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Authors:	Hi Sun Choi, Senior Principal, Thornton Tomasetti Leonard Joseph, Principal, Thornton Tomasetti SawTeen See, Managing Partner, Leslie E. Robertson Associates Rupa Garai, Associate Director, Skidmore, Owings & Merrill LLP
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Frontiers in High-Rise Outrigger Design



Hi Sun Choi



Leonard M. Joseph



SawTeen See



Rupa Garai

Abstract

In 2012, CTBUH published the first **Outrigger Design for High-Rise Buildings Technical Guide**. In 2016, the CTBUH Outrigger Working Group felt it would be beneficial to update the design guide with variations of outrigger systems and tall building projects that have been newly proposed or successfully implemented since that time. The Working Group reached out to colleagues to collect information on recently developed outrigger systems and real project examples that demonstrate their viability and value. The second edition of the guide, published recently in 2017, includes innovative approaches to address previously recognized design concerns and limitations. It also includes more project examples with new approaches to optimize building performance through dampers incorporated within outrigger systems. This paper summarizes the major updates of the second edition and highlights several projects of significance to the contemporary discussion of outrigger technology.



Keywords: Outriggers, Structural Engineering, Wind, Seismic

Design Considerations for Outriggers Supporting Complex Forms

"Stiffness Effects from Overall Systems" is a newly added section of the Technical Guide, which discusses outrigger interactions with complex architectural forms such as twisted, tilted, and tapered shapes, now common trends in contemporary tall building design. For practicality, such designs utilize a vertical core located within the building envelope for most of the height, with outriggers used where the core alone provides insufficient lateral strength or stiffness. A key point here is that the stiffness contribution of the outrigger system will be affected by overall building geometry. Unlike a straight tower with a central core and symmetrical outriggers to perimeter columns at each side, in a tilted structure, outriggers can be asymmetrical and have varying lengths. A second point is that tilted structures have inherent lateral displacements due to the destabilization effect of gravity loads alone, which should be expected. Surprisingly, a study shows that lateral displacements of tilted structures under wind loads can be less than those of an equivalent straight tower, if a beneficial stiffening effect of triangulation

occurs between outrigger levels (see Figures 1 and 2).

The effect of building taper is also discussed. For a building that tapers narrower with height, compared to a straight building of the same total floor area, there are smaller wind and seismic loads imposing on the building structure below thanks to reduced upper-floor footprints and wind tributary "sail" areas, a relatively wider base, and reduced outrigger arm lengths at the building top. The benefits are more pronounced for taller towers.

Hybrid Outrigger Systems

Another new chapter discusses innovative hybrid outrigger systems. While traditional outrigger systems sustain maximum forces when the building is experiencing maximum lateral displacements, hybrid outrigger systems can exhibit different relationships. Several examples of hybrid outrigger systems are presented.

Damped outriggers

The most significant of these, damped outrigger systems use the leverage of stiff

Authors

Hi Sun Choi, Senior Principal
Thornton Tomasetti
51 Madison Avenue
New York, NY 10010
United States
t: +1 917 661 7878
f: +1 917 661 7801
e: HChoi@thorntontomasetti.com
www.thorntontomasetti.com

Leonard M. Joseph, Principal
Thornton Tomasetti
707 Wilshire Boulevard, Suite 4450
Los Angeles, CA 90017
United States
t: +1 949 271 3320
f: +1 949 271 3301
www.thorntontomasetti.com

SawTeen See, Managing Partner
Leslie E. Robertson Associates
40 Wall Street, 23rd Fl.
New York, NY 10005
United States
t: +1 212 750 9000
f: +1 212 750 9002
e: sawteen.see@lera.com
www.lera.com

Rupa Garai, Associate Director
Skidmore, Owings & Merrill LLP
1 Front Street
San Francisco, CA 94111
United States
t: +1 415 352 6847
f: +1 415 398 3214
e: rupa.garai@som.com
www.som.com

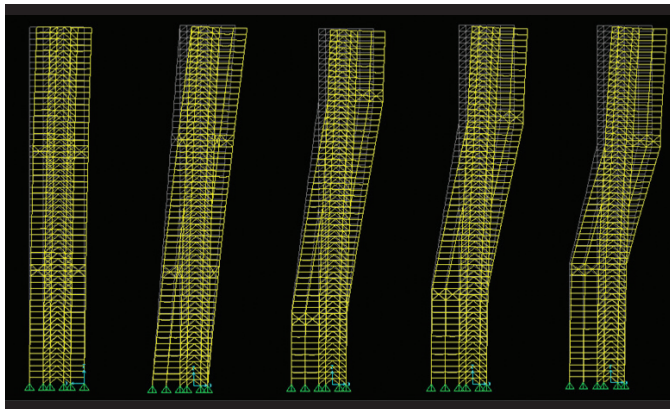


Figure 1. Tilted 60-story study structures with outriggers and tilt angles of 0, 4, 7, 9, and 13 degrees showing exaggerated gravity deformations. Source: Moon 2016

outrigger arms projecting from a building core to efficiently drive nonlinear damping devices. The resulting supplementary damping can significantly reduce tall building accelerations, deformations, and forces from vortex-induced oscillations (VIO) in wind, or reduce building deformations and structural demands in earthquakes. Supplementary damping can take the form of viscous dampers, viscoelastic dampers, tuned mass dampers (TMDs), tuned liquid column dampers (TLCDs), or sloshing dampers. But mechanically damped outriggers can provide supplementary damping contributions comparable to a TMD or TLCD without the attendant space, weight, or tuning requirements.

Viscous dampers work at all frequencies, generate greater resistance as the driving velocity increases, and convert motion to heat based on the resistance times travel distance. Viscous dampers are most efficient, compact, and cost-effective when driven through larger travel distances at higher velocities, making the large relative movements between outrigger tips and perimeter columns an efficient location for placing relatively compact dampers between them. To protect the structure from excessive forces, modern viscous dampers can be designed for a nonlinear response to driving velocities using either of two different strategies: nonlinear resistance and pressure relief.

Mechanisms for increased damping with outrigger systems

Relative vertical movements between ends of stiff, disconnected outriggers and perimeter

columns in tall structures can be leveraged to yield supplemental damping by introducing vertically mounted dampers between the outrigger ends and the perimeter column (Smith and Willford 2007). These movements are proportional to the lateral drift of the structure and can typically be of relatively small magnitude, particularly in wind events. Mechanisms can be utilized to amplify these relatively small vertical movements to potentially increase supplementary damping. A concept for one such mechanism – where the damper movement and velocity are amplified, thus increasing the supplemental damping in the structure – was described by Mathias et al. (2016).

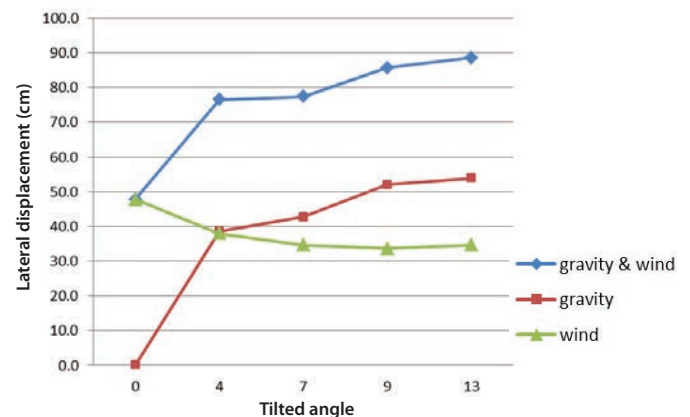


Figure 2. Lateral displacements of 60-story tilted outrigger structures with tilt angles of 0, 4, 7, 9, and 13 degrees. Source: Moon 2016

A damped outrigger system disengages the outrigger elements (reinforced concrete walls or steel trusses cantilevered from the core) from the floor framing at their top and bottom edges and from the perimeter columns. This makes it possible to generate relative vertical movements between the outrigger ends and the adjacent perimeter columns when a structure is subjected to seismic and wind loads; the drift displacements/velocities can be captured to generate supplementary damping. To increase the efficacy of a damped outrigger system and create large vertical velocities that would generate increased damping, the use of a mechanism has been proposed (see Figure 3). The geometric

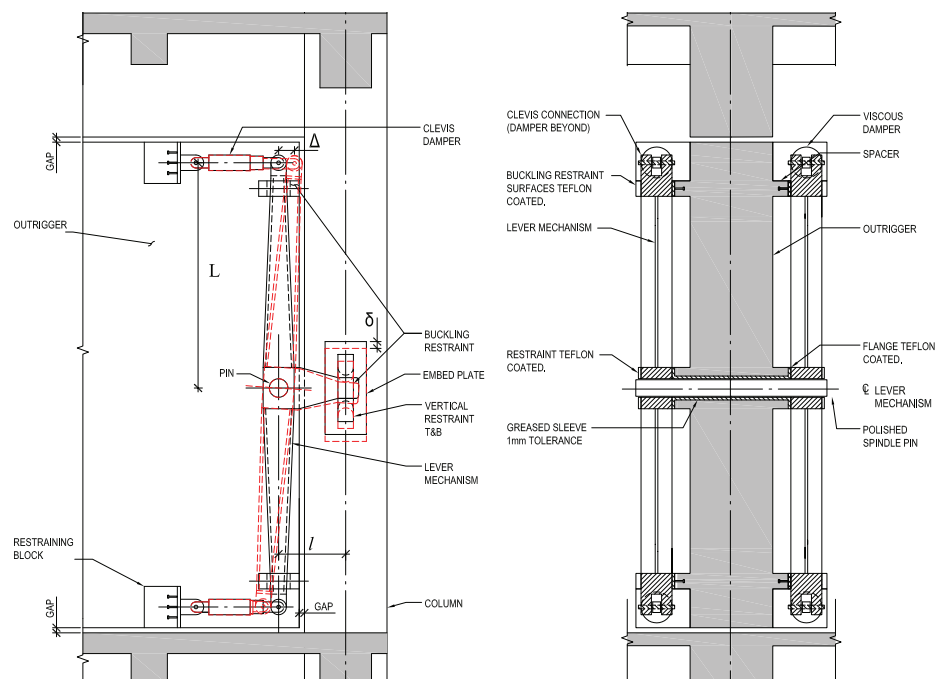


Figure 3. Schematic components of an amplification mechanism (displaced configuration of the system shown in red dotted lines). © SOM

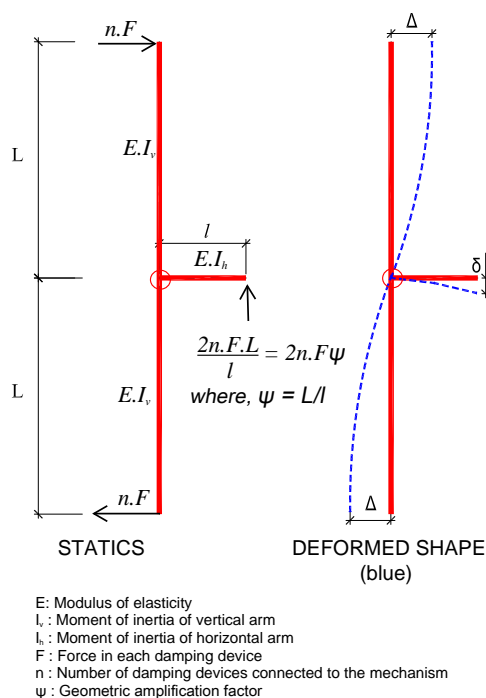


Figure 4. Free-body diagram. © SOM

amplification factor of ψ of the system shown in the figure is $\psi = L/l$, considering the members connecting the central pin and ends of damping devices to be infinitely rigid. The goal is to keep the amplification factor as high as possible, in order to increase the relative displacement magnification and thus increase the velocity in the damping device.

This concept was analytically tested on an under-design 320-meter building in Shenzhen, China, using reinforced concrete outriggers connecting the core to the perimeter columns at levels 15, 30, 45, and 60 in order to increase the structure's lateral stiffness in the short direction. The results of the analysis demonstrated that the horizontal damper (magnified movement) solution provided an increased level of damping and performed better than the other systems studied across all performance indices compared (inter-story drift, roof displacement, and floor acceleration) for seismic and wind loads. Considering the mechanisms to be rigid, the option with horizontal dampers provided a total damping ratio of approximately 14.5%, while the vertical (non-magnified) damper option provided approximately 4.5% total damping, when compared to the base option of an

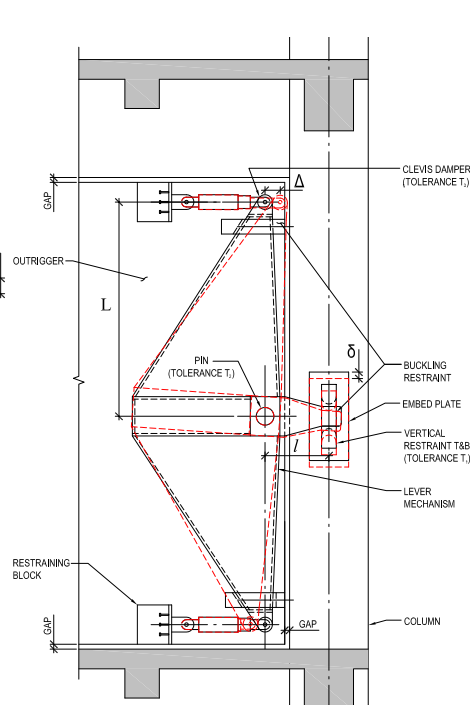


Figure 5. Stiffened mechanism. © SOM

outrigger frame core structure, which provided only 1.5% damping.

However, the vertical arms of the mechanism that connect the central pin to the ends of the horizontal dampers and the horizontal arm that connects the pin to the exterior column are capable of deforming, and there is a need to consider fit-up tolerances that reduce the amplified movement (Δ) and thus the effective supplemental damping of the system. A free-body diagram with deformed shape of the mechanism is shown in Figure 4. In fact, if the arms of the mechanism are too flexible, then the system will not yield the desired amplified movement, thus negating the sole purpose of adding such mechanisms.

It is recommended that the minimum moment of inertia of the vertical arm of mechanism be such that the cantilever tip deflection of the vertical arm under the maximum force capacity of the damper is limited to 20% of the damper stroke. The minimum stiffness of the vertical arm can then be varied as necessary to achieve the desired performance.

Figure 5 shows the concept of a realistic mechanism with tapering stiffened arms,

which is developed to minimize the loss of rigidity due to flexural deformation. Similar details can be developed with steel outriggers. The efficacy of the magnified movement of damping systems depends on the stiffness of the mechanism components and tolerances in the system. Thus, for each structure utilizing mechanisms to magnify outrigger movement to increase supplementary damping, the proportions and tolerances of the mechanism component should be studied and balanced to maximize their efficacy and structural performance.

Fused outrigger systems

Fused outrigger systems place a yielding element in the outrigger load path to set a practical upper limit on force demands at members and connections while absorbing some seismic energy. One example is using a buckling restrained brace (BRB) element as the diagonal member of a steel outrigger truss. Under extreme seismic conditions, BRBs can be thought of as "metallic dampers" since they absorb energy, even though they do not conform to the characteristics of conventional dampers, such as force related to velocity for viscous dampers, or relaxation for viscoelastic dampers.

While energy absorption can benefit seismic behavior, the greater advantages of BRBs are in their linear elastic stiffness in wind load conditions, stable hysteretic behavior in earthquake load conditions, and reliable maximum demands on connections and adjacent members. Since BRB systems cost more than conventional steel outriggers, BRBs make the most sense when the demand-limiting behavior reduces structural costs elsewhere.

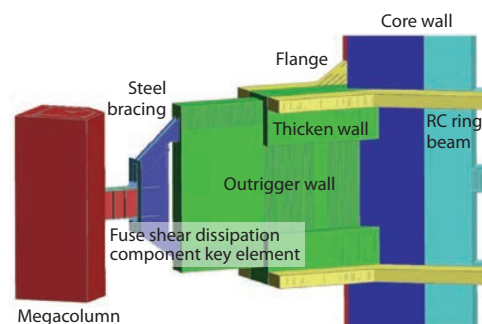


Figure 6. Diagram of a "fused" hybrid outrigger system. © Arup

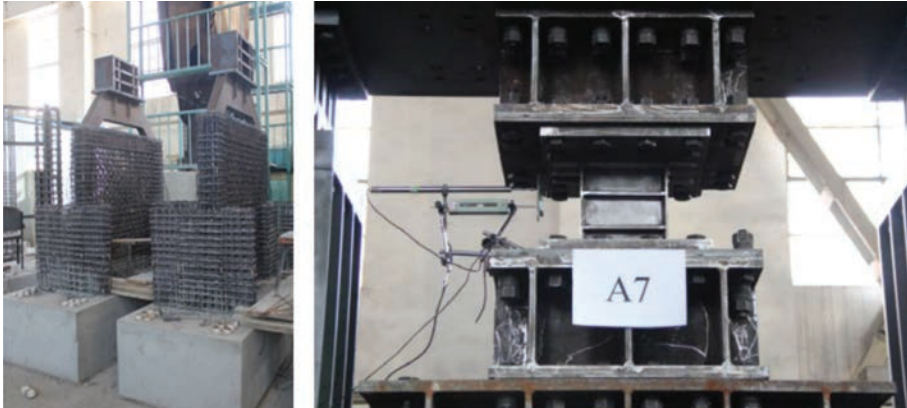


Figure 7. Physical test for fused outrigger component. © Arup

Another example is a concrete outrigger system with a structural fuse link. A steel plate “shear link” element makes the final connection from concrete outrigger tip to the perimeter column. By sizing it to remain elastic under wind loads, the outrigger provides desired building lateral stiffness and overturning resistance contributions, but can yield during a large seismic event (see Figures 6 and 7). Damaged shear-link elements could be replaced after major seismic events, and shear-link connections could be delayed during construction to reduce gravity force transfers from differential core and column shortening.

System Organization and Examples

Mixed steel-concrete core and outrigger systems are now separated into two systems: elastic and yielding outrigger systems. The 335-meter tall Wilshire Grand Center in Los Angeles and Chongqing Raffles City in China, consisting of eight towers, the two tallest of which are 354 meters, are added as examples of mixed steel-concrete core and yielding outrigger system. The Lotte World Tower in Seoul is an example of an elastic system. The project features are summarized below.

Yielding outrigger system

Wilshire Grand Center, Los Angeles

The 335-meter, 62-story tower of the Wilshire

Grand Center was completed in 2017 (see Figure 8). Since the floor plan and reinforced concrete core plan are elongated, three sets of outriggers connect the core to 10 of the perimeter concrete-filled steel box columns to supplement core transverse stiffness for occupant comfort, help resist transverse overturning under strength-level winds, and absorb energy in seismic events. Multistory steel belt trusses occur at two of the three outrigger levels to distribute transverse overturning forces across all columns, enforce similar shortening at all the perimeter columns, and provide “virtual outrigger” assistance for longitudinal overturning forces. BRBs at all outrigger diagonals set reliable upper limits on



Figure 8. Wilshire Grand Center, Los Angeles. © Wilshire Grand Center

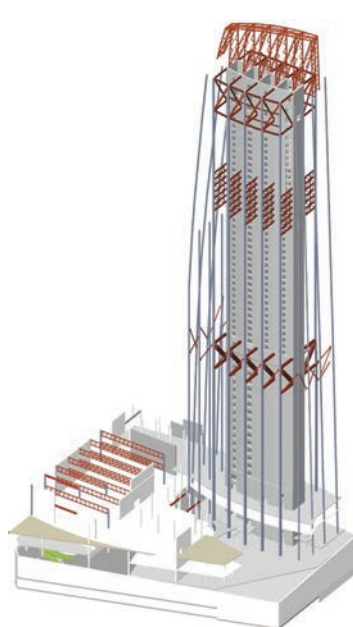


Figure 9. Wilshire Grand Center – isometric showing outriggers at three levels, belt trusses not drawn here. © AC Martin



Figure 10. Chongqing Raffles City, Chongqing. © Capitaland

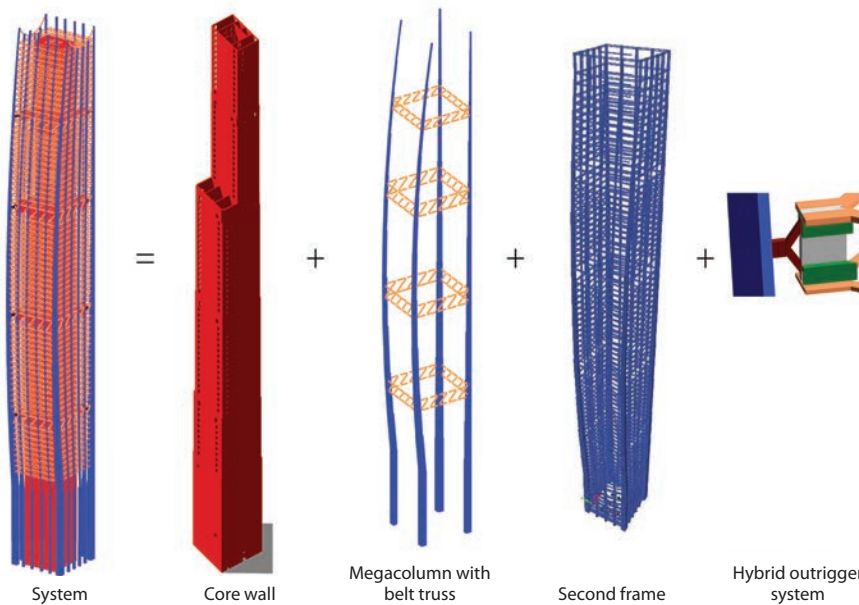


Figure 11. Chongqing Raffles City – structural system. © Arup

demands at connections, at columns, and in transverse walls where high shear occurs at “panel zones” from outrigger action during extreme events. The BRBs work elastically under service loads. Demonstration of satisfactory seismic performance is shown by figures based on nonlinear response history analyses at the maximum considered earthquake level (see Figure 9).

Chongqing Raffles City

Two 300-plus-meter towers in a six-tower complex use a central concrete core, corner megacolumns, multiple belt trusses engaging secondary perimeter frames, and corner outriggers (see Figures 10 and 11). The outriggers include a shear dissipation component, or “structural fuse,” described previously in the Fused Outrigger section. The component was designed to remain elastic for gravity and wind load combinations and seismic events at the 475-year Mean Recurrence Interval level. For maximum considered events (MCEs), the “fuse” will yield in shear, providing energy dissipation while limiting the forces applied to concrete outriggers, megacolumns, and their connections.

Elastic outrigger system:

Lotte World Tower, Seoul

At 555 meters, the 123-story Lotte World Tower stands as the fifth-tallest building in the

world (see Figure 12). The US\$2.5 billion tower and adjacent development features a variety of uses, including office, retail, hotel, officetel (a combination office/apartment common in South Korea), parking, museum, and observation space.

The tower has a tapered shape – with sloping concrete core walls in the middle third of the building and columns sloping in two directions. Occupying the majority of the tower (from the ground level to the 71st floor), the office and officetel floors are steel-framed with a slab-on-truss deck, whereas the hotel floors (from levels 87 to 101) are concrete flat slabs with drop panels. The diagrid structure at the top of the building contains premium office, museum, and observation floors, which are also steel-framed with a slab-on-truss deck, and forms the exterior portion of the “lantern” structure above the

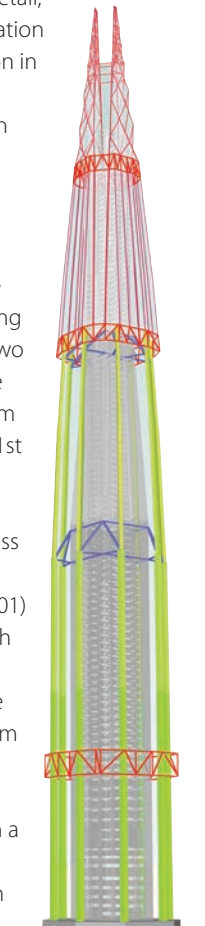


Figure 12. Lotte World Tower, Seoul. © LERA

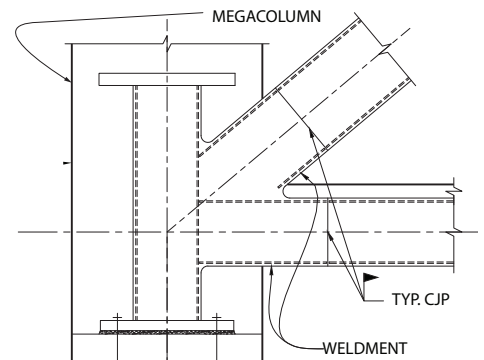


Figure 13. Lotte World Tower – outrigger-to-megacolumn connection. © LERA

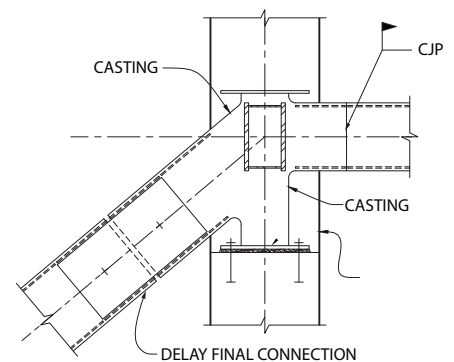


Figure 14. Lotte World Tower – outrigger-to-core-wall connection. © LERA

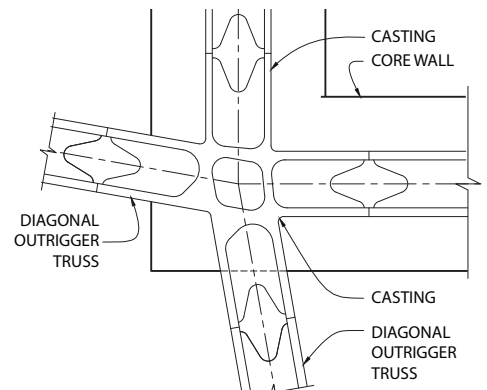


Figure 15. Lotte World Tower – casting for outrigger-to-core-wall connection. © LERA

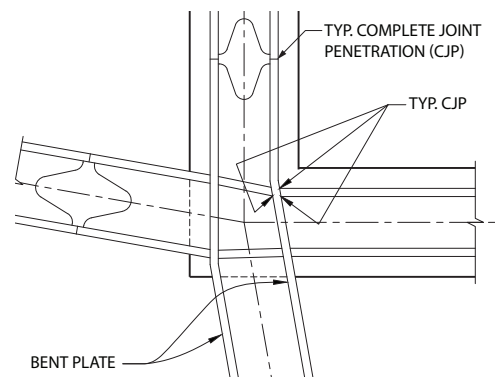


Figure 16. Lotte World Tower – weldment for outrigger-to-core-wall connection. © LERA

highest occupied floor. Though the tapered shape of the building led to challenging structural complexities, it was effective at minimizing wind loads.

The tower's primary lateral load and gravity system consists of eight concrete megacolumns, concrete core walls, and a series of outriggers and belt trusses located at the mechanical, refuge, sky lobby, and hotel amenity floors. The belt trusses transfer the diagrid "lantern" structure to the column configuration of the hotel floors and transfer the columns of the hotel floors to the megacolumns at the officetel and office floors.

Outriggers have been used in tall buildings since the original World Trade Center twin towers in New York. They are used to increase the stance of the building in resisting lateral loads from wind or earthquakes, thereby reducing overturning moments acting on the core. They are also used to control differential vertical displacements between the core and the perimeter columns. At Lotte World Tower, only two levels of outriggers, tying the perimeter megacolumns to the concrete core, were needed to control the tower's drift and lateral accelerations due to wind loads. The 3.3-by-3.3-meter megacolumns at the ground level (unbraced for the first eight levels) are comparatively small compared to other towers of similar height, and even qualify as "slender" members.

The effects of creep and shrinkage, such as differential settlements between the perimeter columns and the services core, also had to be taken into account. The potential imbalance of the floor was partly addressed by vertically cambering the megacolumns during construction, allowing forces to be transferred through the outrigger members as the megacolumns settle further than the concrete core. The structural engineering team recommended delaying the final connections of the outriggers to mitigate the force transfer in the short term, while also designing for the potential force transfer due to long-term creep and shrinkage.

Unlike other projects where the outriggers have vertical steel members extending several

floors above and below the outrigger, the outriggers at Lotte World Tower have a simple cap plate and base plate to transfer its vertical loads through bearing to the concrete megacolumns and the concrete shear walls (see Figures 12 and 13).

With the architectural geometry dictating the megacolumn locations, the outrigger needed to be skewed in plan relative to the core wall. Two options were provided for the outrigger to megacolumn connection; one using a casting (see Figure 14) and the other using a weldment (see Figure 15). Castings for outrigger connections have previously been used in the Shanghai World Financial Center.

In many other projects, belt trusses are located to run through the center of the megacolumn to intersect with the center of the outrigger, creating complicated connections. For Lotte World Tower, the belt trusses are located on the exterior of the megacolumn, thus reducing the complexities and eliminating the three-dimensional structural steel connections that would otherwise be required (see Figure 16).

Conclusion

The complexity of tall building design continues to intensify, as ever-more demanding seismic and wind-performance requirements intersect with more ambitious design and floor-plate-efficiency objectives. The outrigger has proven to be a highly effective mediator in this reciprocal dialogue, but it is by no means a static solution. It must constantly be improved upon and

“At Lotte World Tower, the belt trusses are located on the exterior of the megacolumns, thus reducing the complexities and eliminating the three-dimensional structural steel connections that would otherwise be required.”

strategically refined, as the above project samples and newly revised Technical Guide chapter summaries have indicated. ■

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Editor's Note:

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