Title: **High-Rises, High Seismicity: New Materials and Design Approaches**

Authors: Cary Kopczynski, Senior Principal, Cary Kopczynski & Company
Mark Whiteley, Principal, Cary Kopczynski & Company

Subjects: Construction
Structural Engineering

Publication Date: 2016

Original Publication: CTBUH Journal, 2016 Issue III

Paper Type:
1. **Book chapter/Part chapter**
2. Journal paper
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

High-Rises, High Seismicity: New Materials and Design Approaches

Cary Kopczynski

Mark Whiteley

Authors

Cary Kopczynski, Senior Principal
Mark Whiteley, Principal
Cary Kopczynski & Company (CKC)
10500 NE 8th Street, Suite 800
Bellevue, WA 98004
United States
t: +1 425 455 2144
f: +1 425 455 2091
e: caryk@ckcps.com; markw@ckcps.com
www.ckcps.com

Cary Kopczynski
Cary Kopczynski is senior principal and CEO of Cary Kopczynski & Company (CKC), a structural engineering firm with offices in Seattle, San Francisco, and Chicago. CKC designs major urban buildings throughout the United States and internationally. Kopczynski serves on the American Concrete Institute's (ACI) Board of Directors, is a past president of ACI Washington State Chapter, and served for many years on ACI Committees 318 and 352. He serves on the Post-Tensioning Institute's (PTI) Board of Directors and Executive Committee, and chaired the PTI's Technical Advisory Board (TAB) for six years. Kopczynski is a Fellow of both ACI and PTI, and an Honorary Member of the Wire Reinforcement Institute. He is the current president of the Structural Engineers Association of Washington.

Mark Whiteley
Mark Whiteley is a principal at CKC and the senior project manager for Lincoln Square Expansion (LSE). Whiteley has more than 20 years of experience designing a wide variety of significant high-rise projects throughout the United States. He took the lead in developing design procedures and detailing for implementation of steel-fiber reinforced concrete (SFRC) for shear wall coupling beams at LSE.

When construction completes in 2017, the Lincoln Square Expansion (LSE) will add two 135-meter towers to downtown Bellevue, Washington. The nearly 275,000-square-meter development serves as an excellent example of how innovative structural design can respond to demanding seismic requirements while still meeting cost and schedule targets. LSE's most significant and unique design feature is the use of steel-fiber reinforced concrete (SFRC) in the concrete shear wall coupling beams. This is the first major use of this type of material throughout a project as a part of the lateral system in a region of high seismicity.

Project Description

Lincoln Square Expansion (LSE) is the newest high-rise addition to Bellevue, which continues its growth into a vibrant, world-class city in the Pacific Northwest of the United States (see Figure 1). The LSE broke ground in June of 2014 and is scheduled to complete in 2017. The mixed-use project will include a 41-story tower featuring an upscale hotel and luxury apartments, as well as a 31-story office tower providing 66,000 square meters of Class "A" office space (see Figure 2). Both towers integrate with a four-level retail podium structure and six levels of subterranean parking, which includes 2,200 new parking spaces and will connect to adjacent existing underground parking via tunnels (see Figure 3).

The hotel/residential tower is cast-in-place concrete with a mix of one-way and two-way post-tensioned concrete slabs. The office tower and retail podium frame are structural steel. Special reinforced-concrete shear walls resist wind and seismic loads throughout the project. The subterranean parking structure utilizes one-way post-tensioned slabs with wide, shallow post-tensioned beams to create large open space for user-friendly parking.

LSE is the first major use of SFRC in shear wall coupling beams. This is a new method of designing and constructing coupling beams,

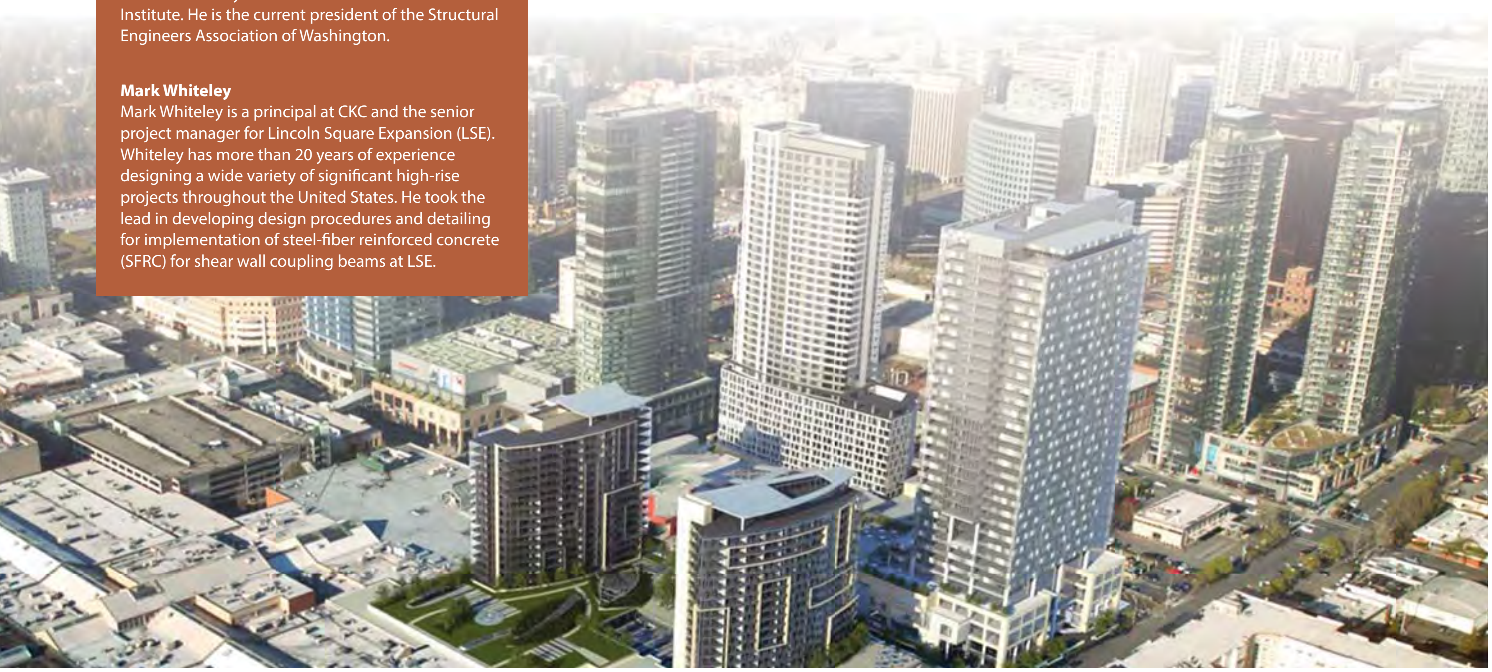

Figure 1. Lincoln Square Expansion, Bellevue. © Neoscape

which can significantly reduce reinforcing bar quantity and improve constructability. The following is a discussion on the process and implementation of SFRC coupling beams in the LSE project, including a description of how performance-based seismic design provided the means for implementation of SFRC coupling beams (see Figure 4).

Performance-Based Design

Since the selected lateral system of special reinforced concrete shear walls is limited to a maximum structural height of 73.2 meters according to a reference standard in ***Minimum Design Loads for Buildings and Other Structures*** (ASCE 2010), a peer-reviewed performance-based design (PBD) approach was necessary for both towers and the below-grade structure. PBD is a methodology for creating acceptable alternates to prescriptive building code requirements, contingent upon explicitly demonstrating that the proposed design meets code-intended seismic performance. This is accomplished by generating a mathematical structural analysis model that is more sophisticated than what would typically be used in a code-prescribed design. The model is used to perform non-linear analyses while considering the stiffness, ductility, and strength of critical structural elements.

Although a more common linear analysis assumes that the stiffness and material properties of the modeled members remain constant throughout the duration of a seismic event regardless of the level of force, utilizing a nonlinear model allows engineers to more realistically define how the various parts of the building move, elongate (stretch), and degrade during an earthquake. The coupling beams and shear wall flexural components have the greatest potential to experience deformations that could lead to strength loss, so nonlinear properties and material definitions were generated for these critical elements.

Walls were modeled using composite vertical fiber elements, which combine both nonlinear concrete and steel reinforcing materials. For the reinforcing steel, a trilinear backbone curve was assumed for both the A706 Grade 60 and Grade 80 materials, using expected material properties in lieu of the specified minimum properties to better approximate in-place behavior. Since the model exhibited limited nonlinear behavior in the vertical concrete elements, a simplified concrete material definition was used in order to reduce computer run time without compromising the analysis results. Capacity-protected elements, such as gravity columns, slab shell elements, slab-column connections, and shear-in-shear and

Figure 2. LSE – Office tower.

basement walls, were modeled with linear properties to capture the intended behavior and detailed to remain elastic.

Seven pairs of site-specific ground motions were developed by the project geotechnical engineer for the location by matching the source, magnitude, frequency, and duration of the risk-targeted maximum considered earthquake (MCEr) spectra, which corresponds to an earthquake with an approximately 2,000-year return period for the project location. Earthquakes from Chile (2010); Tohoku, Japan (2011); and Olympia, USA (1949) were among the base ground motions used. Typically, a building in the

Figure 3. LSE configuration.

Figure 4. Steel-fiber reinforced concrete (SFRC) coupling beams.

Seattle area with a code-prescribed seismic design approach would consider a design earthquake (DE) with a roughly 475-year return period. The performance goals for the project were to evaluate collapse prevention at the larger MCEr ground motion and life safety at DE-level forces, and to remain essentially elastic during a service-level earthquake (SLE) event with a 43-year return period (see Figure 5).

Since LSE consists of various framing systems for the two towers and retail podium above the shared below-grade parking, careful attention was given to the seismic interaction between these structures. A series of seismic joints was implemented at the above-grade levels separating the two towers and retail podium down to level P1 of the garage, where the tower shear wall cores and podium shear walls are locked into basement walls at one common level (backstay diaphragm). There is considerable uncertainty in predicting how seismic forces will transfer from the core walls to the basement walls at the backstay diaphragm. The stiffness assumptions of the slabs and basement walls at this location were important considerations, since these assumptions determined the effective rotational restraint at the base of the towers and determined the distribution of forces across multiple potential load paths. A bracketed approach of varying the stiffness of the floor slabs, basement walls, and soil supports, using both "relatively flexible" and "relatively stiff" assumptions, was utilized.

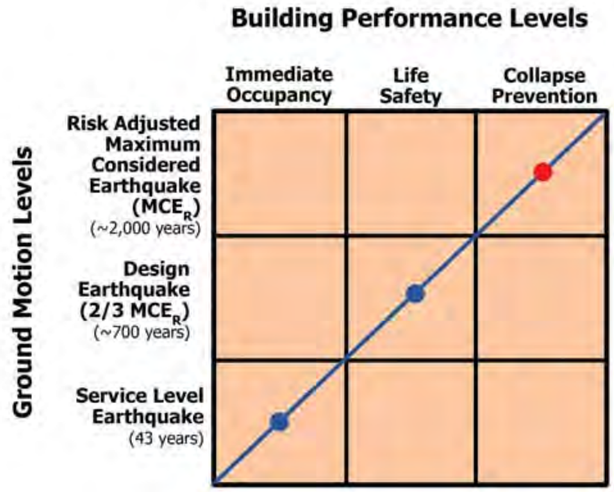

Figure 5. Seismic building performance matrix.

For the more flexible solution, the slabs and basement walls were set to be "highly cracked," with 20% of gross uncracked properties, and the mat foundation springs below the tower cores were set to be quite stiff, at 200% of the design spring stiffness. The goal of these assumptions was to allow more force transmission to the foundation via the core walls. For the stiffer solution, the slabs and basement walls were set to be "moderately cracked," using 50% gross section properties, and the foundation springs below the tower cores were assumed to be softer, set to only 50% of the design spring stiffness. This solution attracts more force through the transfer slabs and basement walls to the foundation.

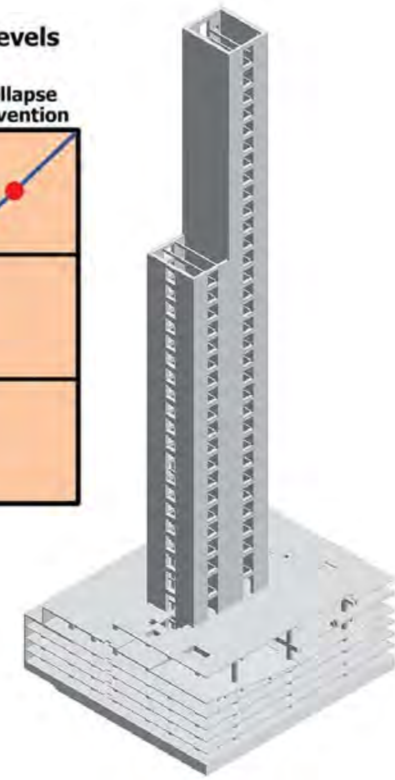

Figure 6. Office tower core.

Results from early nonlinear runs led to adjustments in the amount of reinforcing in the shear walls near the step-back in the dual-cell core that occurs at level 21 of the office tower (see Figure 6). This adjustment eliminated the wall plastic hinge that would have otherwise formed where the core transition occurs. Early runs also indicated several coupling beams exceeded rotational limits in initial design iterations, a condition that was corrected by increasing the flexural capacity in order to reduce the total rotation. This level of fine-tuned detail was achieved via nonlinear modeling and PBD, and would not have been possible using code-prescribed linear analyses. The nonlinear PBD approach provided a better understanding of the structural response to seismic excitation.

The rotation in the coupling beams was kept below the target of 0.05 Radians, the test-determined threshold at which the beams could accommodate rotation with minimal damage and loss of strength. Mean values of the seven ground motions were used to evaluate deformation-controlled actions. The tensile strains in the shear walls were verified to remain in the elastic range

"Steel-fiber reinforced concrete (SFRC) can be used for designs in regions of high seismicity, providing improved strength and added ductility. Further, it saves significant labor and material, because steel fibers replace the tedious process of placing and tying much of the rebar in what are typically the most heavily congested zones."

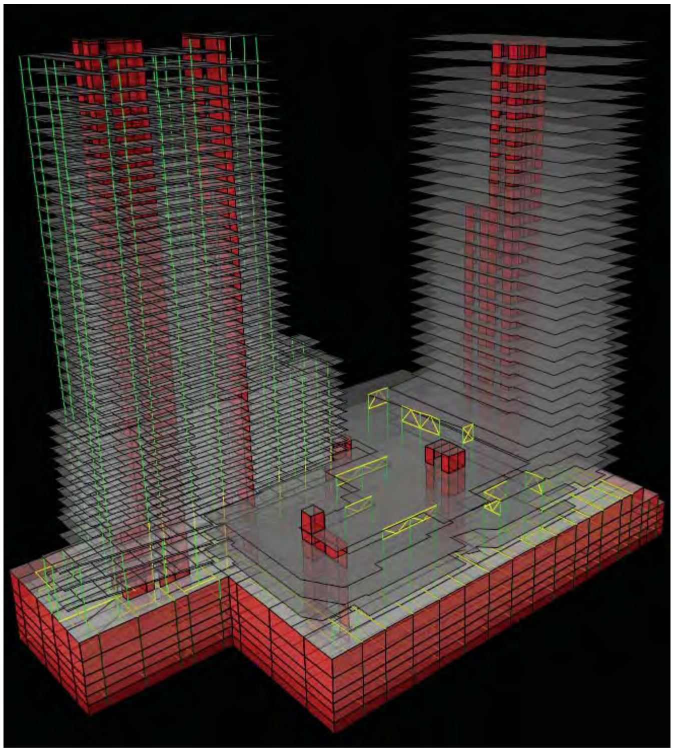

Figure 7. Linear analysis model.

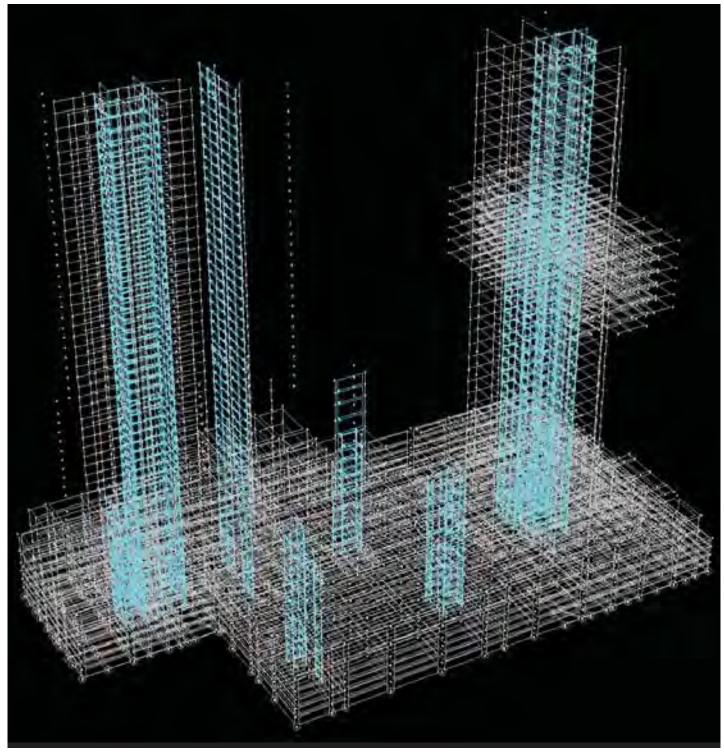

Figure 8. Nonlinear analysis model.

outside of the specified hinge zones, and compressive strains were shown to be well within the useable limits as noted in ASCE/SEI 41–13, which was used as a reference document for this alternate design approach (ASCE 2014). The maximum story drift ratio was increased from a code-prescribed 2% to 3% to account for the larger MCEr demands, and the structure demonstrated adequate stiffness to meet this limit. Shear in the shear walls was evaluated by calculating 1.5 times the mean shear force of the seven ground motions to account for dispersion in the results. The shear capacity was determined using expected material strengths, a strength reduction factor equal to 1.0, and a risk reduction factor according to the Los Angeles Tall Buildings Structural Design Council (LATBSDC 2015). This risk reduction factor was set to 0.80, the inverse of the code-based seismic importance factor of 1.25 per ASCE/SEI 7–10, which amplifies the demand in structures with large occupancies and further reduces the calculated capacity in order to account for the importance of avoiding shear limit states in the core wall.

The PBD design process and detailed analysis already planned for the LSE project created an opportunity to incorporate the first large-scale implementation of SFRC coupling beams. The PBD approach gave greater understanding of how the building would perform using SFRC coupling beams and provided the assurance that this project was an ideal application of SFRC coupling beam design for highly seismic regions (see Figures 7 and 8).

Steel-Fiber Reinforced Concrete

Reinforcing congestion has long been the bane of concrete construction in high-seismic regions. Some of the most difficult and congested reinforcing is found in shear wall coupling beams. Traditionally, diagonal bars are used to reinforce these beams, combined with tightly spaced stirrups and ties. This creates significant congestion and conflict between the diagonal bars and adjacent shear-wall boundary element reinforcing.

While steel fibers are commonly used in tunnel linings, industrial floors, and other applications where high toughness is required, their use in building structures has thus far been limited. After more than a decade of research and development, SFRC for use in shear wall coupling beams is now available. It involves mixing high-strength steel fibers into the concrete used to construct coupling beams. SFRC can be used for designs in regions of high seismicity, providing improved strength and added ductility. Further, this innovation saves significant labor and material, because steel fibers replace the tedious process of placing and tying much of the rebar in what are typically the most heavily congested zones. Discussions with general contractors have indicated that the removal of the diagonal bars can save up to a full day per floor in the construction schedule. The added cost of the steel fibers in the concrete and the crane time needed to bucket-place the SFRC were overcome by the savings in reinforcement quantity and placing labor as determined by the contractors' pricing studies.

The added steel fibers benefit the design of coupling beams in a number of ways. Typically, in regions of high seismicity, the concrete is assumed to have no contribution

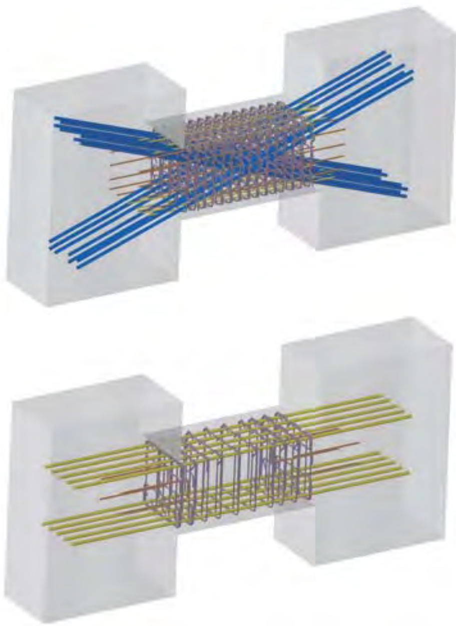

Figure 9. Diagonally reinforced coupling beam (top) and SFRC coupling beam (bottom).

Figure 10. Coupling beam testing at the University of Michigan. © Rémy D. Lequesne.

to the shear strength of the coupling beam. However, testing has shown that the addition of the steel fibers can contribute up 60% of the total shear capacity of the beam. Additionally, the presence of the fibers at the dosages used in the LSE project allow for up to 15% of the flexural (bending) strength of the coupling beam to be attributed to the SFRC material. Essentially, coupling beam strengths can be maintained, or even enhanced, by adding steel fibers and reducing the quantity of traditional reinforcement. This is useful when the coupling beams are designed to have adequate shear and flexural strength to resist wind demands, service-level earthquake (SLE) demands, and the design earthquake (DE) force demands of the building code (see Figure 9).

The value of the fibers extends beyond strength considerations to increase the durability and ductility of the coupling beam. At higher levels of rotation, the SFRC beams tend to develop many small cracks that are distributed over larger areas of the concrete. In a side-by-side test, a traditionally reinforced coupling beam was shown to exhibit high levels of localized damage and concrete spalling, while the SFRC beam at the same rotation held together better as a single unit and had less damage distributed over larger areas of the beam. This can be partly attributed to the ability of the steel fibers to increase the tensile strength of the concrete, raising the force threshold at which spalling occurs (see Figure 10).

For the LSE seismic system, PBD provided a means to implement SFRC in the coupling beams. The only prior use of SFRC in seismic coupling beams was in a 24-story tower in Seattle, for which the authors' firm was also the structural engineer, with only 26 (20%) of the 122 coupling beams using SFRC. This is contrasted against LSE, where the SFRC beams were used in 341 (87%) of the 392 coupling beams in both towers throughout the height of the building.

Modeling of these key elements is critical to reliably predicting seismic behavior. The SFRC coupling beams in LSE were of particular importance. The model considered initial stiffness, strength loss, and cyclic degradation (the tendency of beams to lose strength and deteriorate as the earthquake causes the structure to oscillate back and forth). The values used in the model were carefully calibrated against the results from dynamic lab testing. The final calibrated hysteretic behavior assumptions were then used in the nonlinear analytical models to predict the response of the beams across many cycles of movement during the simulated earthquake motions.

In order to calibrate the element, an analytical model of the test specimen was created, and various parameters were iterated to produce a best-fit match of the lab test results. The best initial stiffness match occurred using 6% of gross section properties, but the final assumptions used approximately 10%, based on equations suggested by Paulay and Priestly (1992), which take into account the height-to-length aspect ratio at each coupling beam. The recommended values in Setkit (2012) were higher and did not match as closely. While the peak strength and strength loss appeared to match well early on, the cyclic degradation was adjusted to be lower than initially thought. The first passes had good correlation between dissipated energy (the areas under the curves) at various loops, but through the peer review process it was agreed to include higher levels of degradation in order to produce less hysteretic area than the testing, but result in a closer match on the stiffness at the higher rotations (see Figure 11).

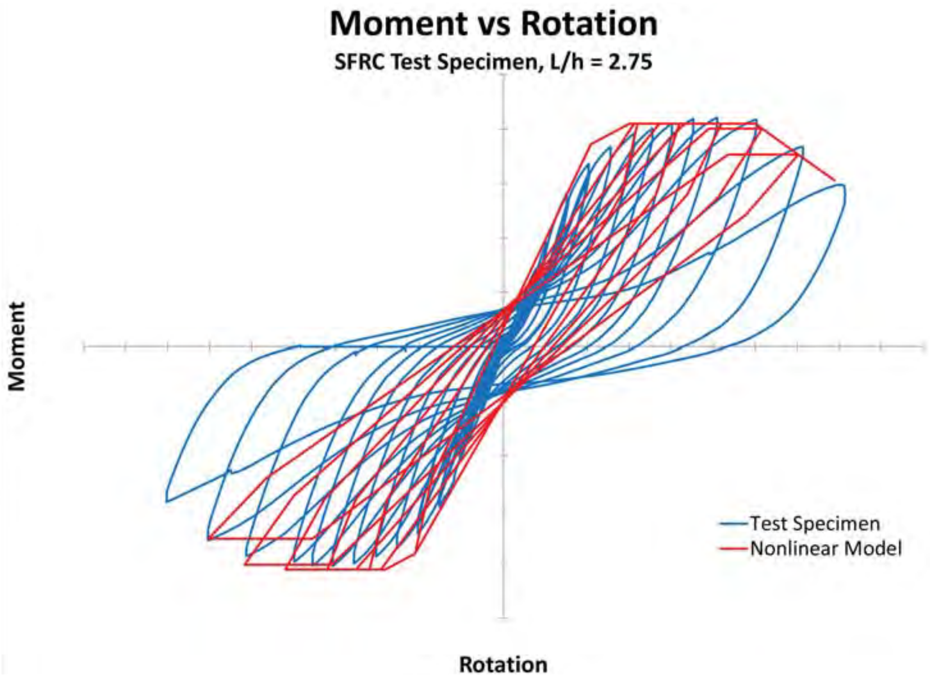

Figure 11. SFRC hysteresis loop.


Figure 12. Dramix® steel fibers.

A detailed quality assurance and quality control plan was generated in close coordination with the contractor to ensure proper construction of the unique SFRC coupling beams. The concrete mix designs were carefully reviewed and the decision was made to use a self-consolidating concrete (SCC) to maintain the workability of the concrete after the steel fibers were added. A step-by-step placement procedure was developed and distributed to the contractor and special inspector. Additionally, samples of the SFRC were tested to verify that the specified compressive strengths were reached and then bisected in order to visually inspect the dispersion of the fibers in the concrete.

Steel Fiber Specifications

Dramix steel fibers manufactured with a fiber dosage of 120 kg/m^3 of concrete by Bekaert, a Belgium-based global supplier of steel fibers, were used at LSE. The fibers are 0.38 millimeters' diameter by 30 millimeters' length cold-drawn steel wire with a tensile strength of 3,068 MPa, hooked at the ends for anchorage (see Figure 12). Fibers were delivered to the producer in subsets of 30. 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. A self-consolidating concrete mix was specified for the SFRC in order to maintain workability at the site, and a bucketing method was used to place the coupling beam concrete. Stayform, a ribbed metal leave-in-place form, was provided at the shear wall-coupling beam interfaces to prevent the SFRC from flowing into the adjacent core walls, a similar condition to the shear wall-coupling beam interface of the test specimens where the SFRC beams were precast.

SFRC Research and Development

The study of SFRC started at the University of Michigan with financial support from the National Science Foundation. Further research was funded by the National Science Foundation Network for Earthquake Engineering Simulation and Bekaert.

The University of Michigan studied reducing, and even eliminating, diagonal reinforcement in SFRC coupling beams. Its researchers tested beams of varying aspect ratios (length to depth) – from 1.75 to 3.3 – concluding that reductions in the reinforcing steel could be made while still preserving the necessary strength and ductility. The team also investigated different fiber types and dosages, eventually settling on high-strength hooked steel fibers proportioned to 1.5% of the total in-place concrete volume (Lequesne 2011). The SFRC coupling beams in the LSE project fall within the tested aspect ratios and use the same steel fiber type and dosage.


Figure 13. The Martin, Seattle. © Lara Swimmer

"With SFRC, the strength and ductility of coupling beams are maintained, while significantly reducing the quantity of reinforcing steel – including elimination of the diagonal bars where applicable. Use of SFRC in coupling beams can result in a 40% reduction in reinforcing, compared to traditional coupling beam construction."

Figure 14. Current SFRC testing.
© Gustavo J. Parra-Montesinos & Angel Perez-Irizarry

Results from this and other structural applications of fiber-reinforced concrete were presented to an American Concrete Institute (ACI) 318 sub-committee, where members were studying new materials, products, and ideas. One of the authors, a committee member, became intrigued with the potential of SFRC for solving seismic rebar congestion problems, ultimately resulting in its first use in The Martin Apartments, a 24-story multifamily residential tower in downtown Seattle (see Figure 13).

The authors worked with Professor James K. Wight of University of Michigan and Professor Gustavo J. Parra-Montesinos of the University of Wisconsin-Madison to develop the SFRC coupling beams. The studies concluded that SFRC coupling beams without diagonal bars would achieve equal or better performance as compared to those with traditional, prescriptive code-compliant designs. With SFRC, the strength and ductility of coupling beams are maintained, while significantly reducing the quantity of reinforcing steel – including elimination of the diagonal bars where applicable. Use of SFRC in coupling beams can result in a 40% reduction in reinforcing, compared to traditional coupling beam construction.

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 LSE resulted in a coupling beam design that eased reinforcing congestion, facilitated faster construction, and reduced total rebar quantity.

Additional SFRC research is currently underway at the University of Wisconsin, funded by the Charles Pankow Foundation (see Figure 14). Its results are expected to broaden the range of fiber types, dosage rates, and coupling-beam aspect ratios available for use by designers of concrete buildings in high-seismic regions. ■

Unless otherwise noted, all image and photograpy credits in this paper are to the authors.

References

AMERICAN SOCIETY OF CIVIL ENGINEERS (ASCE). 2010. ***Minimum Design Loads for Buildings and Other Structures ASCE/SEI 7–10.*** Reston: ASCE.

AMERICAN SOCIETY OF CIVIL ENGINEERS (ASCE). 2014. ***Seismic Evaluation and Retrofit of Existing Buildings ASCE/SEI 41–13.*** Reston: ASCE.

LEQUESNE, R. D. 2011. "Behavior and Design of High-Performance Fiber-Reinforced Concrete Coupling Beams and Coupled-Wall Systems." PhD Dissertation, University of Michigan.

LOS ANGELES TALL BUILDINGS STRUCTURAL DESIGN COUNCIL (LATBSDC). 2015. ***An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region – A Consensus Document.*** Los Angeles: LATBSDC.

PAULAY, T. & PRIESTLEY, M. J. N. 1992. ***Seismic Design of Reinforced Concrete and Masonry Buildings.*** New York: John Wiley & Sons.

SETKIT, M. 2012. "Seismic Behavior of Slender Coupling Beams Constructed with High-Performance Fiber-Reinforced Concrete." PhD Dissertation, University of Michigan.