment Diagraph between Ordinary and Outrigger Frame.

where Mi is the restraining moment of the i-number of outriggers.

From Eq. (2), the base moment gets smaller by either increasing the magnitude of Mi and /or the number of outriggers (i.e., i). However, if the magnitude of Mi is limited or small, even though there are many outriggers, oMbase will still be close to Mbase. In other words, it is more efficient for an outrigger system, building with strong outriggers rather than increasing the number of outriggers with small stiffness.

## 3. Optimium Locations and Topology of Outriggers

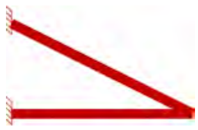
With the location constraints in outriggers installation and findings on Eq. (2), the outriggers stiffness become the prime objective in structural optimization. However, publicly available information on outriggers topology and stiffness is limited. Ho (2016) study is one of the key resources on topology, stiffness and strength relationship in outriggers. Ho (2016) studied several outrigger topologies based on same space constraints. It is very interesting to find out that outrigger strength is not a direct function with stiffness. The results from Ho (2016) are being summarized as in Table 1.

From Ho (2016) studies, it is important to point out that outrigger with highest stiffness may not mean the most structural efficient outrigger system and designer should find the appropriate system in balancing the wind and earthquake cases. For tall buildings under wind cases, stiffness is always the most important to control the drift while ductility is more important in earthquake cases.

## 4. Outrigger Design Issues

There is no difference in designing outrigger elements and typical beam-column elements. One of the key concerns in outriggers design is the lock-in forces due to differential shortening between core and perimeter frame. Shortening of core and perimeter frame are mainly due to elastic deformation, shrinkage and creep. As the stiffness of outriggers is generally very high, a small vertical deflection will induce very large forces in outrigger elements. Although engineers can easily predict the amount of elastic shortening, both shrinkage and creep are time dependent variables. It also means that shrinkage and creep will not occur once the building is complete or under operation. To eliminate the elastic shortening effect, engineers can provide delay joints such that the outriggers can be connected once the structures and majority of the loading are added to all vertical elements. However, engineers must find ways in ensuring the lateral stability during the construction stage or in the situation when the outriggers system is not under operation.

**Table 1.** Summary on Outrigger Topology by Ho (2016) studies

| Topology |  A |  B |  C |  D |
|---|---|---|---|---|
| Material | 1.00 | 1.04 | 1.80 | 1.49 |
| Stiffness | √√ | √ | √√√√ | √√√ |
| Strength | √√√√ | √√√ | √ | √√ |

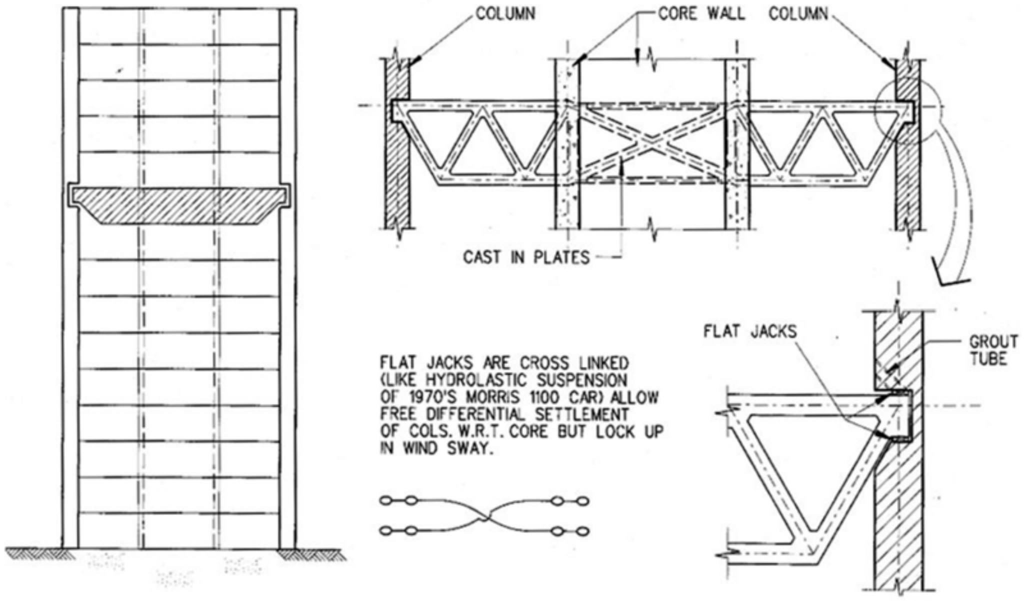



**Figure 4.** Cross-jacks system for outrigger construction (with courtesy of Kwok and Vesey).

# 5. Adjustable Outriggers System

## 5.1. Cross-jack system

Kwok and Vesey (1997) proposed an idea of using flat-jacks in balancing the loads on outriggers/columns connection. The concept allows outriggers to be connected during construction. Through the flat jacks at top and bottom of outriggers, the levels of outriggers can then be adjusted by tuning the top and bottom jacks. The jacks will finally be grouted at the end of construction to provide permanent connections. With Kwok and Vesey's permission, their sketches are replicated here as Fig. 4.

Although the cross-jacks system solves the elastic shortening problem and at the same time maintains the lateral stability, it is unable to handle shrinkage, creep and also the variable live load during the service period of the building.

## 5.2. Shim-plate correction method

A modified version of the cross-jacks system was suggested by Ho et al. (1999) and applied in the design and construction of Cheung Kong Center in Hong Kong in 1995.

Cheung Kong Center is a 300 m tall high-rise building, consists of an RC core wall and a perimeter frame. The perimeter frame is made of concrete filled tube columns at 7.2m c/c. Because the core is in rectangular shape, the outriggers are not able to straightly connect to columns. A belt truss system is adopted to minimize the shear lag effect as well as evenly distribute the outriggers vertical forces to perimeter columns.

The maximum slenderness ratio of the core is 15 and is highly likely to have typhoons during construction. Therefore, the outriggers needed to be in operation once the outriggers are installed. This is to enhance the lateral stiffness of the structure during construction. For all outrigger/perimeter connections, vertical gaps are provided at top and bottom.

Following the completion belt truss and outriggers, steel plates were inserted at both top and bottom side of outrigger tips to allow vertical load transfer. This is called as "Shim Plate Correction Method". The idea is similar to aforementioned "Cross-Jacks Method" but more robust shim plates replace flat jacks in both temporary and permanent stages. Furthermore, strain gauges are installed in the outrigger elements, the gap size can be adjusted through the life cycle of the building to allow for say 10 years or 30 years creep etc.

The locked-in forces in the outriggers due to axial shor-

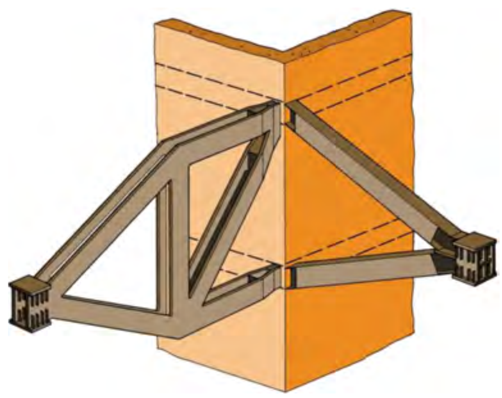


**Figure 5.** 3D images of the outriggers system used in Cheung Kong Center (with courtesy of Arup).

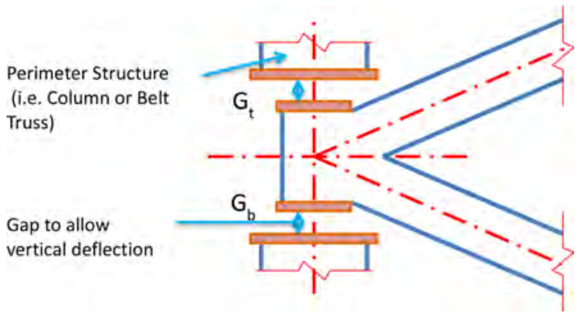



**Figure 6.** Typical Details for Outriggers tips Details used in Cheung Kong Center.

tening in the perimeter frame could be very large. With the author's experience, it could be similar magnitude as forces due to lateral load. In other words, the size of the outrigger would be double if the axial forces due to shortening cannot be released. With the Shim Plate Correction Method, such locked-in forces could be 100% release once the top shim plates were removed. As the outriggers

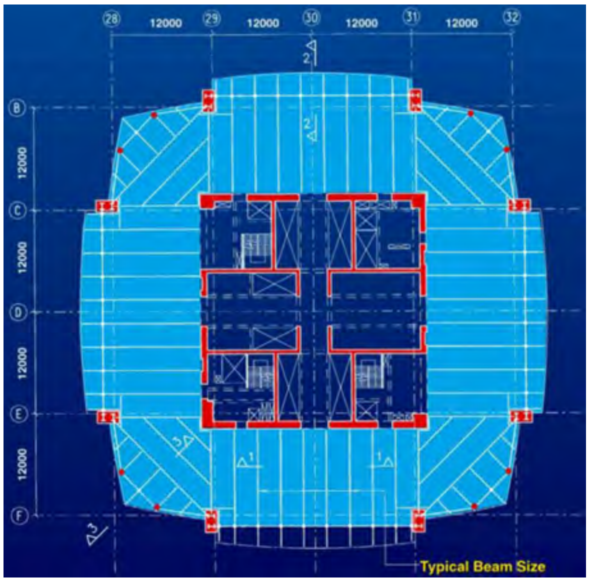



**Figure 7.** Typical Floor Plate of IFC2, Hong Kong (with courtesy of Arup).

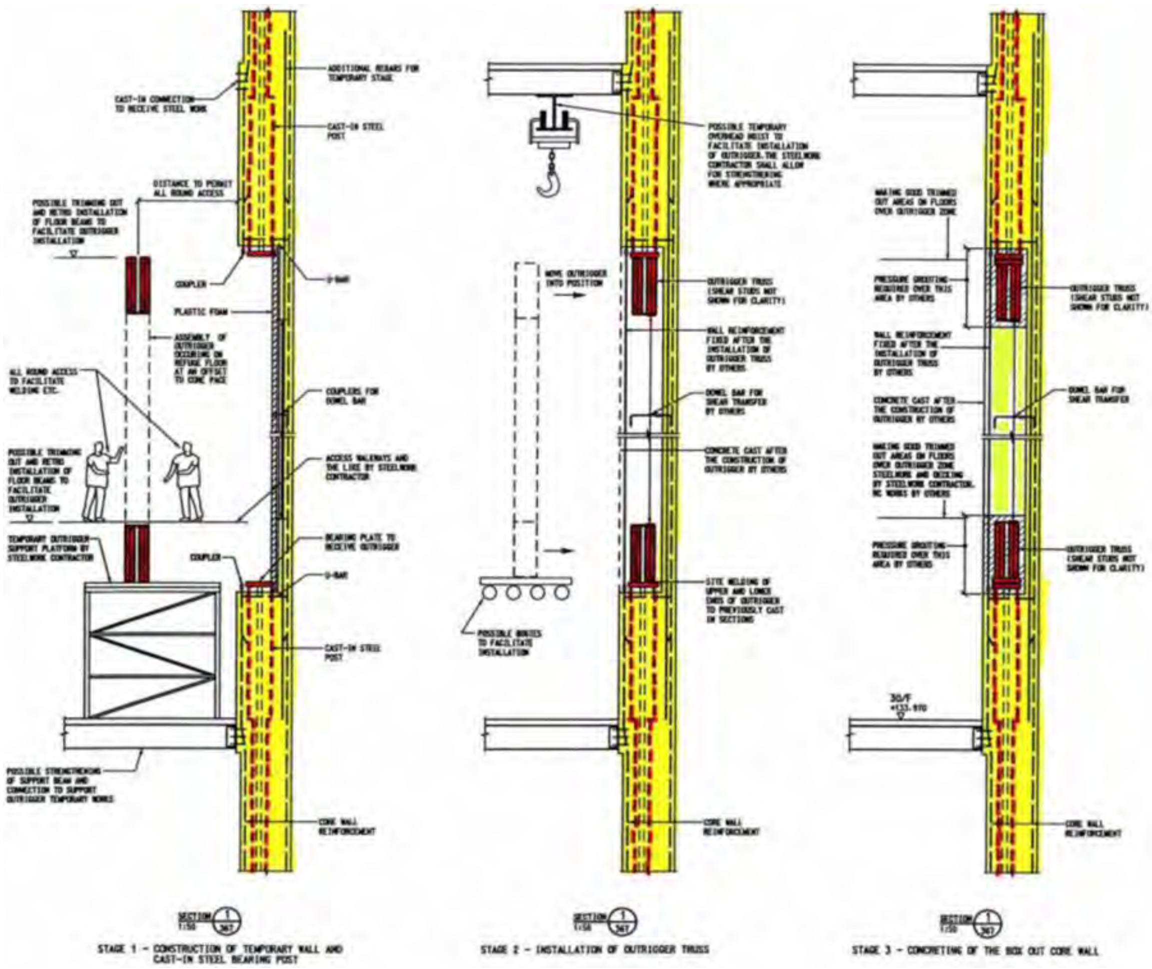



**Figure 8.** Retro-casting Construction Sequence of Outriggers (with courtesy of Arup).

are still in elastic range, the outriggers returns to their undeformed shape. After the relaxation procedure, shim plates will be refilled to allow vertical load transfer. This procedure will be repeated during construction stage. Monitoring process was also carried out after construction and repeat until the axial shortening was found to be steady (i.e., shrinkage or creep has reached). As the axial shortening lock-in force was released in each relaxation procedure, the outriggers will therefore mainly used to resist the lateral load.

**5.3. Retrocasting techniques in outriggers construction**

Following the Cheung Kong Center in which design was started in 1995 and top out in 1997, it was noticed that the critical path for construction is at the outrigger levels. When Arup started the design of the Two International Finance Centre in late 90's, a new method of outrigger construction was introduced. This provides another significant step forward in the development of core and outrigger systems for super high-rise structures. To provide flexible office floor configurations for the tenants connected to the financial industry in this 88 story, 412 m tall tower with 24 m column spacing, mega columns with outriggers system is adopted.

Three levels of triple story high outriggers are provided and located in a straight alignment with the core wall edges. Belt trusses corresponding to the outrigger locations also serve to transfer loads from secondary corner columns to mega columns.

In traditional construction method, the speed of core wall construction will be in the order of 3 to 4 days per floor but nearly a month for outrigger levels due to lifting, welding and installation of outriggers component. To allow fast track construction and not to delay the core wall construction, the core at outrigger levels was partially blocked out as shown in Fig. 8, during construction.

With retro-casting techniques, the construction of core wall will be separated from outriggers. After the installation of outriggers, the core will be backfilled with concrete to form a monolithic element. With retro-casting procedure and very detailed construction plan, the construction speed as normal core wall without outriggers construction could be achieved.

## 6. Damped Outrigger System

Because the fundamental concept of outrigger system is on the increase in lateral stiffness, most engineers will considered that the stiffer the outrigger, the better. This concept is one way is correct but may not be appropriate for buildings in seismic region also with strong wind.

For tall buildings design, the design performance objectives are wind comfort and seismic performance. The common parameter in handling both wind and seismic is the damping of the structure.

Damped outrigger system was developed by Arup and firstly incorporated in the design of the St. Francis Shangri-La Place development in Manila, Philippines. The development is located with 2 km from an active fault but also subject to very strong wind. The reinforced concrete tower is 217 m tall with a core and one level of concrete outriggers in both directions. For each piece of outrigger, it is connected with the columns though a viscous damper. Since the dampers permit relative movement, this system provides a significant increase in damping but a smaller increase in stiffness than provided by a traditional outrigger system.

With the availability of latest technology, viscous dampers can now be designed for a nonlinear response and tuned to meet multi-level performance objectives. In case the dampers fail, the outriggers have been designed to yield in a ductile manner but remain intact.

With the additional damping provided, the wind response also reduces the required structure lateral stiffness and

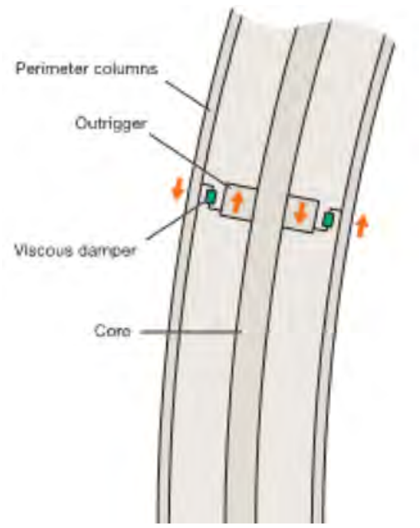



**Figure 9.** Damped Outrigger Concept (with courtesy of Arup).

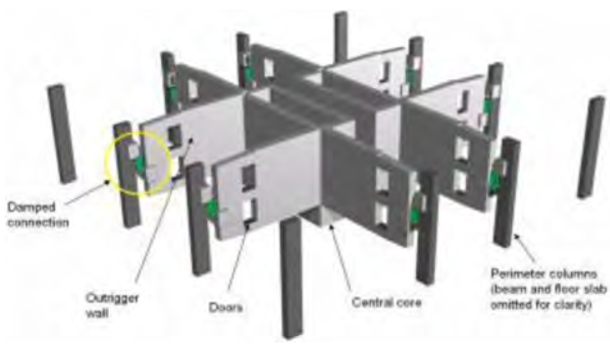



**Figure 10.** 3D images Outriggers Level (with courtesy of Arup).

hence the material cost. The saving of material therefore offsets the additional costs for dampers, testing and installation of this system, increase in useable area and structural performance of the overall structure.

## 7. Concrete Outrigger System with Structural Fuse

Steel outrigger systems were extensively used in a lot of tall buildings as most of tall buildings are either steel or composite structural system. For reasons such as cost, locally available material and workmanship consideration, some high-rises are concrete structures. In such circumstances, concrete outrigger system would first be considered.

The benefit of concrete outrigger system verse steel is high stiffness and low cost. Theoretically speaking, under wind load cases, the outrigger system need to be stiff and behave elastically. In severe earthquake events (i.e., 2475 years RP event), the system should be able to dissipate energy and maintain it robustness as lateral system to protect the buildings against collapse. However, we understand that a pure concrete outrigger system is very brittle. Damped outrigger system as mentioned in section 6 above is good as it serves for both frequent wind and earthquake situations. However, the stiffness of the outrigger system reduces a lot because of the damper. In the case where the outrigger system need to be stiff in gravity and lateral load case without extra damping, damped outrigger system may not be an appropriate system.

In 2014, Arup team (Zhu et al. (2016)) developed a new outrigger system - concrete outrigger system with structural fuse for the Chong Qing Raffles City Project (Fig. 11) which consists of six number of curved towers, the highest two being 300 m tall. Chong Qing is located inland, with relatively low wind load and moderate seismicity. Similar to most tall buildings in Chong Qing, the building is controlled by drift in wind cases. The building itself requires the outrigger to be connected by level 30 to provide lateral stability during construction. Therefore damped outrigger is not appropriate for this project.

With the curved nature of the tower, the structural lateral system for the twin 300 m towers is core/mega columns/ belt truss/secondary frame/outriggers system as in Fig. 12. In between the mega column and concrete outrigger, there is a shear dissipation component (i.e., structural fuse) connecting the outrigger and the mega column. The component was designed such that it remains elastic in gravity, wind cases and also elastic under 475 years RP earthquakes. In the case of 2475 years RP earthquakes, the fuse component yields, provides additional damping and also protecting the concrete outriggers from excessive damage. Fig. 13 list out the component of the system.

The system was tested in scaled model in China Academy of Building Research in Beijing, China (CABR 2015) and demonstrated that it's very stable hysteresis behavior under cyclic load. This is a kind of metallic damper which

**Figure 11.** Chong Qing Raffles City (with courtesy of Safdie Architects).

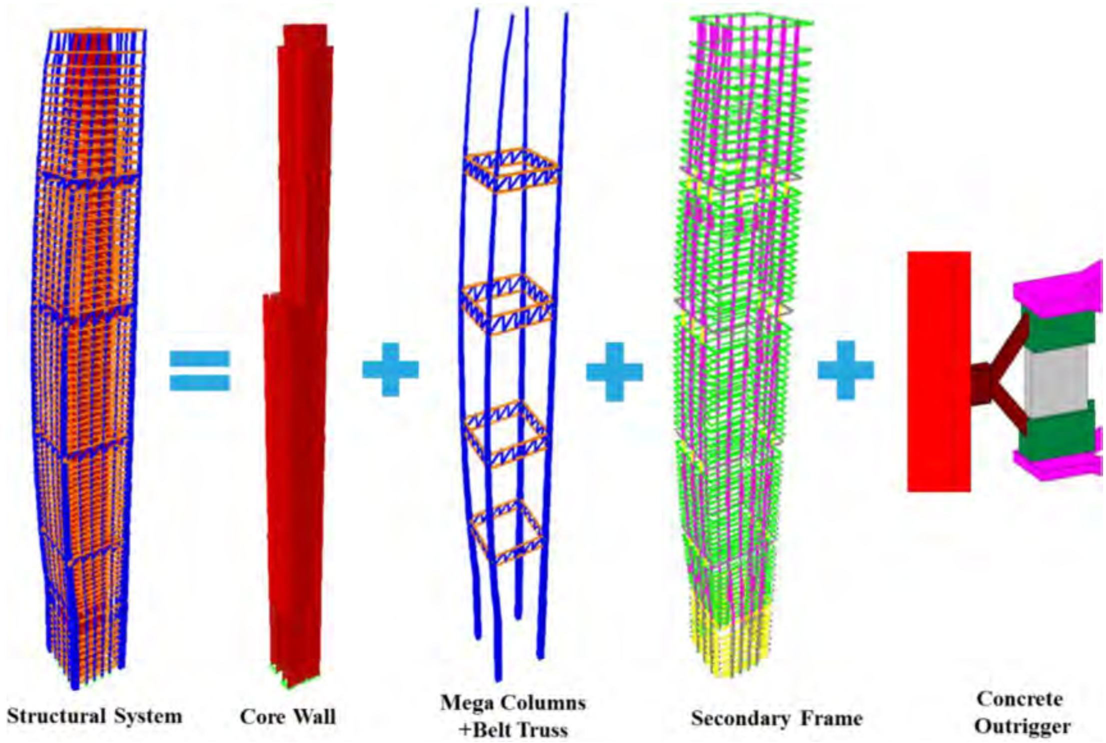



**Figure 12.** Structural System for CQ Raffles City Project (with courtesy of Arup).

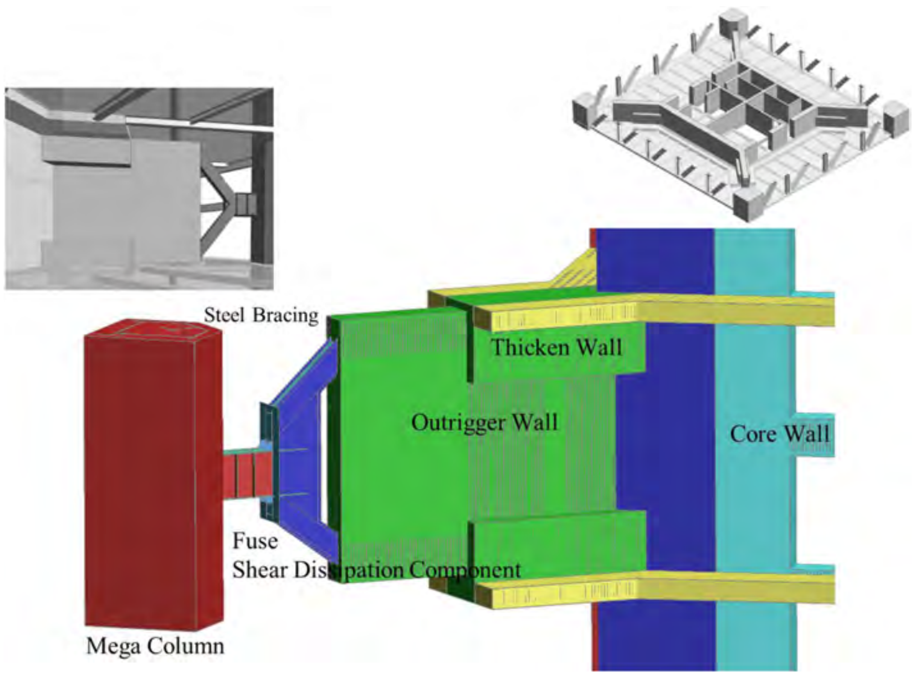



**Figure 13.** Component List for Fused Outrigger (with courtesy of Arup).

dissipate the additional energy in 2475 years RP earthquakes event and hence protect the concrete outrigger and also the building. These fuses could be replaced after severe earthquake.

The Arup fused systems have distinct advantages relative to the conventional RC outrigger of low construction

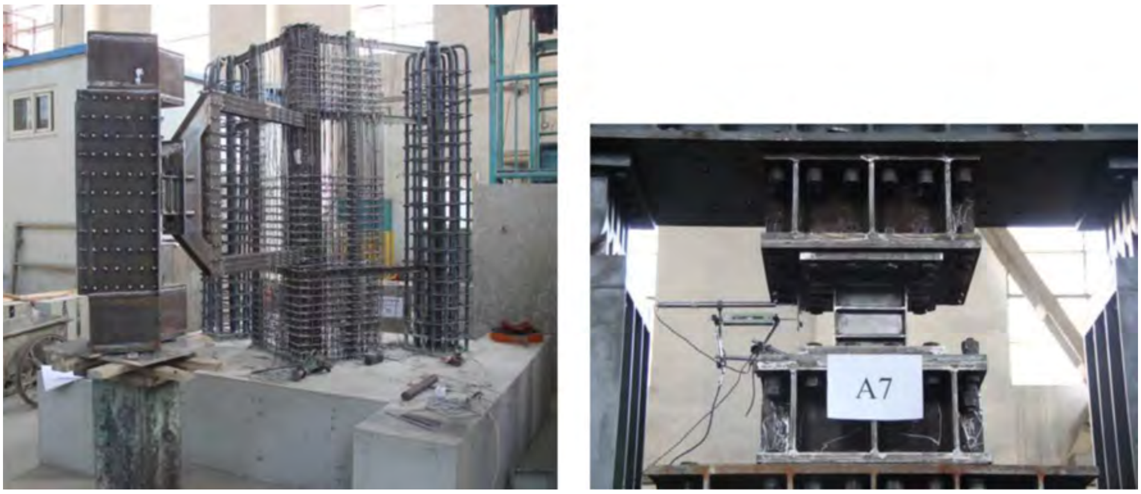



**Figure 14.** Physical Test for Fused Outrigger component.

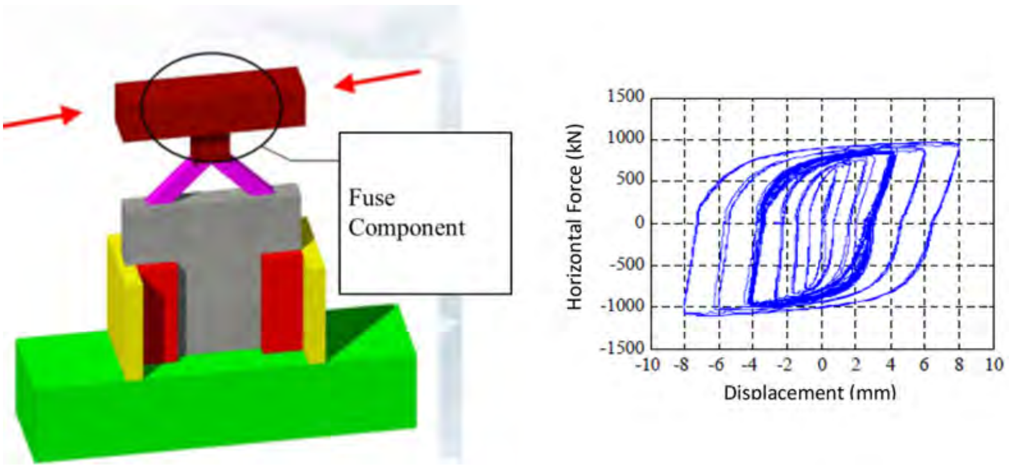



**Figure 15.** The Testing Arrangement and the Hysteresis Behavior of the Fuse Component.

and maintenance cost. The fuse could also use as a delayed joint in connecting the outrigger and mega column if required.

## 8. Concluding Remarks

Historic highlights and milestones are presented to cover the development and application of outriggers system in tall buildings. The theory, concept and optimum topology of outriggers was briefly described to provide quick, ease of reference for practicing engineers. Axial shortening effect is one of the key issues in outriggers design. With the current computer and software power, intricate analysis such as axial shortening effect can now easily be solved by pressing a button. However, if outriggers have to be designed to resist these locked-in forces, it won't be really be an optimum design. The axial shortening effect had to be minimized by means of releasing the outriggers from the shortening effect during construction and life cycle of the building. Methods on adjustable outriggers details were explained. In tall building construction, the construction of the core wall is always on the critical path. Retro-casting method is explained which allows the core wall to be constructed in it originally cycle without any delay due to outrigger installation. Target of high stiffness is not always the only objective for outriggers system. Damped outrigger systems are also introduced in which the stiffness was tuned in order to provide the best multi-objective performance for buildings. Based on performance based approach, the newly developed fused concrete outrigger system will also be a cost effective system if the main objectives of the outrigger system is to provide stiffness without extra damping in cases before 2475 years RP earthquakes. This paper is presented as a historical review and wishes this story remain a fascinating one with epic proportion. The continuous development of outriggers system should be a never-ending story.

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