

Outrigger Design for High-Rise Buildings 2nd Edition

An output of the CTBUH Outrigger Working Group

Hi Sun Choi, Goman Ho, Leonard Joseph & Neville Mathias



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Front Cover: *Two International Finance Centre, Hong Kong* © Arup

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Preface

Since the 1980s, outrigger systems have come into widespread use in supertall buildings, eclipsing the tubular frame systems that were favored previously. These systems have become popular due to their inherent combination of architectural flexibility and structural efficiency, compared to tubular systems that employ closely spaced columns and deep spandrel girders. Despite their modern prevalence, outrigger systems are not listed as seismic load-resisting systems in current building codes, and specific guidelines for their design are not widely available. Recognizing the pressing need for such guidelines, the CTBUH formed the Outrigger Working Group, which released the first edition of the Outrigger Design Guide in 2012. This second edition of the book reflects advances that have been made since the first edition was published. Namely, this edition features: expanded design considerations to reflect current practices, a new chapter on hybrid outrigger systems, expanded system definitions, and updated recommendations and future research objectives.

Objectives of this Guide

This design guide provides an overview of outrigger systems, including historical background, pertinent design considerations, design recommendations, and contemporary examples. The guide has three primary objectives for serving the engineering discipline. First, by developing a familiarity with the unique considerations surrounding outrigger systems, designers will be better prepared to determine if outriggers are appropriate solutions for a given situation. Second, if designers choose to apply an outrigger system, the guide provides technical background information necessary to understand and address key issues associated with their design and implementation. Examples also illustrate the broad range of solutions applied to these issues, since outrigger designs are not typically “one size fits all.” Finally, by presenting key issues and recommendations, including suggestions for future research; the guide provides a framework for further discussions within the

industry. As evidenced by this new edition, the guide is intended to be a living document, updated and revised as advancements continue to be realized in outrigger system design.

Content Overview

Outrigger systems function by tying together two structural systems – typically a core system and a perimeter system – to yield whole-building structural behaviors that outperform those of the component systems. They do this by creating a positive interaction between the two tied systems. The beneficial effect is most pronounced where the responses of the component systems under lateral loads are most disparate. Outriggers find excellent use, for example, in tall buildings that utilize dual lateral systems including a perimeter frame. The very different cantilever-type deformations of core structures and the portal-type deformation of frame structures under lateral loads are harnessed to best effect at a given level to maximize the benefit of outrigger systems in these structures. Outriggers also prove beneficial when engaging perimeter columns that would otherwise be gravity-only elements. In contrast, outriggers are less effective for “tube in tube” dual systems, because core and perimeter tubes exhibit similar cantilever deformation behaviors even before they are linked.

Outrigger system performance is affected by outrigger locations throughout the height of a building, the number of outrigger levels provided, their plan locations, the presence of belt trusses to engage adjacent perimeter columns versus standalone megacolumns, outrigger truss depths, and the primary structural materials used.

Tying together core and perimeter structural systems with outriggers creates unique design and construction problems to resolve. Most significantly, particularly in concrete and mixed-material structures, different levels of axial stress and strain in core and perimeter vertical members cause differential shortening, which increases over time due to creep and shrinkage. Differential movement can cause enormous forces in outrigger members attempting to tie the two systems together. “Virtual” outrigger systems eliminate direct outriggers connecting core and perimeter systems by instead using belt trusses in combination with stiff and strong diaphragms. Although less effective than direct outriggers, “virtual” outriggers have been developed and used to overcome the challenges posed by differential shortening, along with other benefits. Additional solutions to address the issue of differential shortening have been developed and implemented, including shimming and construction sequencing approaches, and the very innovative use of damping mechanisms to address slow, long-term movements and provide opportunities for enhanced structural damping without impacting fundamental outrigger action.

These and a host of other relevant topics have been addressed in this guide, including capacity design approaches, connection design, thermal effects, and more. The apparent conflict of outrigger systems with traditional seismic code requirements are discussed, such as story-stiffness and story-strength ratio

Different levels of axial stress and strain in core and perimeter vertical members cause differential shortening, which increases over time due to creep and shrinkage.

requirements, as well as strong-column weak-beam requirements. For example, outrigger systems add strength and stiffness beyond what is normally available to specific locations over a structure's height, but stiffness and strength ratio requirements in codes are meant to guard against sudden reductions in the normal values of these quantities, not increases. Similarly, strong-column weak-beam requirements developed to protect against story mechanisms in frame structures have less relevance where the core provides a large percentage of available story shear strength. The applicability of traditional code requirements such as these at outrigger floors thus is determined through careful consideration of structural first principles and discussion with building officials and peer reviewers prior to incorporation. New in this edition, in Chapter 3, there is a discussion of "hybrid" outrigger systems that can "tune" the stiffness of outrigger trusses, use leverage of the outrigger arms to drive non-linear damping devices, and use "yielding" materials that absorb seismic energy. Yielding materials are further explored in Chapter 4, as they relate to the increasingly common use of composite steel-concrete construction.

The Outrigger Working Group hopes this guide is useful to design professionals and code writers, and looks forward to receiving feedback that will be used to improve future editions.

1.0 Introduction to Outrigger Systems

1.1 Background

Outriggers are rigid horizontal structures designed to improve building overturning stiffness and strength by connecting the building core or spine to distant columns. Outriggers have been used in tall, narrow buildings for nearly half a century, but the design principle has been used for millennia. The oldest “outriggers” are horizontal beams connecting the main canoe-shaped hulls of Polynesian oceangoing boats to outer stabilizing floats or “amas” (see Figure 1.1). A rustic contemporary version of this vessel type illustrates key points about building outrigger systems:

- ▶ A narrow boat hull can capsize or overturn when tossed by unexpected waves, but a small amount of *ama* flotation (upward resistance) or weight (downward resistance) acting through outrigger leverage is sufficient to avoid overturning. In the same manner, building outriggers connected to perimeter columns

capable of resisting upward and downward forces can greatly improve the building’s overturning resistance.

- ▶ Even though a boat may be ballasted to resist overturning, it can still experience uncomfortable long-period roll. Outrigger-connected *amas* greatly reduce that behavior and shorten the period of the movement. Similarly, building outriggers can greatly reduce overall lateral drift, story drifts, and building periods.
- ▶ Boats can have outriggers and *amas* on both sides or on one side. Buildings can have a centrally located core with outriggers extending to both sides, or a core located on one side of the building with outriggers extending to building columns on the opposite side.

The explanation of building outrigger behavior is simple: because outriggers act as stiff arms engaging outer

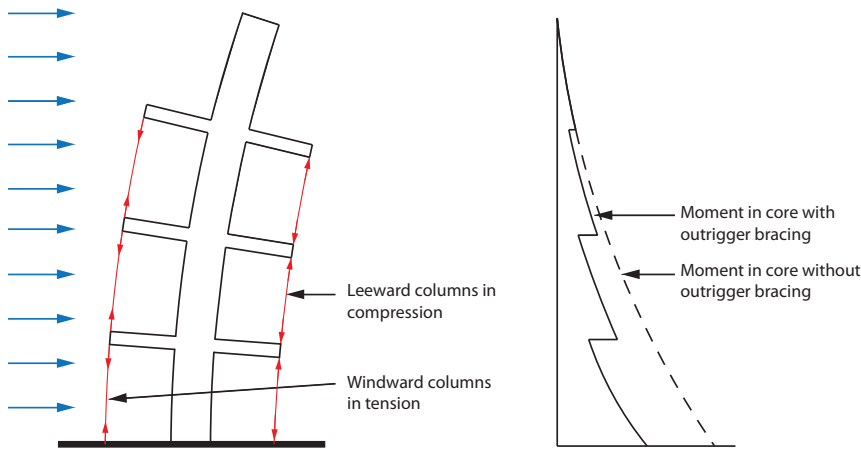
columns, when a central core tries to tilt, its rotation at the outrigger level induces a tension-compression couple in the outer columns, acting in opposition to that movement. The result is a type of restoring moment acting on the core at that level.

Analysis and design of a complete core-and-outrigger system is not that simple: distribution of forces between the core and the outrigger system depends on the relative stiffness of each element. One cannot arbitrarily assign overturning forces to the core and the outrigger columns. However, it is certain that bringing perimeter structural elements together with the core as one lateral load resisting system will reduce core overturning moment, but not core horizontal story shear forces (see Figures 1.2 & 1.3). In fact, shear in the core can actually increase (and change direction) at outrigger stories, due to the outrigger horizontal force couples acting on it.

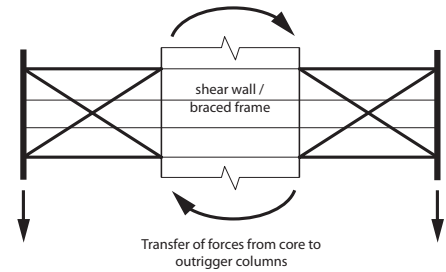
Belts, such as trusses or walls encircling the building, add further complexity. Belts can improve lateral system efficiency. For towers with outriggers engaging individual megacolumns, belts can direct more gravity load to the megacolumns. This minimizes net uplift, the amount of reinforcement or column splices required to resist tension and reduce stiffness associated with concrete in net tension. For towers with external tube systems – closely spaced perimeter columns linked by spandrel beams – belts reduce the shear-lag effect of the external tube, more effectively engage axial stiffness contributions of multiple columns, and more evenly distribute across multiple columns the large vertical forces applied by outriggers. For both megacolumn and tube buildings, belts can further enhance overall building stiffness, through virtual or indirect outrigger behavior provided by high



▲ Figure 1.1: Samoan outrigger canoe. © Teinesavaii.



▲ Figure 1.2: Interaction of core and outriggers. (Source: Taranath 1998)



▲ Figure 1.3: Outrigger at core. (Source: Nair 1998)

in-plane shear stiffness (discussed later), as well as increasing tower torsional stiffness. Belts working with megacolumns can also create a secondary lateral load-resisting system, in seismic engineering terminology.

A core-and-outrigger system is frequently selected for the lateral load-resisting system of tall or slender buildings, where overturning moment is large compared to shear, and where overall building flexural deformations are major contributors to lateral deflections such as story drift. In such situations, outriggers reduce building drift and core wind moments. Because of the increased stiffness they provide, outrigger systems are very efficient and cost-effective solutions to reduce building accelerations, which improves occupant comfort during high winds (Po & Siahann 2001).

1.2 Benefits of an Outrigger System

Deformation Reduction

In a building with a central core braced frame or shear walls, an outrigger system engages perimeter columns to efficiently reduce building deformations from overturning moments and the

resulting lateral displacements at upper floors. A tall building structure that incorporates an outrigger system can experience a reduction in core overturning moment up to 40% compared to a free cantilever, as well as a significant reduction in drift, depending on the relative rigidities of the core and the outrigger system (Lame 2008). For supertall towers with perimeter megacolumns sized for drift control, reduction in core overturning can be up to 60%. The system works by applying forces on the core that partially counteract rotations from overturning. These forces are provided by perimeter columns and delivered to the core through direct outrigger trusses or walls, or indirect or “virtual” outrigger action from belt trusses and diaphragms, as described in [Section 3.6](#).

Efficiency

For systems with belt trusses that engage all perimeter columns, those columns already sized for gravity loads may be capable of resisting outrigger forces with minimal changes in size or reinforcement, as different load factors apply to design combinations with and without lateral loads. In the event that additional overall flexural stiffness is required, the greater lever arm at

outrigger columns makes additional material more effective than in the core. Outriggers may also permit optimization of the overall building system, using techniques such as the unit load method to identify the best locations for additional material (Wada 1990). By significantly decreasing the fraction of building overturning moment that must be resisted by the core, wall, or column, material quantities in the core can be reduced, while outrigger, perimeter belt, and column quantities are increased by a smaller amount. Lower limits on core required strength and stiffness may be defined by amount of story shear resisted by the core alone between outrigger levels, special loading conditions that exist at outrigger stories, or short-term capacity and stability if outrigger connections are delayed during construction.

Foundation Forces

A separate but related advantage is force reduction at core foundations. Outrigger systems help to effectively distribute overturning loads on foundations. Even where a foundation mat is extended over the full tower footprint, a core-only lateral system applying large local forces from overturning can generate such large

3.0 Hybrid Outrigger Systems

The traditional outrigger systems discussed in Chapter 2 are intended to perform as very stiff linear elastic systems under service and factored wind conditions, and often under seismic demands as well. Traditional outrigger systems experience maximum forces when the building is experiencing maximum lateral displacements.

In contrast, hybrid outrigger systems can follow different, mutually exclusive approaches. One approach is to “tune” the stiffness of conventional outrigger trusses to reduce undesirable effects such as gravity-force transfers from differential shortening, while still providing some benefits in building drift and overturning resistance. A second approach is to use the “leverage” provided by stiff outrigger arms projecting from a building core to 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. A third approach is to include yielding materials that set practical upper limits on force demands at members and connections, while absorbing some seismic energy.

China World Tower's outriggers were designed with some flexibility to reduce vertical force transfers resulting from differential vertical shortening.

3.1 Flexible Outrigger System

In the China World Tower (see Figure 3.1), Ho et al. (Ho 2006) introduced a flexible outrigger system (see Figure 3.2). The structural concept of the China World Tower is mainly a tube-in-tube system: a braced composite core plus an external moment frame tube with columns on a 4.2-meter grid. This system was not quite stiff enough to limit drift under lateral load to meet Chinese Code requirements. A flexible outrigger system was introduced to reduce building drift. The outriggers were designed with some flexibility to reduce vertical force transfers resulting from differential vertical shortening.

To further reduce vertical force transfers, the outrigger members were not connected until the structure was topped out. Recognizing that relative displacements between points on a flexible outrigger could drive dampers, a concept of adding dampers as replacements for inclined steel members was considered but not implemented, because the approval process could have adversely affected the construction schedule. The China World Tower was topped out, with curtain wall complete, before the 2008 Beijing Olympics.

The Petronas Towers in Kuala Lumpur, Malaysia included an earlier version of flexible outriggers. The 451-meter-tall (1,492-foot-tall) twin towers, completed in 1996, use mixed construction: concrete-filled metal deck floors with composite steel beams are carried on reinforced concrete core walls and a circular perimeter moment frame of concrete haunched “bowtie” beams and columns, a true “tube-in-tube” system. Each tower also has a “bustle,” a half-height, somewhat narrower tower connected to each floor for additional open-plan office space (see Figure 3.3). Tower wind loads are larger in the



▲ Figure 3.1: China World Tower. [ed: © Goman, Arup]

transverse plan direction, with tower and bustle side-by-side than in the longitudinal plan direction with bustle behind the tower.

Soft outriggers to assist the core and perimeter frame in the transverse direction are located at tall mid-height mechanical rooms. Each outrigger consists of three parallel reinforced concrete beams, one each under Levels 38, 39, and 40, linked by one-story reinforced concrete midspan posts to form Vierendeel trusses (see Figure 3.4). The beams were cast first to engage the core and four perimeter columns. The posts had delayed-pour zones left open until late in tower construction to allow construction-phase differential shortening between core and columns to occur with little restraint. Full outrigger stiffness was achieved once the delayed-pour zones were filled and cured. Proportions of the Vierendeel trusses were established to develop enough outrigger stiffness to be useful in helping overall building

behavior, but avoid attracting too much gravity transfer force from long-term differential shortening.

3.2 Damped Outrigger

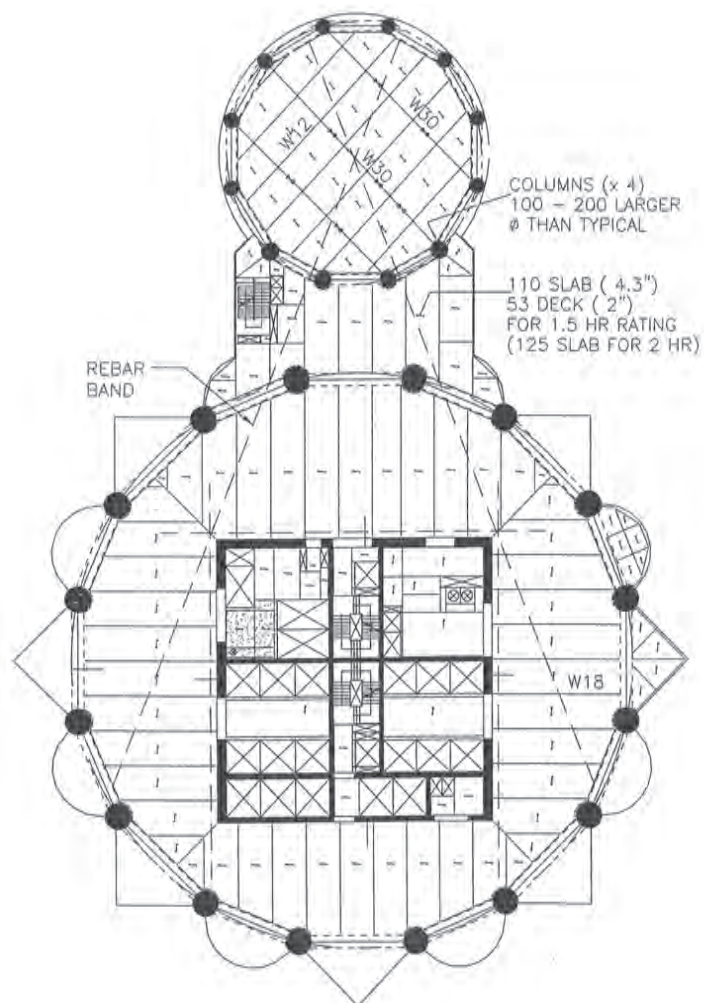
Tall slender buildings are frequently sensitive to crosswind excitation from vortex-induced oscillations (VIO) that can adversely affect occupant comfort and generate large overturning forces in windy conditions. There are several possible ways to reduce VIO effects. One way is to provide building shape modifications, such as the double-stairstep corners on Taipei 101 that disrupt vortex formation, subject to architectural or space-planning requirements. Another approach is to alter building dynamic properties by changing building mass or stiffness, but that can be expensive or impractical if large changes are needed to address VIO concerns.

A third approach is to introduce supplementary damping, which can be an efficient and cost-effective solution to improve occupant comfort and reduce deformations from lateral loads. Damping is well understood and widely accepted by the engineering community for mitigating dynamic load effects. For a hypothetical 400-meter flexible tower with minimal inherent damping levels, supplementary damping could reduce the dynamic overturning moment by approximately a factor of three (see Figure 3.5).

In actual building designs, the beneficial effects of damping can be significant; for example, the dampers at Shangri-La Place discussed below are intended to reduce building accelerations from service-level wind by 35% of the original value, when inherent building damping is supplemented to reach 7.5% of critical damping. Supplementary damping in the range



▲ Figure 3.2: Flexible outrigger used in China World Tower. [ed: © Arup]



▲ Figure 3.3: Petronas Tower lower plan showing additional "bustle" floor space and outriggers to core corners.

4.0 System Organization and Examples

4.1 System Development

As core-and-outrigger systems were developed in the 1980s and 1990s, it became clear that core stiffness was critical to successful outrigger systems. While cores can be steel-braced frames or concrete shear walls, concrete provides stiffness economically while providing fire-rated separations. In contrast, steel-core columns sized for stiffness can grow large enough to adversely affect space planning where they protrude into corridors and elevator hoistways. Large central cores encompassing elevator shafts and stairwells, combined with the development of higher-strength concretes and high-rise forming and pumping technologies, have led to concrete as the dominant choice for core structures in very tall towers employing outriggers today. Another widely-used approach is composite construction, with continuous steel columns embedded within concrete columns, and sometimes in core walls

as well. Composite construction will typically be more expensive than conventional reinforced-concrete construction, but offers benefits that include smaller plan dimensions of columns and walls, reduced creep and shrinkage; direct, reliable steel-to-steel load paths at connections, and the means to distribute forces into concrete encasement gradually, rather than all at once at the connection.

For supertall towers using outrigger systems without a complete perimeter moment frame, a large core size is critical to providing great building torsional stiffness, since the exterior frame contributes relatively little. Wind tunnel testing and monitoring of actual occupied tall buildings has confirmed that torsional motions have potential for being the most perceived by building occupants, so torsional stiffness for motion control can be important.

Horizontal framing is also a consideration in outrigger systems, as

outrigger truss chords that are deeper and heavier than typical floor framing can affect headroom below and may lead to non-typical story heights to compensate for such conditions.

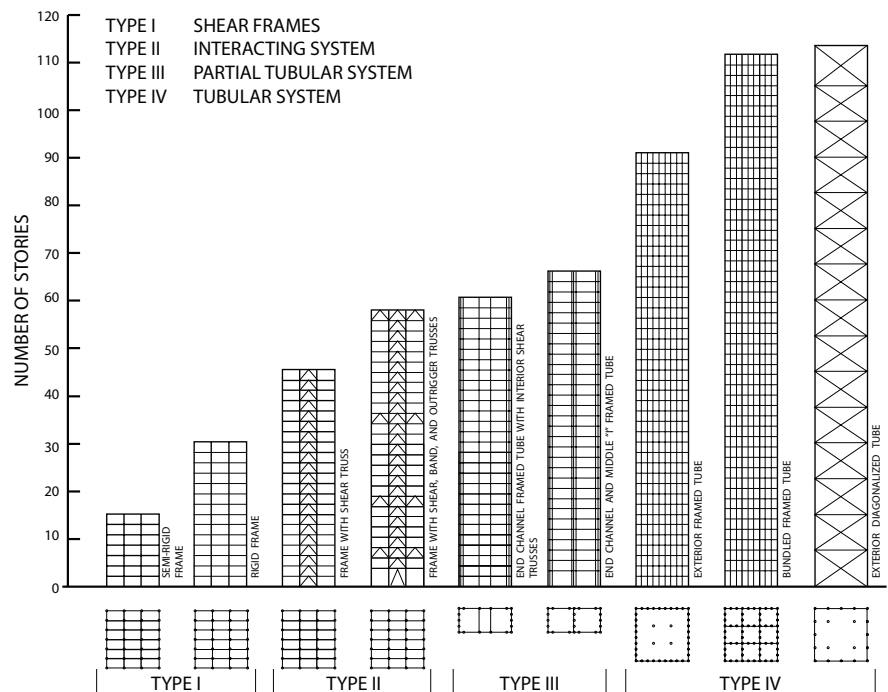
Core-and-outrigger systems can generally be categorized based on their structural material. Examples of various system assemblies in the following section highlight the ways the core-and-outrigger system has been adapted to a wide variety of building types and architectural design concepts, including some of the tallest towers in the world, both constructed and proposed.

4.2 All-Steel Core-and-Outrigger Systems

U.S. Bank Center (formerly First Wisconsin Center)
Milwaukee, USA

One of the first examples of the system as configured in steel is the

As core-and-outrigger systems were developed in the 1980s and 1990s, it became clear that core stiffness was critical to successful outrigger systems.



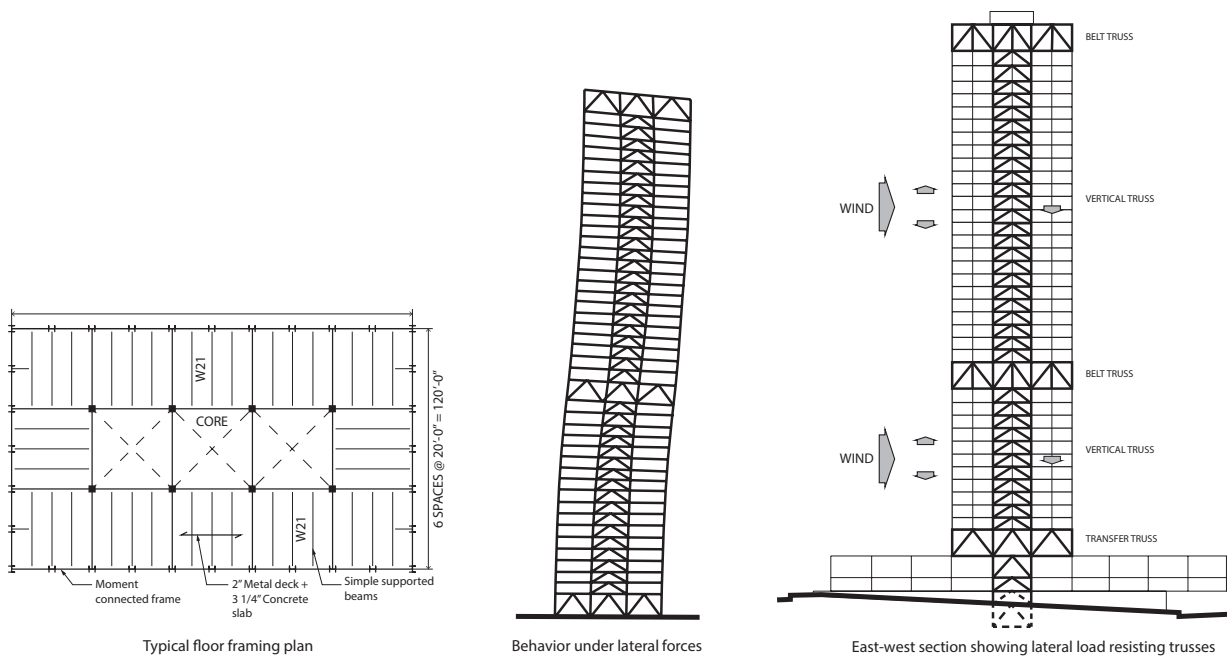
▲ Figure 4.1: Structural systems comparison table from the 1970s. © CTBUH

42-story U.S. Bank Center in Milwaukee completed in 1973 (see Figure 4.2). Engineers at the time termed the system a “partial tube.” Indeed, the system charts developed at the time indicated the core-and-outrigger system as being applicable only to mid-rise buildings (see Figure 4.3). They considered that outriggers extended the useful range of core-only systems only marginally. This underestimated their effectiveness for ever-taller towers.

The system was selected by the engineers and architects to “create a light open-frame type structure on the exterior, with columns six meters apart along the perimeter. The frame is continuous with the belt trusses, which are expressed architecturally on the exterior.” The structural organization was consistent with some key system features still used today: stiff two-story-deep outrigger trusses placed at the mechanical levels, linked with belt trusses in order to engage



▲ Figure 4.2: U.S. Bank Center, Wisconsin. © Marshall Gerometta/CTBUH



▲ Figure 4.3: U.S. Bank Center – structural diagrams. (Source: Beedle & Iyengar 1982)

The Council on Tall Building and Urban Habitat's Outrigger Working Group has addressed the pressing need for design guidelines for outrigger systems with this guide, now in its second edition, providing a comprehensive overview of the use of outriggers in skyscrapers. This guide offers detailed recommendations for analysis of outriggers within the lateral load resisting systems of tall buildings, for recognizing and addressing effects on building behavior and for practical design solutions. It also highlights concerns specific to the outrigger structural system such as differential column shortening and construction sequence impacts. In this edition, a new chapter explores the use of "hybrid" outrigger systems that can "tune" the stiffness of outrigger trusses, use leverage of the outrigger arms to drive non-linear damping devices, and use "yielding" materials that absorb seismic energy.

Several project examples are explored in depth, illustrating the role of outrigger systems in tall building designs and providing ideas for future projects. The guide details the impact of outrigger systems on tall building designs, and demonstrates ways in which the technology is continuously advancing to improve the efficiency and stability of tall buildings around the world. The new second edition features updated design considerations to reflect current practices, Expanded systems organization and examples, and updated recommendations and suggestions for future research.

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