Council on Tall Buildings and Urban Habitat Korea

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

*International Journal of High-Rise Buildings*
*September 2022, Vol 11, No 3, 197-205*
*https://doi.org/10.21022/IJHRB.2022.11.3.197*

# Innovative Design and Practice in Horizontal Skyscraper-ChongQing Raffles

**Li-Gang. Zhu**†

[1]*Arup shanghai office Director*

**Abstract** One of important design challenges in Chongqing Raffles City Plaza project is Sky Bridge structural design and its connection scheme in high level. This article systematically describes the structural system and its design and analysis methodology, with discussing the impacts on structural performance due to different connection approaches. The seismic isolation scheme in high level is innovatively adopted to the final design. Under the conditions of various load cases, the different models and assumptions are implemented. A full assessment on Sky Bridge's structural performance, seismic isolation, and its connection is conducted in terms of seismic performance based design. By co-operating with architecture, MEP and other disciplines, the structural economy index is fulfilled.

**Keywords** Sky Bridge, Connected structure at high level, Seismic isolation design and analysis, Connection design, Performance-based design

†Corresponding author:
li-gang.zhu
Tel: +
E-mail:
li-gang.zhu@arup.com

## 1. INTRODUCTION

Raffles City Chongqing (RCCQ) is located at the heart of Chongqing, at the confluence of the Yangtze and Jialing rivers. This strategic position is fitting for this mega-scale development, the design of which was influenced by and serves as a symbol of Chongqing's past as a trading center and its long-held status as a gateway to western China.

The high-rise complex was designed in collaboration with Safdie Architects and was inspired by historical images of great Chinese sailing vessels on the river. Gently arcing towards the water, the towers form the apex to the city's peninsula, like the masts of a ship, with its sail pulling the city forward.

Raffles City Chongqing is a mixed-use development, with a total floor area of 1.13 million $m^2$. It comprises a shopping mall and eight curved towers - two 350 m-tall north towers and six 250 m-tall south towers - which house 1,400 residential units, offices, 200 serviced apartments and 450 hotel bedrooms. One of the north towers is fully dedicated to residential use, making it the tallest residential tower in China. The second north tower is office space below the skybridge, with the hotel above.

Six of the towers are linked 250 m above ground, with four of the 250 m-tall towers capped by the 15,000 $m^2$, 300 m-long skybridge, The Crystal, which faces southwards over the city. Two smaller skybridges link it with the two 350 m-tall towers. The Crystal brings amenities and (ground conditions are variable, and green space high into the sky, housing the hotel lobby, bars and restaurants, a public observatory, and a clubhouse, swimming pool and gymnasium-type facilities for the residential apartments.

In this amazing and unique project, there are many challenges and innovative sulltions on these challenges . the below figure show the Features of the Challenges and Innovation in Design and Construction. But in this paper will focus on the conservatory seismic design.

## 2. Conservatory articulation study

### 2.1. How to make a conservatory float above the four 250 m height towers

In design concept stage, we referred to our different experiences of linked towers, such as CCTV which locates in high seismic intensity region and adopted rigid connection, MBS which locates in low wind and without considering seismic region and adopt independent approach. For the conservatory bridge of RCCQ, which is in moderate wind and low seismic intensity region. We firstly think the isolation scheme is more reasonable. So, three scenarios were considered to connect the conservatory to the towers (Figure 4).

For comparison, a simple base case for the scheme with a monolithic arrangement was initially explored. Here, with the conservatory rigidly connected to the towers, the forces developed in the structure would be large, requiring large structural components and bulky detailing which would

**Figure 1.** Raffles City Chongqing. @CY Tang

have significant cost implications and encroach on lettable space.

The second scenario considered splitting the conservatory into sections so that each tower supported one portion. Movement joints in the conservatory would allow each portion to move relative to one another while still being fixed to the tower. Further analysis of this option revealed that provision for up to 3m of relative movement would be needed for this system to work. A movement joint which could accommodate this amount of movement would be unsightly in the sleek conservatory, as well as impose too many restrictions on how the space could be used. Constructing the hammerhead towers would also take longer and, hence, be more expensive, so this solution was also ruled out.

The third scenario explored the use of bearings, which would have the effect of reducing the magnitude of the forces transferred to the conservatory from the towers during earthquakes. Connecting the conservatory and four towers dynamically would lead to a lighter structure, which appealed to the architect and would have the added benefit of being much less expensive than the base case. The impact of using bearings on all towers or just two and allowing the other two towers to be rigidly connected to the conservatory was investigated to determine where efficiencies could be made. To limit movement experienced by the conservatory and towers during an earthquake and to reduce the size of bearing required, dampers were also considered. The expectation was that a lighter structure would become feasible if a damping mechanism was incorporated, leading to a reduction in material costs.

The combination of fixed and isolated conservatory-tower connections was quickly ruled out due to problems arising from the fixed connections (as described for the monolithic case) and high material costs, which left one possible solution - to use bearings on top of all four towers.

The three scenarios can be further split 5 options to study the different connectivity.

In all, 900 linear and non-linear analyses were carried out to explore scenario three, each with a typical run time

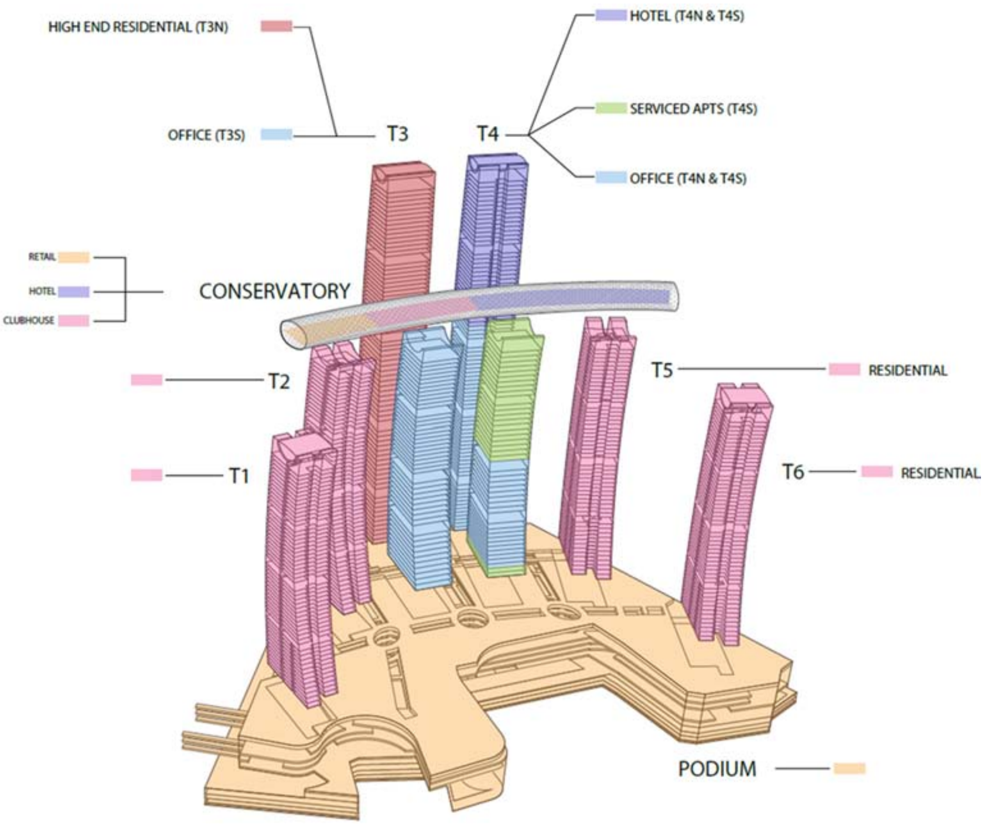

**Figure 2.** Project funcation diagram. @Safdie Architects / CapitaLand(China) Investment Co Ltd

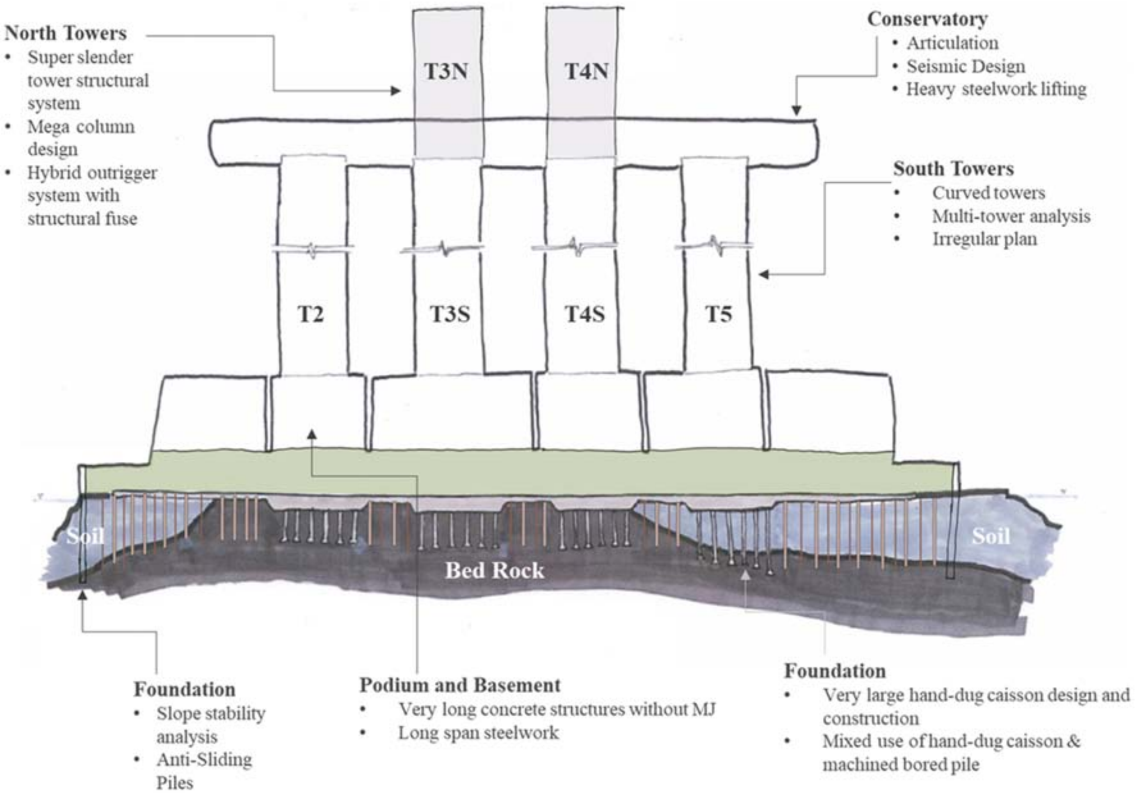

**Figure 3.** Project challenges diagram.@Arup

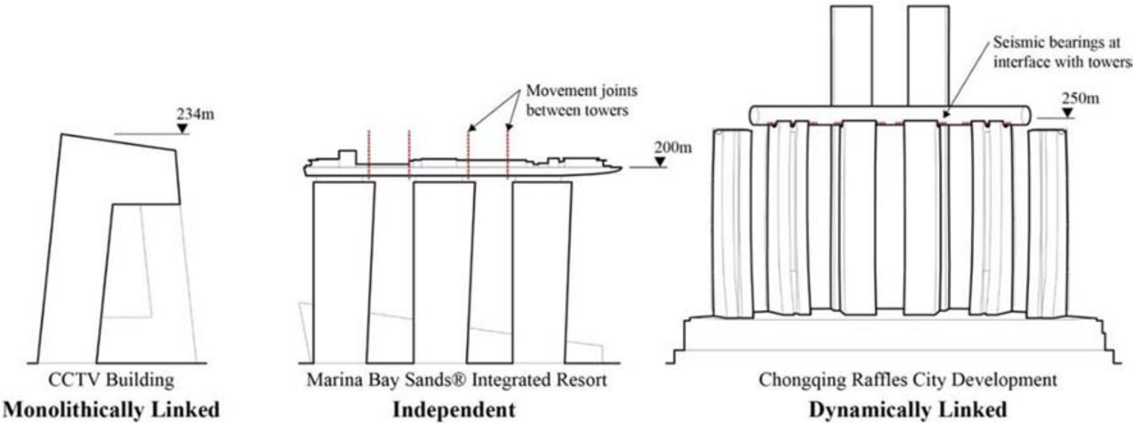

**Figure 4.** below illustrates conservatory/tower interface options of different Arup-design iconic projects.

of 30 hours per model, taking approximately 27,000 hours in total.

Through huge analysis, we can sum the valuable contribution from the different options in Figure 6.

## 3. Conservatory isolation bearing study

### 3.1 FPB vs LRB

At the first stage, the bridge is fixed on the tower which cause larger shear force in the rare earthquake case. So the design team decide to use flexibility connection. We tried LRB (Lead Rubber Bearing), FPB (Friction Pendulum Bearing) and bearing combined with damper. We also tried different sizes and parameters with different products in each scheme, the below Figure 7 Comparison of FPB

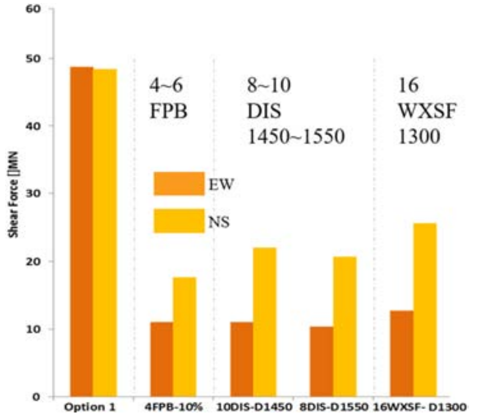

**Figure 7. Comparison between FPB and LRB of different contractor.**

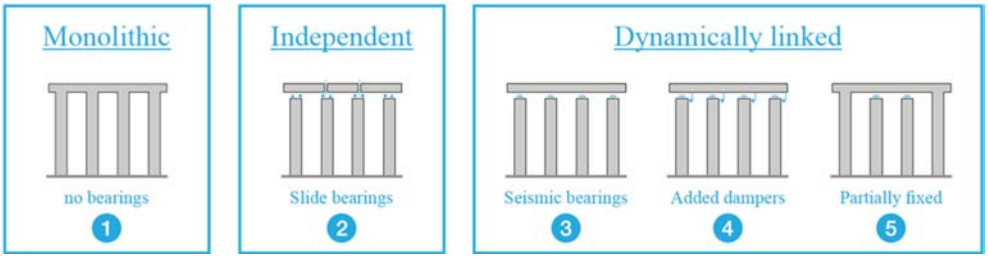

**Figure 5.** Exploring the connectivity between the conservatory and towers.

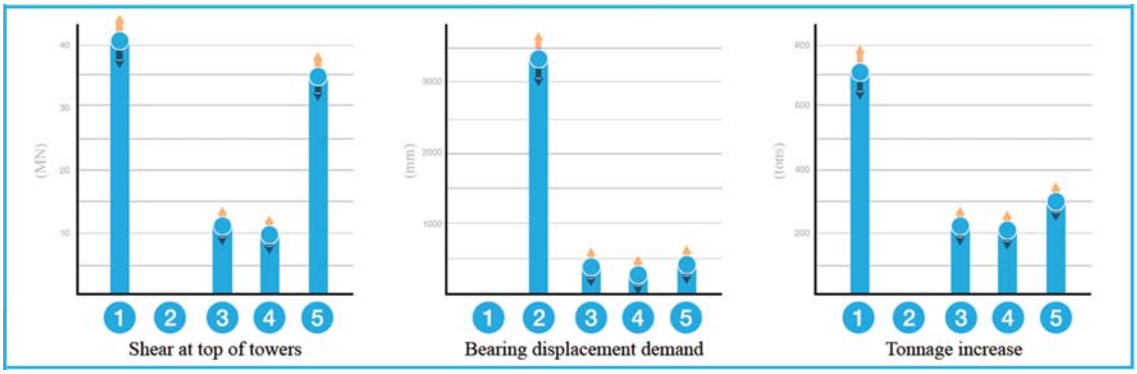

**Figure 6.** Valuable contribution of different options.

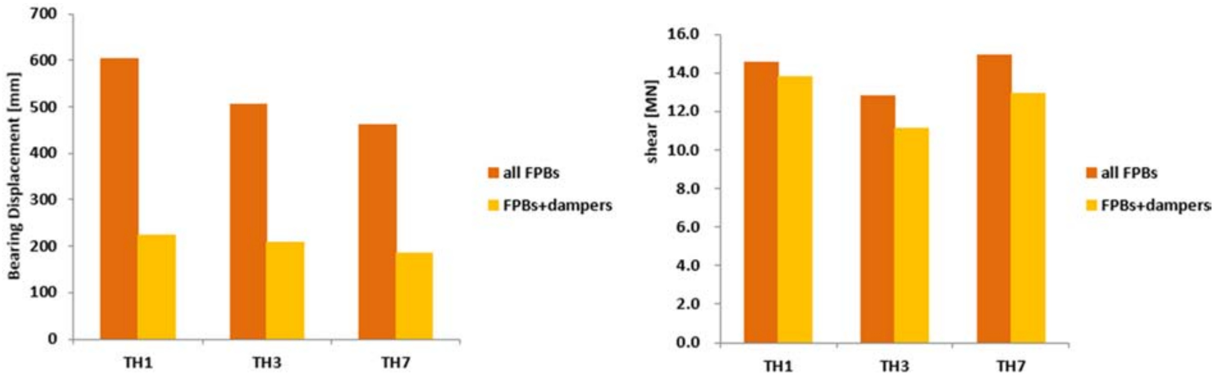

**Figure 8.** Comparison of with damper and without damper.

| Damper + FPB | FPB only |
|---|---|
| Little impact on the displacement because of weight | Great impact on the displacement because of weight and friction |
| Movement joint around elevator shafts and bridge seem manageable | Currently no appropriate technical solution for the movement joint |
| integrated fuse function(low maintenance costs after the earthquake) | Require specific mechanical fuse function(Need to be replaced after the earthquake) |
| Lower speed index can guarantee lock fixed on the normal wind conditions | To resist wind load of normal conditions by friction is not recommended in the specification(The unpredictable vibration can make friction coefficient decreases as the value of dynamic friction coefficient) |
| Force distribution is more reasonable | Failure time of different tower fuse is not the same |
| Fatigue load is relatively small | Fatigue load under the joint action of temperature and wind loads is a greater impact on the fuse |
| More accurate releasing force | To estimate the releasing force is difficult |
| Can adapt thermal displacement and deformation during the construction phase | Because gravity and temperature loads will cause prestress?Set fuse after even bridge construction |
| Do not produce out of situation on the actual situation-Do not need to set the tension mount | The most serious conditions have 45mm detachment-need to set the tension mount |
| Using more commonly used dynamic friction coefficient 5% | Higher dynamic friction coefficient 7% |
| More commonly used performance parameters | Difficult to maintain a stable state |
| | Having a risk of viscosity - slip effect, and then leading a high acceleration of even bridge |
| Easily reset | Having a potential problem of returning to the center |

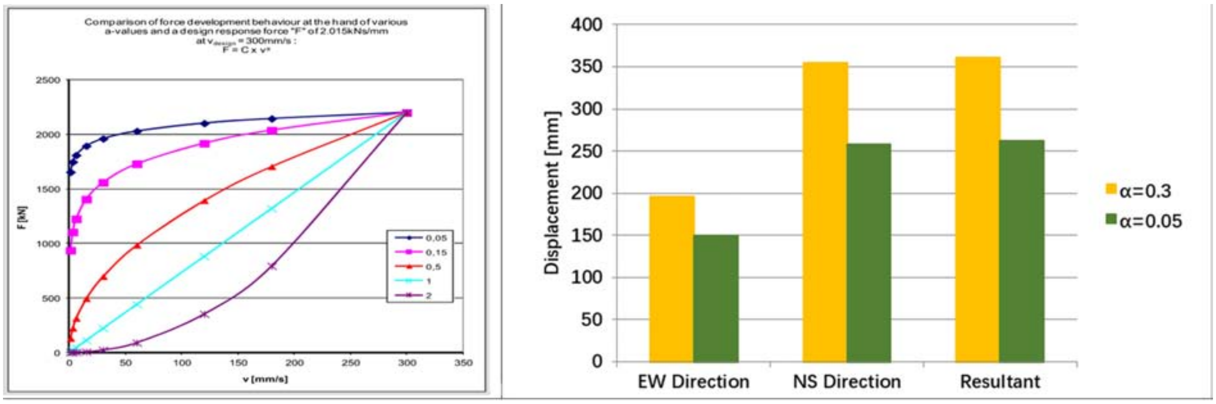

**Figure 9.** Comparison of large damping index and small damping index.

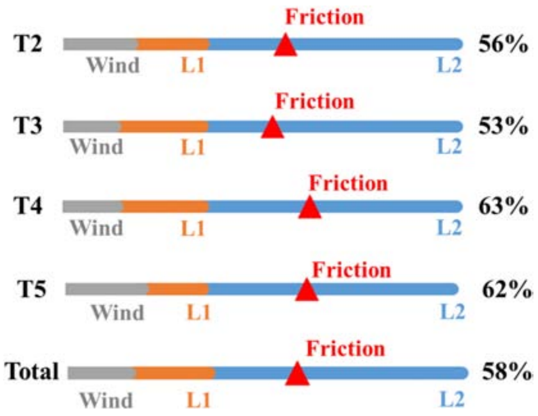

**Figure 10.** The interface shear of every tower under different loading case.

and different LLRB products.

For the pure LRB scheme, vast bearings will be needed and the size are also very big. But the comparing with the fixed model the shear force reduce about 61%. After added the dampers into the model, the displacement reduced about 150% comparing with pure FPB scheme. So the FPB can reduce the friction coefficient which much stable in high speed situation. The shear can also be reduced although it may not as effective as displacement, but it is benefit to the design.

### 3.2 With Damper Vs Without Damper

In design progress, we found some bearings were in tension in some instances under the time history analysis. In order to reduce the tension and lifting of bearings, avoid adopting the tension FPBs, we introduced viscous dampers. Through analysis, we further demonstrate the dampers can contribute more values: not only eliminate the lifting, but also reduce the bearing displacement demand from 600 mm to 220 mm. The dampers is also role of the limit device of FPBs and then achieve the Robust design.

The below table summarize the different key points with and without the use of damping: structural element size/reinforcement ratio/acceleration/wind and seismic forces

### 3.3 Large damping index vs Small Damping index

For damping parameter study, compared the different damping indexes to find out optimal parameter. We know the smaller the damping index a of the viscous damper:

(1) The fuller the curve, the fuller the elimination curve, and the higher the efficiency of consuming external impact energy.

(2) The lower the correlation between velocity and damping force, the damping force is almost horizontal and straight, and the strength requirements of the connected structure are greatly reduced. Through the assessment of the effect of damping index, we noticed:

- A larger damper index results in larger seismic displacements.
- A smaller index (~0.05) is necessary to guarantee that the conservatory is locked under wind loading

We further observed the interface shear under different loading case (L1,L2 and wind loading), the frication force

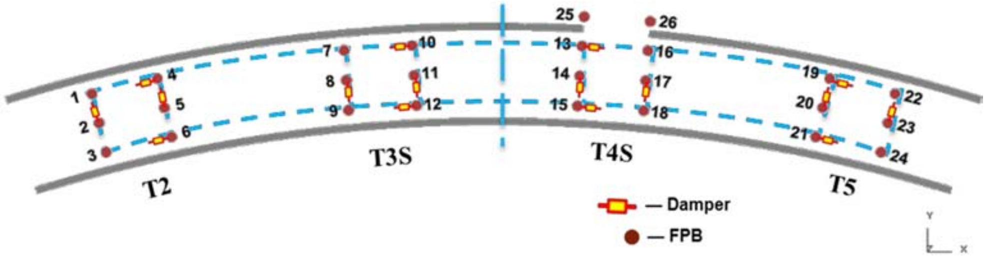

**Figure 11.** Final articulation scheme.

**Table 1.** Final articulation scheme – FPB characteristics

| | Design parameter | Value – optimized scheme |
|---|---|---|
| FPB | Configuration | 6 no. at Towers T2, T3S and T5<br>8 no. at Tower T4S |
| | Maximum displacements | 400 mm at Towers T2, T3S and T5<br>450 mm at Tower T4S |
| | Curvature radius | 4.5 m |
| | Dynamic friction coefficient | 5% |
| | Average service load | 15MN |
| | ULS specified load | 28MN at Tower T2<br>33MN at Towers T3s and T4s 26MN at Tower T5 |
| | Internal hinge rotation | +/-0.01rad |

**Table 2.** Final articulation scheme – Viscous damper characteristics

| | Design parameter | Value – optimized scheme |
|---|---|---|
| Seismic dampers | Constitutive law | $F = CV^{\alpha}$<br>F: Force [N]<br>V: Velocity [m/s]<br>$\alpha$ : Velocity exponent C: Constant $[Ns/m]^{-\alpha}$ |
| | Law parameters | $\alpha = 0.3$<br>$C = 5e6MN/(m/s)^{-0.3}$ tuned to obtain 5000 kN at V = 1 m/s |
| | Configuration | 4 no. per Tower<br>(2 in longitudinal, 2 in transverse directions) |
| | Maximum stroke | 400 mm at Towers T2, T3S and T5<br>450 mm at Tower T4S |
| | Integrated fuse function | Fuse release force 2MN at approx. 1.5 mm/s |

of every tower which FPBs provide is about 60% L2 seismic loading, so if we need conservatory bridge can move under L2 case, the initial damping force is needn't large.

### 3.4 Design implementation

The final articulation scheme is illustrated in Figure 11 below. This layout takes into account the latest geometry of the conservatory support truss and the location of electrical and mechanical plants at the tower interface. It also aims at facilitating maintenance access and reducing congestion while maintaining isolation efficiency.

The viscous damper parameters applied during the Detailed Design and Validation stages are given in Table 2:

## 4. Performance-based seismic design for conservatory bridge

We adopted the design concept of dynamic connection for the first time. This concept also means Connection Performance- based design under different states from service-level(wind and level1 earthquake) to extreme Level.

Under service state the FPB provide the static fraction force to "fix" the conservatory

And under Level 2 and 3 the seismic force of the interface will exceed the static fraction force, the conservatory will slide, then FPB and dampers will work to dissipate the energy.

## 5. Conservatory bridge structures

The Crystal is made up of three primary steel trusses, interconnected by secondary steel and enclosed by a lightweight space truss enclosure. With different topping out dates for each supporting tower, a detailed construction sequence analysis was carried out to prove the whole installation method was practical and safe. Arup worked closely with the contractor on the sequence analysis, installation method and temporary works design, before the sequence gained approval from the expert panel review.

## 6. Assessment of the extreme seismic case

The same comprehensive model was used to assess the seismic performance of the conservatory and of the supporting towers. The complete analysis model is illustrated in Figure 4:

Interface elements, FPB, viscous dampers were modelled explicitly, see Figure 5 below. Detailed design and locations of the connections were updated as the structural envelope was progressively frozen.

| Performance-based design under different loading case | | | |
|---|---|---|---|
| | Service level earthquake / wind / temperature | Moderate earthquake | Extreme earthquake |
| Objectives | The static friction of the friction pendulum bearing ensures "Fix" | Friction pendulum bearing sliding and dampers work | Friction pendulum bearing sliding and dampers work |
| Model | ETABS/Sap2000 elastic model with Conservatory fix on the multi-towers | The key elements capacity check with the conservatory fixed on the multi-towers in ETABS/Sap2000 model<br>Deformation check by Nonlinear with Ls-Dyna model | Deformation check by Nonlinear with Ls-Dyna model |
| Analysis Approach | RSA and THA | RSA and THA | THA |

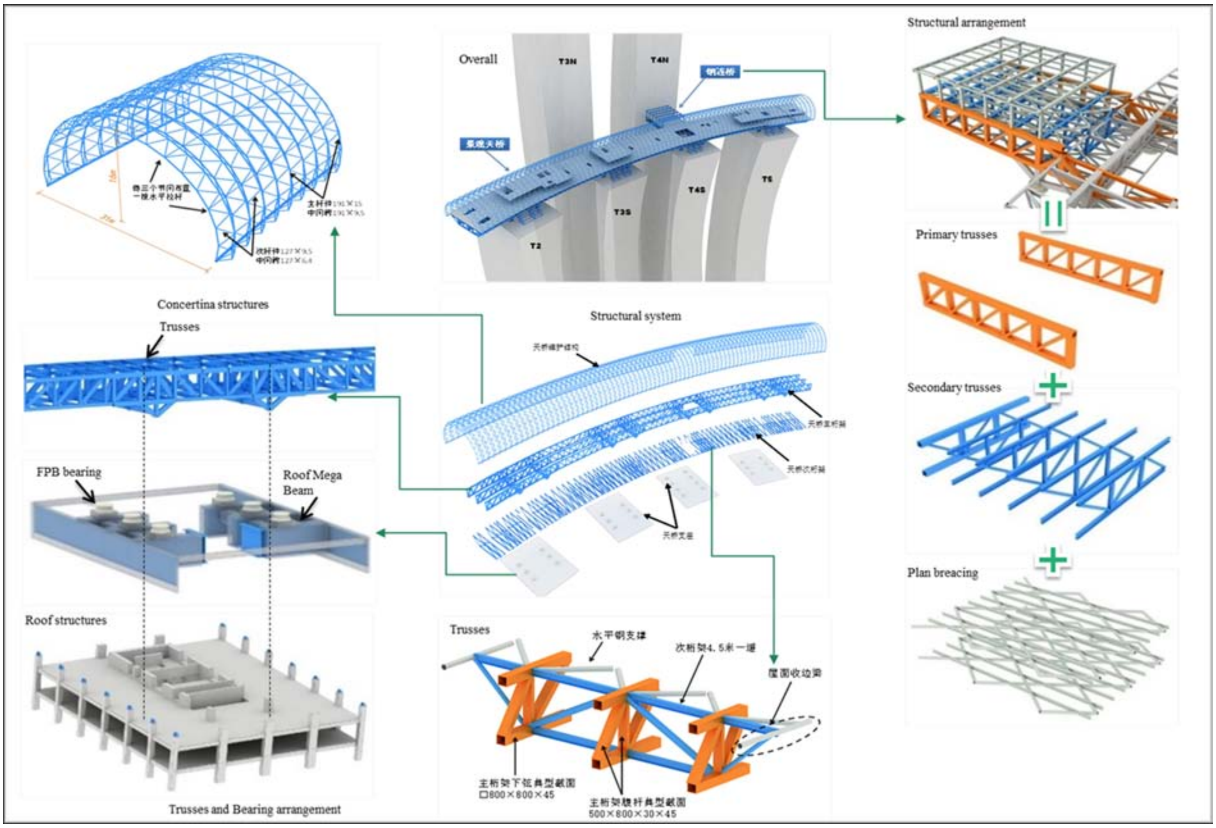

**Figure 12.** Conservatory bridge structural system

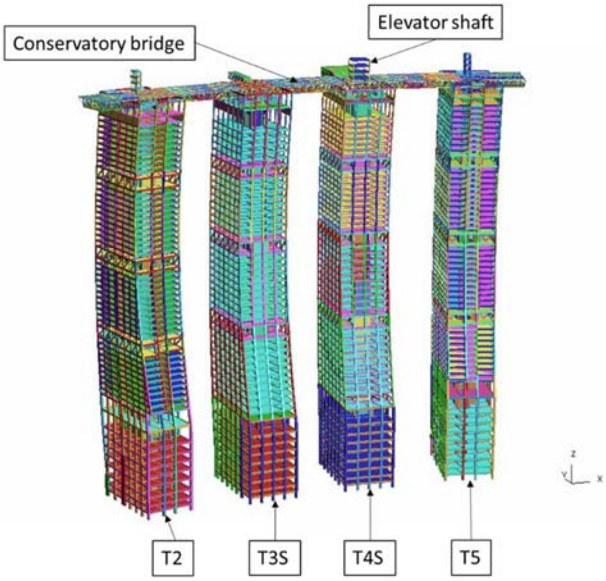

**Figure 13.** Complete LS-DYNA analysis model.

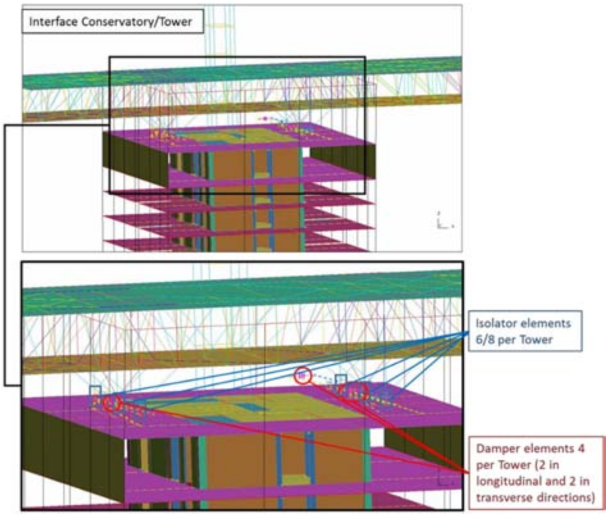

**Figure 14.** Details of conservatory/tower interface – Final Scheme.

Maximum seismic force and displacement demands during the entire seismic events were compared with the structure's capacities on a component-by-component basis. Figure 15 below compares the critical component damage with FEMA 356/ASCE 41-06 criteria [4] under the MCE seismic event.

For all Level 3 ground motions considered, the damage levels in the critical structural tower components, as per FEMA 356/ASCE 41-06 criteria, remain within Immediate Occupancy limits (IO) and are deemed acceptable. A 1:25 scale shaking table test in Tongji university was carried out to demonstrate the seismic performance of the six towers joined by The Crystal and the dynamically linked skybridges under extreme earthquake events.

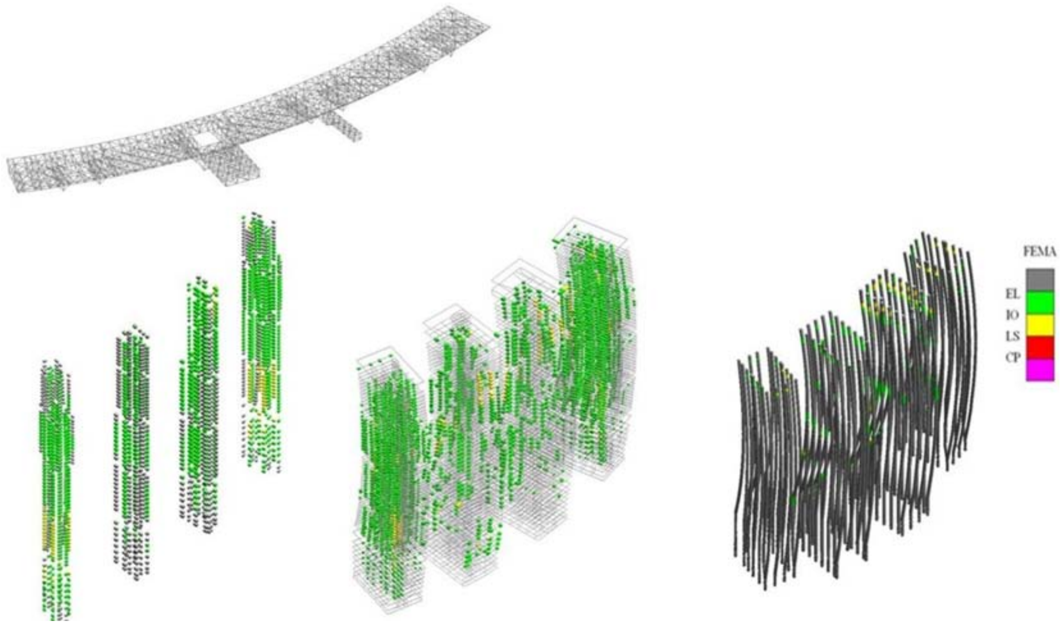

**Figure 15.** Critical member damage – FEMA criteria – Typical MCE event.

**Figure 16.**

## References

Lancelot, F., Ching, R., Hand, J., "Isolation scheme assessment on the Raffles City Chongqing using LS- DYNA" 1st China LS-DYNA Conference 2013, FEA Information Engineering Journal, Volume 2, Issue 11, November 2013, (ISSN 2167-1273).

Book: CTBUH Damping technologies for tall buildings Theory, design guidance and case studies.

Arup Journal 2021 Issue 1.

LS-DYNA® Keyword User's Manual, Version 971. Livermore Software Technology Corporation (LSTC): Livermore, CA 94551-5110, USA, May 2007.

Safdie Architects http://www.msafdie.com/file/4218.pdf.

Arup Raffles City ChongQing seismic EPR report.