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10-story Mass Timber 'Rocking' Frame Sails Through Seismic Shake Tests

By Nadine M. Post
May 9, 2023

The shake-table specimen, at 112 ft in height, is the tallest mass timber frame ever tested for seismic resilience. *Photo by Rachel Judlowe*

A 10-story mass timber “rocking” frame, designed to be resilient enough to withstand powerful earthquakes with little or no structural damage, proved its worth May 9 during seismic simulations at the largest high-performance outdoor shake table, located at the University of California San Diego.

During the first test on May 9, the research team simulated the 1994 Northridge quake, a magnitude-6.7 temblor in Los Angeles. Soon after, they ran the magnitude-7.7 Chichi quake that struck Taiwan in 1999.

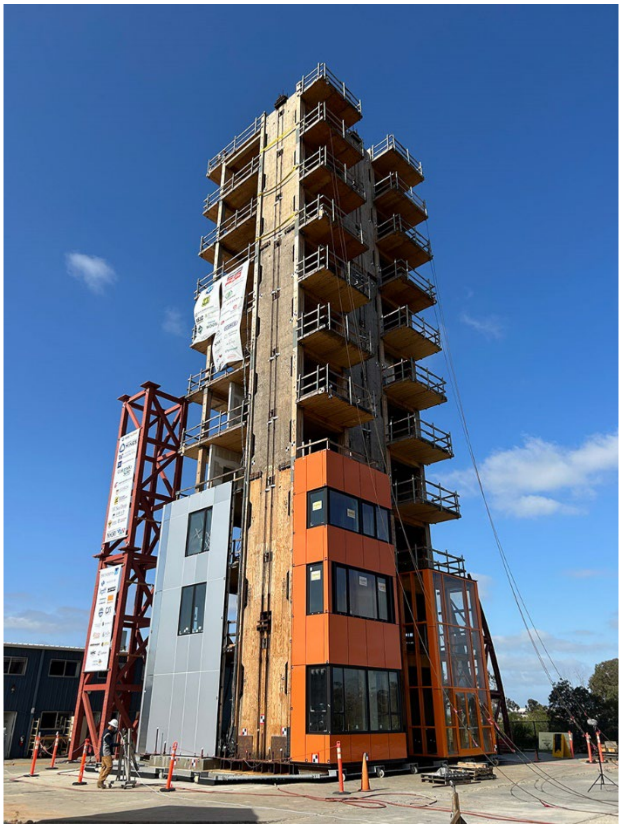
In both tests, the specimen “performed exactly as we expected,” said Shiling Pei, principal investigator for the National Science Foundation's Natural Hazards Engineering Research Infrastructure TallWood Project, in an email to ENR after the tests.

May 9 shake table tests at UC San Diego included simulations of magnitude-6.7 and magnitude-7.7 quakes.
Courtesy Colorado School of Mines, UC San Diego, NEHRI TallWood Project

After detailed inspection, researchers found no structural damage. "The building remained damage free after two major design-level earthquakes back-to-back," said Pei, also associate professor at Colorado School of Mines, which serves as the contractor for the TallWood Project.

"We found a way to build tall wood [structures] that are earthquake-proof for design-level shakes," he added, saying there was very little damage to nonstructural systems, on first inspection.

The 112-ft frame is the tallest mass timber building ever tested. "No one has ever seen such a large building shake, except for real earthquakes," said Pei, in a phone interview.



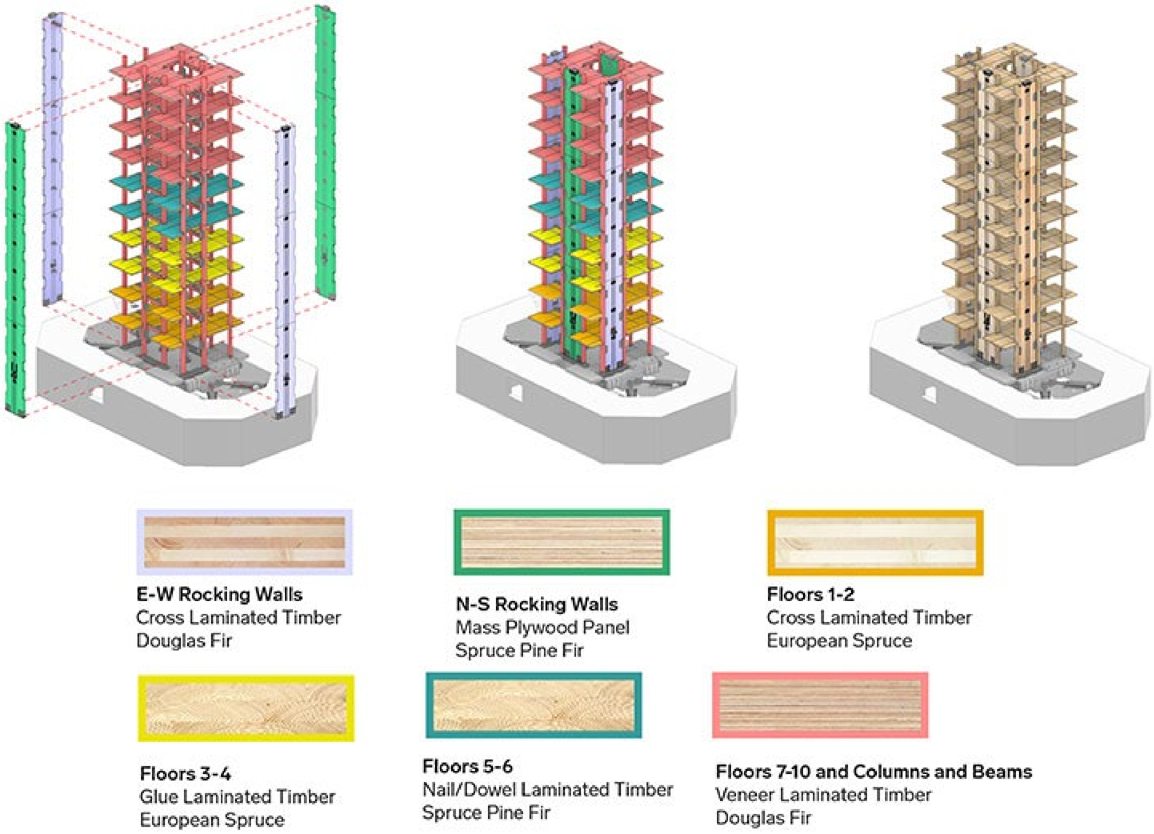
Post-tensioned rods run the full height of the 112-ft-tall specimen's mass-timber rocking walls.
Photo by Reid Zimmerman

The research, funded by the National Science Foundation, will culminate in design and construction guidelines for the rocking-wall system. A final report will be issued later this year, says Pei, but an article titled *Prescriptive Seismic Design Procedure for Post-Tensioned Mass Timber Rocking Walls*, co-authored by Pei and five others, appeared last year in the ASCE Journal of Structural Engineering.

"After the entire project is done, we will try to put the rocking-wall system into the building codes," he adds.

The footprint of the specimen, designed by LEVER Architecture, is 32 ft x 34 ft. The columns sit on the 40-ft x 25-ft shake table but the floor deck cantilevers beyond the table on one side, according to LEVER.

The 112-ft-tall specimen has four partial façade assemblies, a number of interior walls and a 10-story stair tower. It is composed of mass timber floor panels, consisting of cross-laminated timber (CLT), glue-laminated timber, laminated veneer lumber (LVL) or nail/dowel laminated timber panels, depending on the floor level.



TallWood project frame contains several types of mass timber in the floors, walls, columns and beams. *Graphic by LEVER Architecture*

The mass timber floor panels work with LVL beams and columns primarily to resist gravity loads. For resistance to quake loads induced by the shake table, vertically post-tensioned mass-timber rocking walls, 10-ft wide and the full height of the frame, exist on all four sides of the specimen, though one wall is set inside against the stairwell.

Two walls are CLT panels and two are mass plywood panels. MPPs are certified as a type of CLT but instead of using boards stacked in alternating layers, MPPs use layers of thick plywood, according to Freres Engineered Wood, which supplied the MPPs.

For the post-tensioning, the rocking walls each have two high-strength threaded bars running full height, which precompress the CLT panels or mass plywood panels, says Reid Zimmerman, structural technical director of the Portland, Ore., office of KPFF Consulting Engineers, and a member of the TallWood design and construction team. Reid worked with researchers, primarily at the University of Washington, to design and analyze the frame’s lateral system.

At the bottom of the walls, the rods anchor into the foundation. At the top of the walls, the rods attach to a steel "saddle" assembly which transfers the load from the threaded rods into the mass timber wall panels.

During shaking, the mass timber panels rock, lifting at the heel end and compressing at the toe end of the walls, while always controlled and brought "back to center" by the post-tensioned rods, says Zimmerman.

The specimen is based on the unbuilt 12-story Framework project, designed by LEVER with KPFF. Framework was fully permitted when the developer pulled the plug. But the research done for the tall-timber building is serving as the basis for code changes and more.

"Framework's impact on this test was huge," says Zimmerman. "The majority of the lateral connections were inspired by or similar to Framework," he adds.

These include the steel plates at the corners of the base of the rocking walls, which react against steel shear keys to resist horizontal base shear, preventing sliding, says Zimmerman. They also "armor" the wall against toe crushing.

The compressive force provided by the post-tensioning rods is evenly distributed along the wall's length prior to shaking. During shaking, and as the wall rocks about its leading edge, referred to as the wall toe, the previously uniform compressive stress concentrates at the toe. The steel plates at the wall base help to reduce potential crushing from the concentrated compressive stress, Zimmerman explains.

Steel plates at the base of the rocking walls react against triangular steel shear keys, at the base corners, to resist the wall horizontal base shear, preventing sliding. They also "armor" the wall against toe crushing. Mirror image U-shaped flexural plates at wall cutouts connect the walls to the columns, which do not rock, and yield in flexure, dissipating quake input energy. *Photo by Reid Zimmerman*

Another important detail of the rocking wall system is the U-shaped flexural plate, fabricated by bending a flat steel plate into a U shape. One leg of the U is bolted to the edge of the wall and the other to its adjacent column.

As the heel edge of the mass timber wall rocks up, the relative displacement between that and the column, which does not rock upward, forces the U-plates to “roll out,” Zimmerman explains. As they roll, they yield in flexure and dissipate the quake input energy, he adds.

Though the flexural plates can handle many cycles of yielding, especially since the yielding is shared along the plate length during the rolling action, they also can be replaced, he adds.

Another connection of importance is from the floor to the rocking wall. The connection allows horizontal force transfer during shaking while also accommodating uplift due to wall rocking. This is necessary to achieve a resilient design where uplift due to wall rocking does not cause damage to the floor system, says Zimmerman.

The floor-to-wall connection includes a steel “tongue” plate that cantilevers into a rectangular steel “pocket” lined with polytetrafluoroethylene, in this case Teflon, in the wall. The wall panel can therefore uplift and rotate freely about the steel “tongue” plate during shaking while the floor remains both positively connected to the wall and undamaged, according to Zimmerman.

Three of the four rocking walls are located along the specimen’s perimeter, which is partially clad to test the performance of nonstructural components. The fourth wall is in the interior, alongside the stairwell. *Photo by Reid Zimmerman*

Shake Table Upgrade

A recent upgrade of the shake table increased the numbers of axes of shake—better simulating actual seismic events, according to the University of California San Diego. It is now able to reproduce the full 3D ground motions that occur during quakes, when the ground is moving in all six degrees of freedom—longitudinal, lateral, vertical, roll, pitch and yaw, according to the school.

The table has the largest payload capacity in the world and is capable of carrying and shaking structures weighing up to 2,000 metric tons, or 4.5 million lb, says the school.

Total funding for the TallWood Project is $6.2 million, including seismic shake-table tests in 2017 on a two-story timber frame. In addition to the National Science Foundation, the project also received support from U.S. Forest Service, Forest Products Laboratory, and a number of industrial partners.

A consortium of universities is collaborating on the TallWood project. In addition to Colorado School of Mines, the schools are University of Nevada, Reno, Colorado State University, University of Washington, Washington State University, University of California San Diego, Oregon State University, and Lehigh University.

“Everyone is benefiting from the tests,” says Brooke Whitsell, senior project manager for Timberlab, which built the frame. “We are hoping to encourage people to do performance-based design until the codes are adopted.”

Jonathan Heppner, LEVER’s principal for the test frame, calls the research “exciting,” adding the design guidelines “will help with the permit approval process,” even before the rocking frame is incorporated into the building code.

Since the beginning of May, the team had run 20 other tests simulating smaller quakes. In all, there was no damage to the frame, says Pei.

All testing will be done by May 20. Next week, “we will run even bigger earthquakes” than Northridge and Chichi, Pei says. "We will reach [maximum considered earthquake-level] tests by the end of next week."

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