INNOVATIVE CONCRETE CORE FOR TALL TOWERS

By Joe Ferzli, P.E., S.E., and Jason Thome, P.E., S.E.

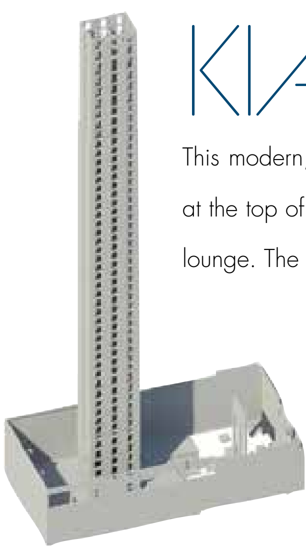

Figure 2. Kiara lateral system.

KIARA is a 41-story, 435-foot-tall luxury apartment tower over a seven-level podium with six levels of below-grade parking in Seattle's South Lake Union neighborhood, near Amazon's global headquarters. This modern, sleek tower features over 460 residential units, 15,600 square feet of retail space, and two rooftop decks – one at the top of the podium with a freestanding outdoor pavilion and the other at Level 41 with lush landscaping and an indoor sky lounge. The project is targeting LEED Silver. Construction started in 2016 and was completed in the summer of 2018 (*Figure 1*).

The tower is composed of two alternating curved vertical elements that slenderize and break down the massing into an elegant, layered composition of alternating glass colors. The top of the tower is terraced, and the rooftop provides an additional garden and owner's lounge where residents can see stunning views of Lake Union, the Space Needle, and Elliot Bay.

Project Challenges

The project posed several challenges. The unbalanced loading was about 2.5 times larger than the lateral loads due to seismic and wind. The site dropped 20 feet from East to West. The concrete core was limited in depth in the east-west direction to maximize the architectural program efficiency on the residential floor. Cary Kopczynski & Company, Inc. P.S. (CKC), structural engineers for the project, developed a ductile core lateral system with multiple elements of ductility and seismic energy dissipating mechanisms. This was accomplished by incorporating steel fiber-reinforced concrete (SFRC) in the shear wall coupling beams on all four sides. SFRC significantly reduced reinforcing bar quantity and improved constructability, leading to a four-day cycle at the tower floors. SFRC eliminated the need for all diagonal bars, which are typically extremely congested and very difficult to install. Performance-based design (PBD) provided a means for the design of the SFRC coupling beams.

Ductile Core System

Coupled core systems are a combination of wall piers that are solid or connected with coupling beams with various span to depth ratios. *Figure 2* illustrates the Kiara central

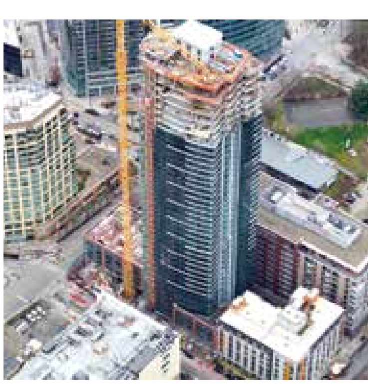

Figure 1. Kiara Tower.

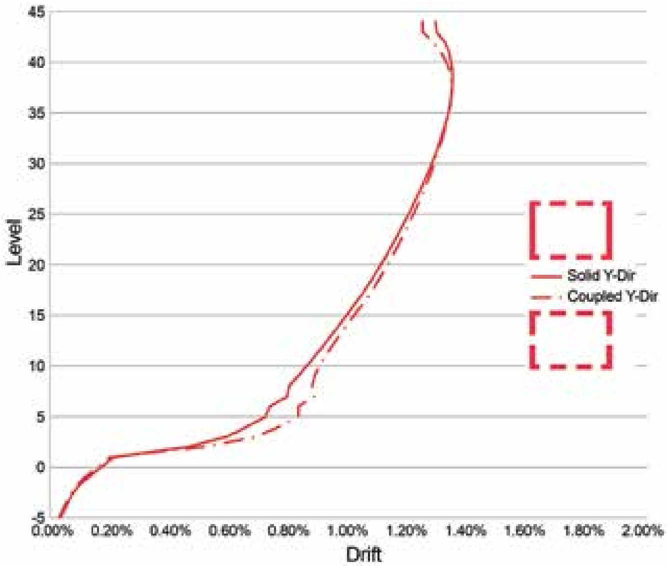

Figure 3. Seismic drift comparison.

core wall system extending 48 stories above the mat foundation with six levels of basement.

The geometry of the lateral system has a significant impact on the overall behavior of the building. In a concrete core system, the seismic energy dissipating mechanisms are hinge regions located at the base of the wall piers and the ends of the coupling beams. A lateral system with low energy dissipation leads to higher shear, flexural, and diaphragm demands.

CKC performed a series of sensitivity studies to evaluate core shear and interstory drift, with and without additional openings and coupling beams being introduced into solid shear walls. It was observed that the shear demands in the system could be significantly reduced, both in the shear walls and at the transfer diaphragms, without excessive impact to the seismic drift of the building, by the addition of coupling beams at targeted locations on all sides of the core. *Figure 3* compares the Kiara tower inter-story drift over the building height with and without coupling beams in the short direction of the core. As shown, the two plots are similar in that there is a minimal increase in seismic drift by adding the coupling beams at the center of the wall.

Coupling beams are detailed to accommodate large inelastic deformations while maintaining adequate strength. The internal forces generated in the system, such as core wall moment and shear, can be significantly reduced by increasing the system ductility. *Figure 4* illustrates two core wall studies for a 450-foot (138 m) tower and the 435-foot (134 m) Kiara tower for A and B cases, respectively, using a PBD approach. Both core wall systems are located in a high-seismic region with special reinforced concrete shear wall lateral systems. Nonlinear models were generated using PERFORM-3D software (by CSI) and were subjected to at least seven pairs of scaled maximum considered earthquake (MCE) level ground motions.

The effect of the coupling beams on the shear core demand is exemplified in the Core Wall A configuration study. The core is two-celled and utilizes SFRC coupling beams. All coupling beams have a span-to-depth ratio of 3.0. A parametric study was completed where the number of coupling beams was varied in the short direction of the core and compared to solid wall piers. The results were quite dramatic (*Figure 5*).

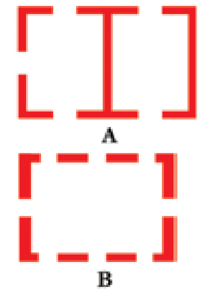

Figure 4. Core Wall configurations.

With only one coupled wall and two solid walls, the peak core shear forces were approximately 22,000 kips (97,860 KN) at the dynamic base. When all three walls in the same direction where coupled with SFRC coupling beams, the peak core shear forces reduced to 12,500 kips (55,602 KN), dropping the shear demand at the base of the core wall system by 45%.

The Kiara core, Core Wall B in *Figure 4*, is the perfect example of increasing ductility in core wall systems by introducing coupling beams. To mitigate high shear loads at the base of the structure due to seismic and unbalanced soil loading, as well as to decrease the required amount of shear reinforcing in the shear walls and transfer diaphragm, a series of coupling beams were added on all four sides of the central core. While some of these openings were required for the architectural program, several openings were added to introduce distributed ductility and additional energy dissipating mechanisms through coupling beams in the lateral force-resisting system.

The lateral force due to unbalanced soil loading was 2.5 times larger than the lateral seismic force at the base of the building. The central core resisted a large portion of the unbalanced soil lateral force. The introduction of coupling beams in the walls resisting the unbalanced soil load reduced the elastic shear force that would have been imposed on the core by dissipating the energy through the plastic hinging mechanisms at the end of the coupling beams. Thus, the building response improves during a seismic event and mitigates the damage to the vertical load carrying lateral elements such as the shear wall piers.

Steel Fiber-Reinforced Concrete

The code-prescribed coupling beam options of conventional horizontal reinforcing or diagonally reinforced coupling beams, largely based on research conducted in New Zealand in the late 1960s and early 1970s, are appropriate in many systems but can have limitations. For example, diagonally reinforced coupling beams have excellent hysteretic properties and drift capacities but are often quite congested and challenging to place in the field. The ends of the sloping diagonal bars must extend into the adjacent boundary elements of the shear walls, causing conflicts with the heavy vertical and transverse bars. The cost saving was mostly related to labor time savings. The reinforcing material savings were offset it by the additional cost for the fiber concrete mix. However, the labor time to place the fiber coupling beams was significantly reduced compared to a conventional diagonal beam.

Additionally, when the project requires the geometry of the coupling beams to become relatively slender (e.g. a span-to-depth ratio on the order of 3.0), the effectiveness of the diagonal bars decreases with the resulting shallow angle of inclination.

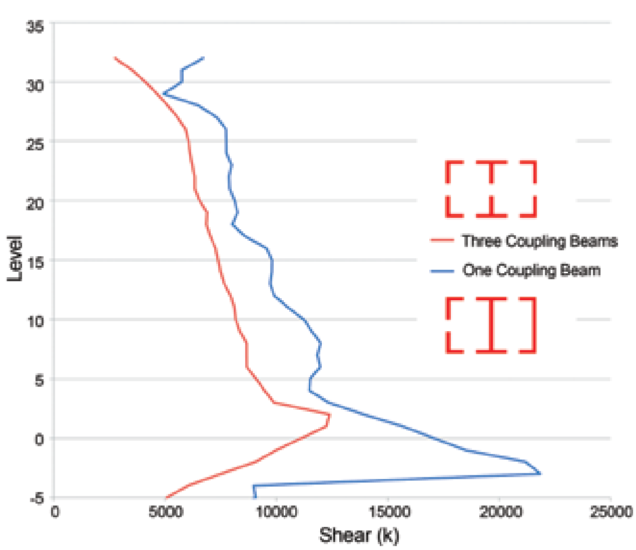

Figure 5. Core Wall A shear results.

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One option is to utilize conventionally detailed coupling beams. This type of detailing can accommodate larger span-to-depth ratios, but both the drift capacity and the amount of seismic energy able to be dissipated are reduced.

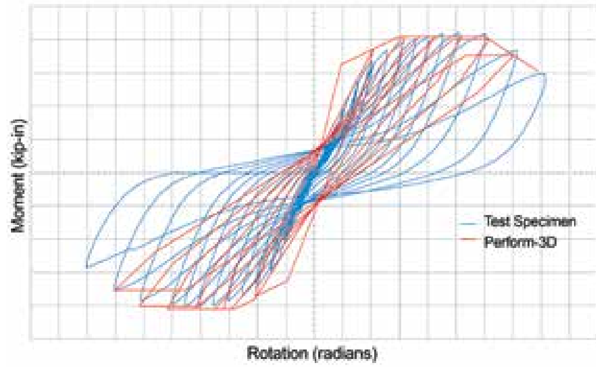

Figure 6. SFRC coupling beam hysteresis loops calibration.

Figure 7. Kiara SFRC coupling beam.

SFRC coupling beams have been reported to be a very effective alternative to conventionally reinforced concrete beams while ensuring an equivalent or higher level of strength and ductility. A collaborative effort between structural engineers and researchers has shown a potentially economical application of SFRC for reinforced concrete buildings. This decade-long effort culminated with a recent Charles Pankow Foundation report, *Evaluation of Seismic Behavior of Coupling Beams with Various Types of Steel Fiber Reinforced Concrete*. These fibers allow the diagonal reinforcement to be eliminated, the transverse reinforcement to be reduced, and generate value by increasing the speed of construction.

Kiara tower was designed using 386 SFRC coupling beams throughout the central core. SFRC coupling beam nonlinear properties were calibrated to replicate the hysteretic results from testing and modeled using PERFORM-3D. *Figure 6* illustrates the hysteresis loops for the SFRC test specimen and calibrated performance-3D component model.

Since an SFRC coupling beam design procedure is not yet prescribed in ACI 318, *Building Code Requirements for Structural Concrete and Commentary*, a series of nonlinear analyses were essential to demonstrate acceptable performance. A geometry and concrete mix were selected to fall within the range of tested specimens. The flexural strength was determined at two critical locations: one at each extreme end of the beam where the SFRC contribution to flexural strength is neglected, and one at the termination of the added u-bars where a flexural strength increase of approximately 15% from the SFRC material was considered. The shear strength was determined by assuming the SFRC resists up to $3\sqrt{f'c}$, limited to 60% of the total shear strength. The beam ends where plastic hinging may occur are detailed to be fully confined, while the interior of the beam has transverse reinforcement proportioned per shear demands.

By introducing SFRC coupling beams in the core wall system, the project energy dissipating mechanisms were enhanced to reduce the total internal forces in the lateral system. Even though similar core wall response could be achieved using diagonally reinforced coupling beams, SFRC coupling beams provided a significant reinforcing quantity reduction of 30 to 40% and expedited the reinforcement placement schedule. *Figure 7* illustrates the reinforcing in a typical Kiara tower coupling beam before placing steel fiber concrete (shown to the right) and the ability to accept beam penetrations.

The concrete for Kiara coupling beams contained Dramix© steel fibers manufactured by Bekaert, with a fiber dosage of 200 lb/yd^3 (120 kg/m^3) of concrete. The fibers are 0.015-inch (0.38mm) diameter by 1.18 inches (30mm) cold-drawn steel wire with hooked ends for anchorage. Fibers were delivered to the producer in subsets of thirty. The subsets were bonded with water-soluble glue that dissolved when mixed into the concrete, allowing the fibers to separate and disperse throughout the mix. After workability was confirmed at the site, a bucket was used to place coupling beam concrete.

Constructability

Kiara is an excellent example of collaborative work between researchers, design consultants, and contractors to achieve success through teamwork on all aspects of this project. The owner, architect, engineer, and contractor worked closely from the early design phase to create a one-of-a-kind building that not only expresses the architectural intent, but also meets the project budget and schedule.

Weber Thompson is the architect responsible for Kiara's architectural design. Holland Partners and Holland Construction were the owners and general contractor responsible for the overall coordination and day-to-day oversight of the project. Conco was the concrete subcontractor responsible for the structural frame construction. Close communication between Holland Construction, Conco, and CKC was the key to the successful implementation of Kiara's unique core design. Early buildability meetings were scheduled between Conco and CKC to streamline the reinforcing detailing of the core wall and to ensure compatibility with the formwork. Also, mockups of the SFRC coupling beams were done to finetune the concrete mix design and placing procedure. Making constructability central to the structural design and detailing created synergy between the design and construction team. The construction team went above and beyond to quickly implement the constructability plans, leading to a four-day cycle at the tower levels.

Core Innovation

Concrete core wall geometry and SFRC coupling beams were vital to deliver an efficient ductile core and added to the success of the Kiara project. By breaking up many of the solid wall piers in the central shear wall core and using highly ductile coupling beams, the overall lateral force demands and reinforcement quantities were significantly reduced. SFRC provides the structural engineering profession with a valuable tool for improving the constructability of reinforced concrete buildings in high seismic regions. The use of SFRC in Kiara resulted in a coupling beam design that eased reinforcing congestion, facilitated faster construction, and reduced rebar tonnage.▪

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