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Outrigger System Design Considerations

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Abstract

Outrigger systems have been widely used in super tall buildings constructed since the 1980's, eclipsing previously favored tubular frame systems. However, outriggers are not listed as a seismic lateral load resisting system in any code. Design guidelines are not available. The CTBUH formed the Outrigger Working Group to develop the first-ever outrigger system design guide with an historical overview, considerations for outrigger application, effects on building behavior and design recommendations including concerns specific to this structural system such as differential column shortening and construction sequence impacts. Project examples are presented for various outrigger system types, including advancements in their technology. The guide provides a basis for future discussions on this important topic.

Keywords: Outrigger, Code, Design guidelines, CTBUH, Outrigger working group, Tall building design

1. Introduction

Outrigger systems are widely used to provide efficient lateral load resistance in tall slender contemporary buildings. Outriggers are rigid horizontal structures connecting a building core or spine to distant columns. They improve stiffness against overturning by developing a tension-compression couple in perimeter columns when a central core tries to tilt, generating a restoring moment acting on the core at the outrigger level. Outrigger system behavior is simple in principle, but analysis, design, detailing and construction of a complete core-and-outrigger system is complex in practice: being indeterminate, distribution of forces between the core and the outrigger system depends on the relative stiffness of the elements, differential strains between elements and other factors. The Council on Tall Buildings and Urban Habitat Outrigger Working Group has developed a design guide presenting outrigger history, design considerations, recommendations and contemporary examples, while encouraging further discussions within the design professions. This article is a capsule summary of the guideline using the same format. Readers are urged to refer to the full document for more complete discussions and details.

1.1. Benefits of an Outrigger System

One important outrigger benefit is reduction of building acceleration at upper floors by decreasing lateral displacements through reduced overturning moments. For systems with belt trusses that engage all perimeter columns, columns already sized for gravity loads may be capable of resisting outrigger forces from lateral loads. Reducing core overturning reduces shear and flexural demands within the tower foundation mat. Overturning forces are spread across the whole tower footprint width. Outriggers and belt trusses can help reduce differential vertical shortening between columns, or between a column and the core. Belt trusses can also cause perimeter columns to act as fibers of a perimeter tube that is less stiff than a continuous framed tube but contributes significant torsional stiffness. When considering sudden loss of local member or connection capacity, outriggers can provide alternate load paths to aid disproportionate (progressive) collapse resistance. Supertall buildings with outriggers may have a few exterior mega columns on each face, which opens up the façade system for flexible aesthetic and architectural expression compared to closed-form tubular systems.

1.2. Challenges for Outrigger System Design

Incorporating an outrigger system in the design of a tall building requires resolving numerous engineering challenges and coordinating with other members of the design team affected by its framing requirements. Outrigger systems include elements in vertical planes (walls, truss diagonals) that can potentially interfere with occupiable or rentable space. Running outriggers across mechanical floors requires careful coordination with mechanical room layouts, access requirements and service routes to avoid potential conflicts.

Floor diaphragms interact with outrigger systems. In a direct or conventional outrigger system, models with incorrect or unrealistic diaphragm properties will report incorrect force values in outrigger chords supporting

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slabs, as well as incorrect building deformations. Diaphragm stiffness modeling is particularly important for indirect 'virtual' outrigger/belt truss systems, as the diaphragms are key elements in the load paths that make the system work.

Conventional or directly-framed outrigger system designs must address the potential for load redistribution between columns and core resulting from differential axial strains. Unlike all-steel systems, concrete buildings experience long-term vertical deformations due to cumulative creep and shrinkage strains in addition to elastic shortening. The magnitude and timing of such deformations will differ between members as stresses, concrete mixtures, volume-to-surface ratios and reinforcing ratios differ. This makes prediction of differential movements a complex time- and sequence-related challenge. Force transfers can also occur through conventional or direct outriggers when the columns and core experience differential temperature conditions, as from perimeter columns exposed to weather.

Outriggers located at just a few points along building height tend to generate large forces to help counteract core overturning moments. The challenge increases at mixed systems such as steel outrigger trusses between concrete mega columns and concrete core walls, and at composite systems with steel members embedded within or enclosing concrete.

The numerous special members and heavy connections of outriggers and belt trusses and changes from typical floor framing at outrigger levels can significantly slow the erection process. Delaying outrigger connections to allow for initial differential shortening would reduce gravity load transfer forces, but on some projects outriggers must act for potentially high winds during the construction period, as well as for deflection control for partial operation of buildings still under construction, a practice common in some parts of the world.

The ASCE7-05 standard referenced in model building codes such as the International Building Code includes 82 seismic structural systems and combinations but no outriggers. This omission is not surprising since no single standard design approach is suitable for all outrigger situations. Outriggers and belt trusses are stiff and strong elements at discrete locations within a structure. This can be inconsistent with seismic design approaches based on distributed stiffness and strength. Strong outriggers may also apply forces large enough to load other elements to the point of damage and non-ductile behavior.

Soft story seismic provisions in model building codes typically look at the change in story stiffness from one story to the next story up. In an outrigger system the outrigger floors exhibit smaller story drift from a reverse shear force in the core. As a result, outriggers could be considered as inherently 'stiff stories' and the stories immediately below an outrigger are always 'soft stories.' This should not disqualify use of an outrigger system since the stories between outriggers still provide ductility.

In a core-and-outrigger system, the strong column weak beam provision does not appear necessary or appropriate at perimeter columns because the central core walls or core braced bays already provide a strong spine. The strong column weak beam philosophy could be appropriately applied to the interaction of outriggers and the core through capacity based design limiting outrigger forces, or performance based design evaluating forces from realistic seismic excitation.

1.3. Conditions Less Suitable for Outrigger Systems

Structural systems governed by story shear deformations, such as moment frames, would not benefit enough from outriggers to justify their cost. Outrigger systems interact with cores based on relative stiffness. If a core is already comparatively stiff or the aspect ratio (building height/core width) is low, it may be impractical or inefficient to attempt providing further stiffness through outriggers.

An unsymmetrical system may have outrigger force couples involving axial forces in the core, complicating core analysis and design. Gravity force transfers in an unsymmetrical system can result in an overturning moment cranked into the building, leading to lateral displacements under gravity loads. However, this does not mean unsymmetrical systems cannot be used.

If controlling torsional forces and deformations is of primary importance, a perimeter tube (frame) or belt truss system would be more effective than an outrigger system without belts.

Limitations on outrigger column sizes may render an outrigger system ineffective, especially if outriggers are limited to locations high in a building since larger column sizes would be needed for increased stiffness to offset the softening effect of the long distance to the outrigger.

2. Design Considerations for Outrigger Systems

2.1. Appropriate Conditions for Outrigger Systems

For an aspect ratio exceeding 8 or so the structural premium to control drift and resist overturning is large enough to consider introducing outriggers to alleviate dependence on the core for overturning resistance and maximize useful space between the core and exterior columns.

When direct or conventional outrigger walls or trusses are not acceptable for the building due to space limitations or a column layout which is not aligned with the core walls, an indirect, 'virtual' outrigger or belt truss system may be used. In an indirect or virtual outrigger belt truss design, corner columns tend to provide most overturning resistance, but may not attract much of the gravity load unless specific attention is paid to relative stiffness of all system elements. Ideally the same member

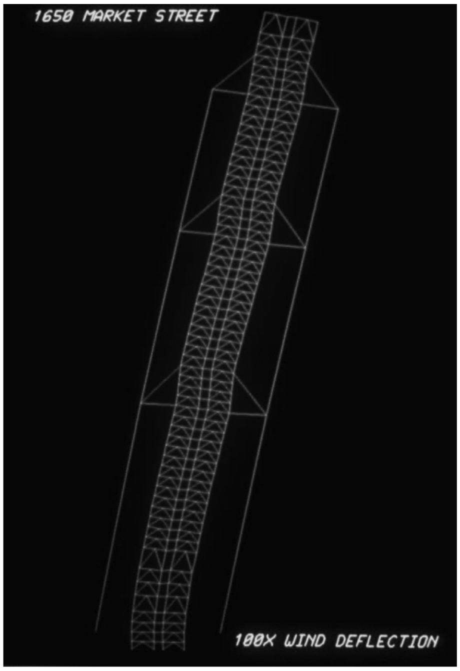


Figure 1. One Liberty Place deflected shape.

sizes work for strength and for stiffness.

2.2. Load Transfer Paths in Outrigger Systems

When a structure containing an outrigger system is loaded laterally, the outriggers resist core rotation by inducing perimeter columns to push and pull in opposition, introducing a change in the slope of the vertical deflection curve (Fig. 1). A portion of the core overturning moment is transferred to the outriggers and, in turn, tension in windward columns and compression in leeward columns.

The same stiff outriggers that generate interaction between core and columns under lateral loads will also cause interaction under vertical loads. Differential shortening, whether from elastic shortening, inelastic creep and shrinkage or thermal effects will lead to forces being transferred between core and columns through the outriggers (Fig. 2). In concrete systems it is more likely that columns will be acting at higher stress than core walls under gravity loads, so outriggers typically tend to transfer outer column gravity load to the core when core and columns are both concrete. With a concrete core and steel perimeter columns, the effect reverses over time as creep and shrinkage causes the core to shorten more. Load transfer effects can be minimized through control of construction sequence or use of special connection details as discussed later.

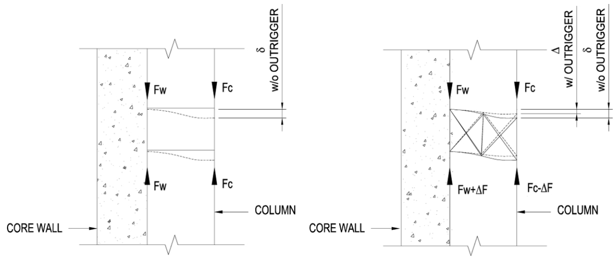


Figure 2. Transfer of gravity loads from columns to core.

One major advantage of the indirect or virtual outrigger or belt wall system is that it is not affected by differential inelastic vertical deformations between core and perimeter, so no vertical load transfer occurs between the core wall and perimeter columns. However, a belt truss can experience vertical load transfer forces if it tries to equalize axial strains that differ between adjacent perimeter columns.

2.3. Determining Locations of Outriggers in Elevation

The short load path from column to core by direct outriggers makes them stiff and efficient. To achieve the same stiffness benefit, indirect outriggers (belt trusses or walls) would be required on more floors than direct outriggers. This tradeoff is rarely an issue in reality; the particular benefits of each outrigger type lead to their use in different building conditions. Both outrigger types can also be present in the same building, as where multiple outriggers offer desired stiffness and strength benefits, but not every outrigger level desired can accommodate direct outrigger trusses, or where differential shortening is more problematic for direct outriggers at some levels than at others. The requirements and benefits of each outrigger type are discussed elsewhere in this document.

Optimal outrigger locations will differ for different buildings and for different optimization criteria (top floor drift, story drift). As a starting point with one outrigger a general guideline would locate it at half of the building height. For two outriggers, ⅓ and ⅔ height would be a good starting point. If one of the outriggers must be at the top the second truss would optimally be at 50% to 60% of building height. If there are three outriggers, ¼, ½, and ¾ height points are good to start design, but if one is a top outrigger the others may be at ⅓ and ⅔ height. As discussed above, any selection of outrigger locations must consider both the realities of space availability, such as mechanical floor locations, and the influence of member size decisions on this indeterminate system.

2.4. Diaphragm Floors

Understanding diaphragm behavior is important for any outrigger system. If a belt wall or virtual outrigger system is used, a stiff, strong floor diaphragm is required at the top and bottom chord of each belt wall in order to transfer the core bending moment, in the form of floor shear and axial forces, to the belt wall and eventually to the columns. Indeed, the floors at belt walls of an indirect outrigger system are significantly thicker, or specially trussed, to provide that stiffness and strength. However the effect must not be exaggerated: a simple rigid-diaphragm modeling assumption must not be used. Improperly modeled diaphragms will result in misleading behaviors and load paths, and incorrect member design forces, for both indirect 'virtual' outrigger/belt truss systems and direct, conventional outrigger systems.

2.5. Stiffness Reduction

Analytical studies must consider appropriate stiffness regimes depending on the load conditions, especially for concrete construction. When considering concrete core walls and columns, different stiffness reduction factors apply for service-level wind (gross sections), factored wind and factored seismic cases, as well as further reductions in the presence of cracking, as described in ACI 318. If a nonlinear analysis has modeled explicit changes in member stiffness at different load levels there is no need to apply general stiffness reduction factors as well. However, nonlinear analyses are typically performed only after preliminary member sizing has been performed on the basis of simpler, elastic models. To the extent that geometric nonlinearity (P-Delta effect) is not explicitly considered by the analysis method, lateral stiffness should be reduced to reflect it.

2.6. Differential Column Shortening Effects

In a high-rise building, columns are typically highly strained from gravity loads, and small differences in strain between adjacent columns, or between columns and the core, will accumulate to result in significant differences in axial shortening over a building's height. Large strains can be induced in outriggers that link columns and a core that shorten by different amounts. The resulting strains can generate very large forces within the outriggers, transferring a portion of gravity loads between columns and core. If no special measures are taken, for some designs gravity transfer forces can be of similar magnitude to the outrigger design forces resisting lateral loads. To avoid having to design for such large forces, or being surprised by potentially damaging forces and displacements in structural and nonstructural elements, differential shortening between vertical members should be considered throughout the design and construction process.

Ideally the gravity system is coordinated with the lateral system so that members of similar materials are used and axial stress levels under gravity are similar for all vertical members. That will minimize differential column shortening. However, in real concrete buildings columns typically have higher axial stresses than core walls and shorten more as a result. The reverse may be true in steel braced core buildings. Outriggers connecting the two types of elements will try to transfer load through the outriggers, for example relieving concrete columns and loading concrete core walls.

Time-dependent differential shortening effects are greatest when different materials are used in the core and in the perimeter columns. In a concrete core and steel perimeter design, for example, all post-construction core shortening generates differential shortening. That can be a large number, reaching several inches (cm) over time.

Time-based load combinations should be considered. Because gravity load transfer forces vary with time, especially from creep and shrinkage effects, total forces in the core and outrigger columns will vary with time as well. To cover both the immediate and long-term load distribution cases, separate load combinations should be determined both with and without the transfer forces present. Construction strategies can also affect transfer forces, as discussed in section 2.10 below.

2.7. Thermal Effects Management

Outriggers that link exposed perimeter columns and a temperature-controlled internal core can experience large forces induced by temperature differences. The magnitude of temperature difference should consider realistic heat flow paths, including the ratio of surfaces exposed to the exterior and interior, and the thermal properties of the material. At a minimum the effect should be considered in all load combinations that include the self-strain load T arising from thermal effects for a realistic range of exterior and interior temperatures. The load factor applied should reflect the probability of occurrence: a larger factor should apply if using seasonal or daily average maximum and minimum temperatures, while a smaller factor could apply if extreme recorded temperatures are used.

ASCE 7-10 is not yet referenced in current codes, but it addresses self-strain load(s) T with general statements. For factored load combinations, it states, "Where applicable, the structural effects of T shall be considered in combination with other loads." Also, "The load factor on T shall not have a value less than 1.0." For load combinations under Allowable Stress Design the wording is identical except for a 0.75 load factor. These statements validate the idea that T should not be limited to selected load combinations, while complicating establishment of appropriate T values. Due to the low probability of simultaneous extreme temperatures and earthquakes or rare winds, a less-than-extreme value for T is recommended so that a load factor of 1.0 (or 0.75 for ASD) is appropriate in combinations with wind (W) or earthquake (E) loads. For combinations without wind or earthquake loads, a higher load factor on T can be applied to cover potential extreme temperatures.

2.8. Load Path from Connections

When core, outrigger and column are all structural steel, the connections will be large but can be conventional. When forces must transition between different materials, establishing an appropriate load path requires study and creativity; there is no single 'correct' approach.

For a load path from steel outrigger to concrete core

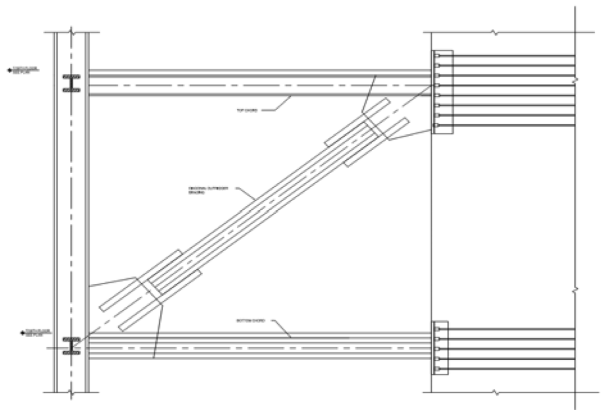


Figure 3. Outrigger connections through embedded plates and deformed bar anchors.

wall, the connection can be made through an embedded plate, flush with the concrete face using composite shear connectors ("headed studs") to resist the vertical component of the force in the outrigger diagonal, while long horizontal bolts developed within the wall can take the horizontal force from a member end plate through nuts on projecting threaded ends. However, this approach maybe not appropriate for large force and reversible cyclic outrigger forces. Deformed bar anchors welded to the embedded plate provide another approach to the load path (Fig. 3).

Continuous embedded steel members can permit more conventional, direct steel-to-steel connections but have their own drawbacks. Concrete construction is much more complicated when working around heavy steel members, and accuracy of steel placement and subsequent connection fit up can be affected by the concrete encasement (Fig. 4). Design of the embedded steel requires thought: if sized just for strength, to minimize tonnage, will the resulting steel strain be incompatible with surrounding concrete, leading to deterioration? How will forces exit the steel to enter the concrete – bond, headed studs, other methods?

Partial height embedded steel members covered with headed studs can use conventional steel-to-steel connections and transfer the force to surrounding concrete along

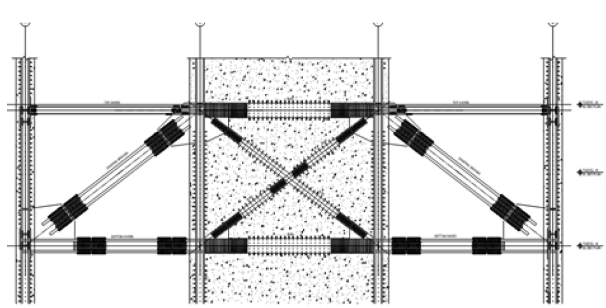


Figure 4. Outrigger connections with continuous steel members.

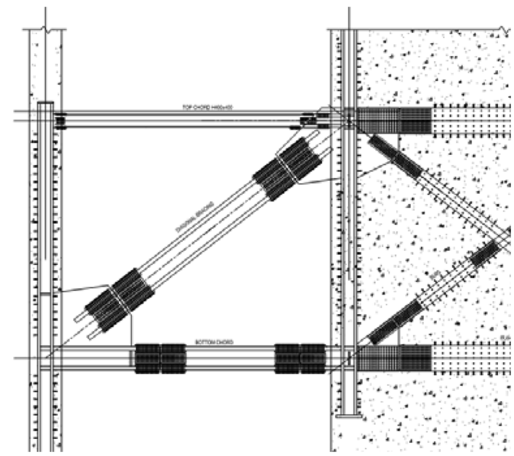


Figure 5. Outrigger connections using local embedded steel through headed studs.

the axis of the steel member (Fig. 5). Appropriate design shear values for headed studs, bond and end plates must be determined. Steel member length depends on the shear transfer values and the forces to be transferred. While partial height members reduce the number of stories that concrete work is affected, headed shear studs on all faces can affect the minimum wall thickness that can fit both steel and reinforcement.

Localized short steel stub members can permit more conventional steel-to-steel connections while limiting impact on concrete construction to the immediate area. Ability to set and hold the stubs accurately for fit up, and provide a suitable load path are challenges for this approach.

A large bearing plate at each end of a stub, sized like a column base plate, can distribute upward and downward forces over the plan cross section of a concrete column or core wall corner or intersection (Fig. 6).

Concrete to concrete connections may also be complex, depending on outrigger geometry (Fig. 7). Transitioning

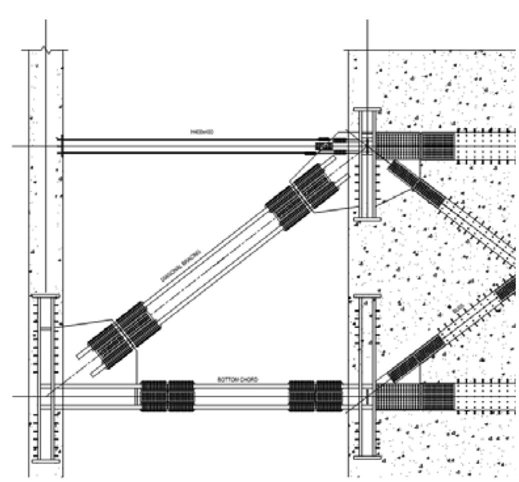


Figure 6. Outrigger connections using steel stubs through studs and end plates.

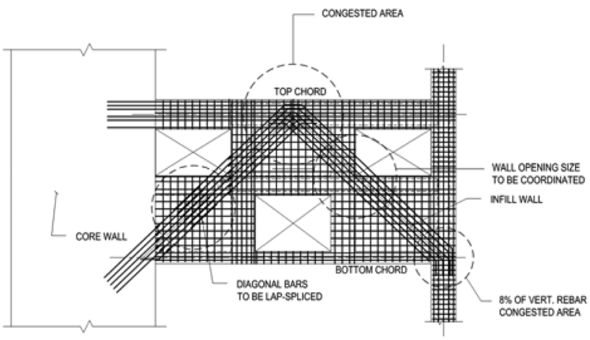


Figure 7. Concrete outrigger wall showing bands of reinforcing bars.

diagonal reinforcing into horizontal and vertical reinforcement, developing bars, lapping bars and anticipating and resolving different strain values and patterns for compression and tension in the outrigger member must all be addressed.

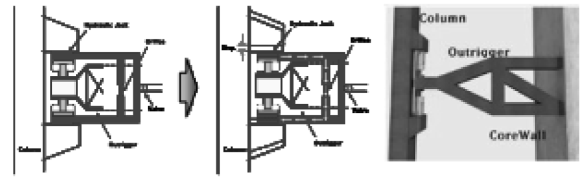
2.9. Panel Zone Load Path

When outrigger levels are few and far between, the pattern of shear forces in the core wall is similar to shear in a moment frame column: panel zones, in this case outrigger levels, are locations of larger-than-typical, reverse-direction shears. The core-as-column analogy is not perfect: unlike column webs, core wall panels are typically perforated by lines of doorway openings. Shear stiffness and strength of coupling beams crossing openings may limit 'panel zone' capacity. Building designs have addressed this condition several ways.

If openings can be omitted at one or more stories at the outrigger level, it may be practical to design the resulting story-high (or deeper) coupling beam to resist the larger wall shear force. A strut-and-tie model may be applied where opening sizes and locations permit. This requires clear paths with adequate face width and wall thickness for compression struts, bands of continuous reinforcement or embedded tension members for tension ties, and adequate room at strut/tie intersections for force-transfer nodes. If outrigger connections and load paths are already based on embedded steel members, panel zone forces can be resolved through an embedded complete steel truss. This requires favorable geometry, which is also true of the other approaches.

2.10. Outrigger System Construction Sequence

Construction of a core-and-outrigger building has two key aspects: mitigation of differential shortening and effect on overall construction schedule. While construction sequence for most buildings may be considered as 'means and methods' separate from design, that is not true for outrigger systems due to differential axial shortening effects as mentioned in section 2.6. No matter which structural systems and materials have been selected by



(a) Installing Bi-directionally Interlocked Oil Jack (b) Interlocking Operation (c) Schematic View after Installation

Figure 8. Oil jack outrigger joint system.

the designer, time dependent shortening effects cannot be neglected or eliminated. They can, however, be reduced through construction sequence.

Delaying final outrigger connections linking core and columns until after topping out can reduce, but not eliminate, additional forces in the outrigger system since differential post-top-out axial shortening of core and columns will occur. These forces must be considered in the design. Minimizing these additional forces would preserve more of the outrigger capacity to resist lateral forces. This requires a system that allows later adjustment of the outriggers connections. Several such systems have been proposed and some have been implemented in recent tall buildings.

Shim Plate Correction Methods, Oil Jack Outrigger Joint Systems (Fig. 8) and Cross Connected Jack Systems have been proposed or used to minimize differential shortening impact during and after construction by using hydraulic cylinders or shim stacks to frequently or continually adjust for slowly developing differential movements but resist rapid wind or seismic movements.

2.11. Code Interpretations for Seismic Load Resisting Systems

Current seismic design provisions in building codes, such as the International Building Code (IBC) and Eurocode 8, were not developed for application to tall buildings since they comprise a small portion of overall building construction. Prescriptive seismic design provisions in these building codes do not sufficiently address many facets of seismic design of tall buildings, such as the outrigger systems frequently used for lateral load resistance of tall buildings; they are not currently included as an option under the Basic Seismic-Force Resisting System table in the IBC. In addition, many building codes have height limitations on many practical and popular seismic force resisting systems, which block their use in tall structures if following prescriptive provisions.

The CTBUH has prepared guidelines addressing the issue of seismic design of tall buildings. It presents the most appropriate approach as being performance based design (PBD) rather than prescriptive design. PBD, as permitted in the code as an alternative to prescriptive design, offers clear benefits for achieving better tall building designs. It requires clearly defined performance objectives, procedures for selecting and scaling earthquake ground motions for design, nonlinear modeling methods that produce reliable estimates, acceptance criteria for calculated demands and a framework for the design and review of alternative-design buildings. Outrigger members can be designed to remain elastic under the Design Basis Earthquake or the Maximum Considered Earthquake, or can be 'fused' to limit the member forces and absorb seismic energy in a large earthquake event.

2.12. Soft Story and Weak Story Seismic Requirements

Prescriptive code seismic requirements limit the permissible variation in stiffness or strength from story to story. In particular, codes discourage having a stiffer or stronger story above a softer or weaker story. This would appear to prohibit outrigger systems, since the story below an outrigger is usually significantly less stiff and weaker in shear than the outrigger story. However, such an objection would be short-sighted: the code requirement is intended to guard against a uniformly stiff or strong building having a soft or weak story where deformations would be concentrated, as may occur at a lobby or other non-typical level. Outriggers create the opposite situation. A building with multiple stories of similar stiffness and strength is additionally strengthened and stiffened at the few outrigger floors. Having many similar floors provides ample opportunities for well-distributed ductile behavior between outriggers, while the outriggers provide positive global effects. Performance-based analysis can demonstrate that behavior is acceptable under this system.

2.13. Strong Column Seismic Requirement and Capacity Based Design

The intent of the amplified seismic load requirement may be met in some designs by performance based analysis. For lateral systems sized for other criteria, such as stiffness and strength under extreme wind loads, nonlinear time history studies may be able to demonstrate that demand under load combinations including seismic effects never exceeds capacity at outriggers and the columns to which they connect, even for the maximum considered earthquake event. This situation is more likely to occur at outriggers and mega columns near mid-height: gravity load will comprise a large portion of the column axial demand, column net tension is less likely to occur there than at outriggers high in the building, and outriggers may be designed for large forces that include gravity load transfers between core and columns.

Capacity based design can avoid the need for highly ductile column axial performance, by limiting applied forces from seismic events to a maximum value in combination with well established factored gravity forces from dead and live loads. The capacity-based approach to avoiding column failure relies on having non-column members yield or buckle first. Establishing outrigger members small enough to serve as 'fuses' may be achievable by optimization. Where the lateral load resisting system is being sized for stiffness, as may occur where wind criteria are governing the design, the requirement can be met by a variety of combinations of column stiffness and outrigger stiffness. For example, making columns larger to resist capacity-based outrigger forces will add to system stiffness. That may permit downsizing the outrigger members themselves while meeting required system stiffness. The smaller outrigger members would limit the maximum force columns could experience. Since core-and-outrigger systems are indeterminate, changing the outrigger and mega column stiffnesses will also change the forces they attract. Several design cycles may be required to simultaneously achieve the required stiffness and a hierarchy of strength.

2.14. Strong Column Weak Beam Concept in Outrigger Systems

The strong column, weak beam provision, called the column-beam ratio in AISC Seismic Provisions and minimum flexural strength of columns in ACI 318 seismic provisions, specifically refers to special moment frames, checking that lateral loads will cause yielding in beams rather than in columns. It is intended to avoid hinge formation in multiple columns at the same level, which could cause story collapse.

Applying the strong column weak beam provision to a core-and-outrigger system building is inappropriate because outriggers are not moment frames. It is also problematic because any realistic outrigger truss or outrigger wall viewed as a 'beam' connected to the outrigger column at top and bottom chord levels will not yield in flexure (chords yielding or buckling) before the column does. In a core-and-outrigger system where the core itself provides the majority of inter-story stiffness, it is evident that story collapse should not occur even if columns develop flexural hinges. By that logic, a strong column, weak beam criterion should apply only for viewing the core as a 'column' and the outriggers as 'beams' because the central core walls or core braced bays will provide the strong spine desired for favorable seismic performance. Even if perimeter columns hinge at outrigger top and bottom chord levels, the story cannot collapse as long as the core is standing.

Therefore the performance based seismic design approach for outrigger system buildings is highly recommended as it looks at responses to realistic seismic events. A PBD approach can demonstrate that capacity-limiting measures such as BRB diagonals work. Alternatively, the need to design an outrigger as a 'weak beam' can become moot if members sized for strength and stiffness are shown to remain elastic in a nonlinear time history response analyses and the core can resist the resulting forces.

2.15. Capacity Based Connection Design

A general seismic design principle is to have connections stronger than members. The intent is to maximize ductile behavior by distributing post-yield strains along as much of the member length as possible, rather than having yielding, and potential fracture, concentrated within the connections. For massive outrigger members sized to satisfy stiffness requirements, it may not be practical to provide connections stronger than the maximum capacity of the member. In such cases the results of nonlinear time history analyses as part of a PBD approach can be used to determine realistic connection demand. The connections can be designed to resist the demand from unreduced seismic conditions while staying elastic, or with limited 'hot spots' of yielding that do not significantly affect the ability of the connection to resist anticipated demand.

3. Core and Outrigger System Organization and Case Histories

Many different outrigger systems have been applied to tall buildings. Throughout the design guide the project examples listed below illustrate outrigger system types:

All-Steel Core and Outrigger Systems: First Wisconsin Center, Milwaukee, Wisconsin, USA; New York Times Building, New York City, USA.

All-Concrete Core and Outrigger Systems: Waterfront Place, Brisbane, Australia; Two Prudential Plaza, Chicago, Illinois, USA; Millennium Tower, San Francisco, California, USA; Trump Tower, Chicago, Illinois, USA; Plaza 66, Shanghai, China.

Mixed Steel-Concrete Core and Outrigger Systems: Dearborn Center Proposal, Chicago, Illinois, USA; One Rincon Hill, San Francisco, California, USA; Cheung Kong Center, Hong Kong, China; Chicago Spire Proposal, Chicago, Illinois, USA; 300 North LaSalle, Chicago, Illinois, USA.

Ultra Tall Building Outrigger Systems: Miglin-Beitler Tower Proposal, Chicago, USA; Jin Mao Tower, Shanghai, China; Taipei 101, Taipei, Taiwan; Two International Finance Centre, Hong Kong, China; Shanghai Tower, Shanghai, China.

Virtual or Indirect Outrigger Systems: Plaza Rakyat Office Tower, Kuala Lumpur, Malaysia; Tower Palace III, Seoul, South Korea.

4. Special Topics

Occupant comfort in windy conditions is typically an important criterion for tall building design, and often has a major influence on the structural design. Vortex-induced oscillations (VIO) can generate problematic crosswind movements. VIO can be reduced by building shape modifications that disrupt vortex formation. Another approach is to alter building dynamic properties by changing building mass or stiffness, but that can be expensive or impractical. Supplementary damping is an efficient and cost-effective way to improve occupant comfort. Supplementary damping can take the form of viscous dampers, viscoelastic dampers, tuned mass dampers, tuned liquid column dampers or sloshing dampers.

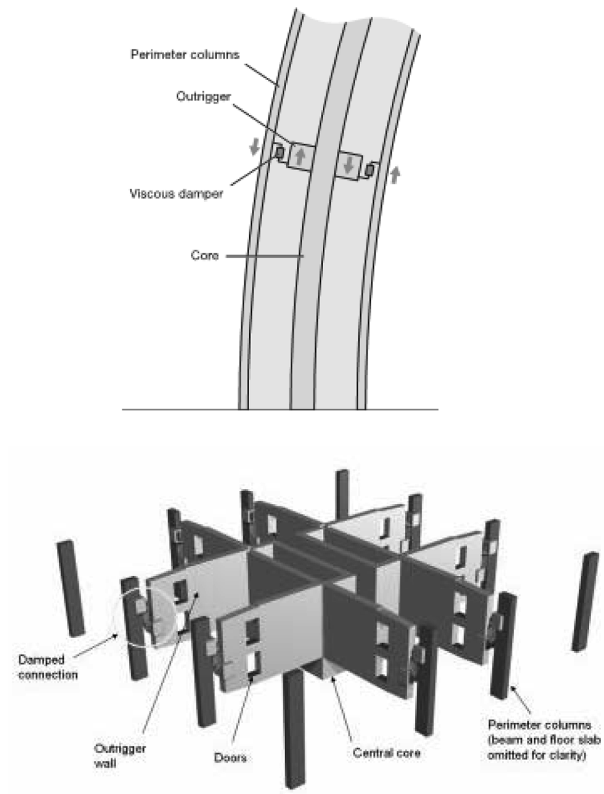


Figure 9. Damped Outrigger Elevation and Isometric.

While outriggers typically serve as rigid connectors between a core and perimeter columns to increase stiffness and strength against overturning, the geometric leverage offered by outriggers can also be used to drive supplementary mechanical damping devices: large relative movements between outrigger tips and perimeter columns can efficiently drive relatively compact dampers bridging between them (Fig. 9). Smith (2008) reports the dampers at Shangri-La Place reduce building accelerations by 35% of the original value with a damping ratio of 7.5% of critical damping.

5. Conclusions

Building core-and-outrigger systems have been used for half a century, but have kept evolving to reflect changes in preferred materials, building proportions, analysis methods and design approaches. Practical implementation of outrigger systems still requires considerable thought, care and project-specific studies.

Outrigger design is not amenable to a standardized procedure due to the variety of challenges posed, solutions used and new concepts being developed. This may frustrate designers looking for a single authoritative standard. However, the real value of this guideline document is to stimulate thoughtful discussions of outrigger systems within the engineering profession, encourage researchers to investigate behaviors related to such systems and address and resolve many of the issues through subsequent editions. The authors look forward to participating with the rest of the tall building community in these exciting developments.

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