On the Brink

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Advanced seismic analysis and design keep a crucial 15-story building near the Hayward Fault from becoming history.

JUST FIVE MILES FROM CALIFORNIA'S HAYWARD FAULT STANDS the California Department of Transportation's (Caltrans) District 4 headquarters, a 15-story steel moment frame structure that houses the San Francisco Bay Area's transportation operations, including its emergency response team.

The structure was built two years after the destructive 1989 Loma Prieta earthquake. Its integrity was not questioned until three years after Caltrans' operations moved in, when the 1994 Northridge earthquake damaged numerous steel moment frame buildings in the Los Angeles area. As a consequence, seismic retrofitting became mandatory. A team under the direction of Degenkolb Engineers, and including The Crosby Group, employed extensive state-of-the-art analysis techniques to design and test a retrofit scheme that will protect the building.

Existing Building Performance

Every 150 years or so, the Hayward Fault generates severe quakes. This puts the Caltrans District 4 building in an especially vulnerable period, since the last major event on the fault occurred in the 1868. Experts forecast that the next major earthquake on the Hayward Fault will be in the destructive 6.7 to 7.2 range.

The Caltrans District 4 structure was designed to meet the 1988 Uniform Building Code. It has one basement level, a first-story lobby with public space, four levels of above-grade parking, and ten stories of office space. The building also has a large atrium above the parking levels. Full-height moment frames are located along the perimeter frame lines. There are also two interior transverse moment frames adjacent to the atrium on either side.

Recognizing the potential vulnerability of the existing SMRF system as a result of the Northridge damage, the State of California commissioned a study that included both a preliminary evaluation of the building's structural system and laboratory testing on a few moment connections similar to that of the existing building. These tests were performed by the University of California, Berkeley at the Pacific Earthquake Engineering Research Center. The results confirmed that the existing connections were vulnerable to fracture and demonstrated even less rotation capacity than smaller specimens tested for the FEMA-sponsored SAC Steel Program. The results also led to the conclusion that a seismic upgrade was required. In accordance with the state guidelines, the building needed to be seismically upgraded to an expected performance level that includes minor repairable structural damage, moderate non-structural damage that may entail extensive repair, minor risk to life, and the ability to return to operations within weeks of the earthquake.

Analysis and Development of Upgrade Schemes

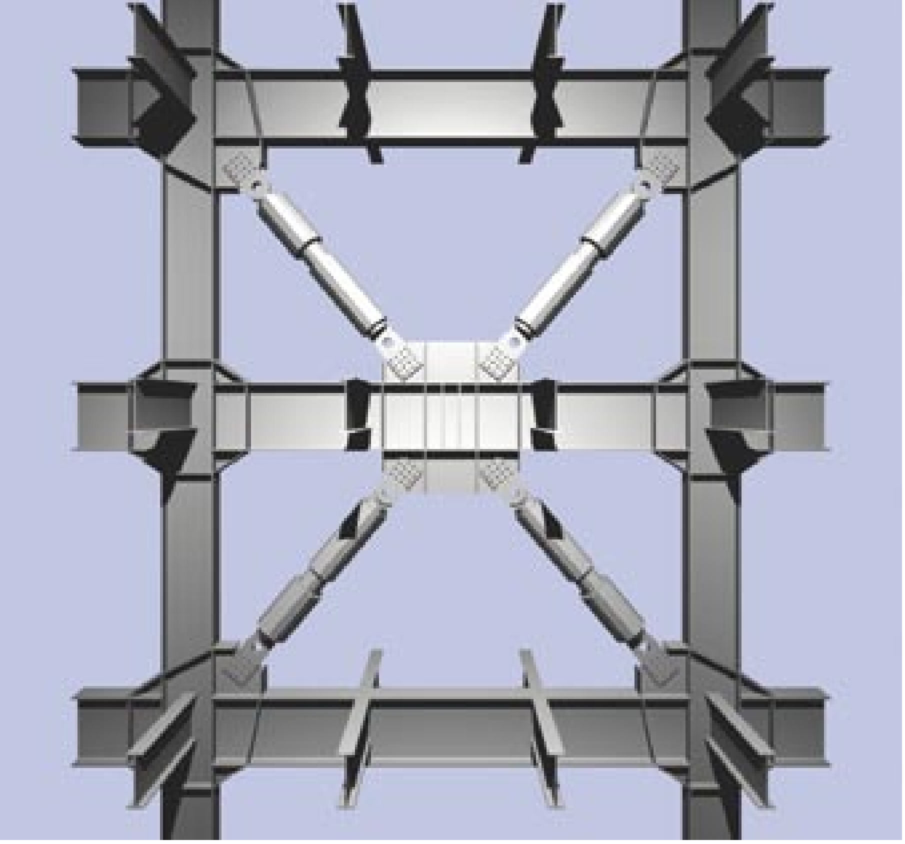
Site-specific response spectra were developed to represent the Design Base Earthquake (DBE, BSE-1) and the Maximum Considered Earthquake (MCE, BSE-2) in accordance with FEMA 356, the document used as the basis of the retrofit design criteria. These spectra represent anticipated earthquakes of Richter magnitude 7.0 and 7.25. At the DBE level this resulted in a first-mode spectral acceleration of approximately 0.4 g. Seven pairs of time-histories for use in the nonlinear response history analysis were also developed and scaled in accordance with FEMA requirements.

In the early evaluation stages, the team led by Degenkolb performed multi-mode, two-dimensional nonlinear pushover analyses and single-degree-of-freedom nonlinear dynamic time-history analyses to estimate the necessary upgrade measures.

Four strengthening schemes were developed: an all-connection-strengthening scheme, a connection-strengthening-plus-dampers scheme, a buckling restrained brace scheme, and a base isolation scheme. Each scheme was designed to meet the design criteria and was compared on the basis of construction cost and associated "soft" costs such as construction phasing, long-term and short-term staff relocation, and other facility downtime. Ultimately, the scheme that combined connection upgrades with the addition of viscous dampers was selected for the upgrade.

By selecting maximum practical damper sizes and placing the connection upgrades and dampers at the same locations, the selected strengthening scheme minimizes the number of work locations. The damper layout avoids interference with major points of entry and interior building flow and will add 228 dampers to the building's perimeter. Of 1,218 existing moment-resisting connections in building, 746 are being strengthened. Column splices will be strengthened in selected locations where connection strengthening occurs.

In the working drawings phase of the project, two RAM Perform (now CSI's PERFORM-3D) models were constructed: one two-dimensional model for each primary direction of motion. In each model the moment frames were modeled completely, and the gravity columns and orthogonal moment frame columns were modeled for secondary effects. Rigid diaphragms were assumed.



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By co-locating the connection upgrades with the damper locations, the seismic strengthening scheme limited the number of work locations.

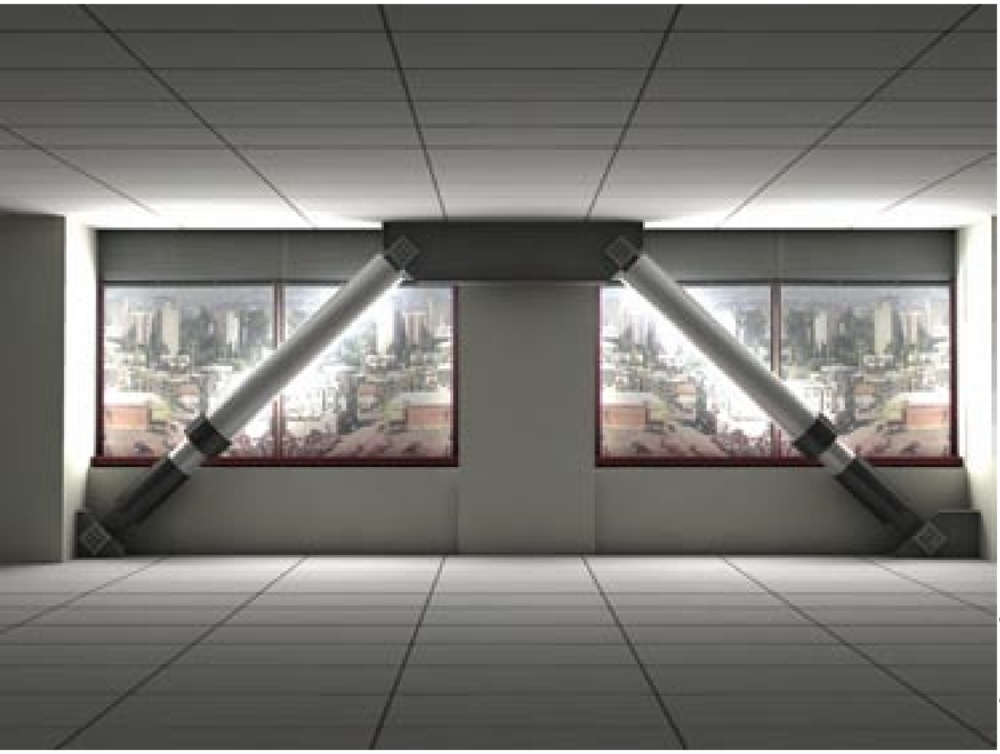
The moment frames were built with compound elements with elastic and inelastic components. Beam elements were built from an elastic beam section and a nonlinear moment-rotation hinge for strengthened connections or a nonlinear fiber section for the existing connections. Since not all existing connections were to be retrofitted (for economic reasons), a model of the existing connections that simulates their fracture behavior needed to be developed. The existing connection model took advantage of a fiber model technique, with the connection model being comprised of three different types of fibers: one fiber representing the top flange, one fiber representing the bottom flange, and one fiber for each of the bolts in the shear tab. Using the fiber section allowed the existing connection model to closely mimic tested behavior.

The fiber model captured the top and bottom flanges fracturing at different moments, both of which are significantly below the expected moment strength of the beam. It also captured the post-flange-fracture effect, where the bending capacity of the connection relies on the couple between the shear tab bolts in shear and the fractured flange in bearing, and the individual fracture of each shear tab bolt at the expected bolt ultimate strength.

Full-scale Testing to Confirm the Upgrade Design

Deep column sections and large beam sizes were beyond the scope of previous testing on the connection upgrade schemes that were considered, and therefore, connection strengthening schemes involving deep columns and very large beam sections were experimentally tested to validate the proposed rehabilitation scheme.

Four full-scale, double-sided steel moment connection tests were commissioned so that the proposed strengthening scheme could be properly validated. Specimens included a representative width of composite steel deck and concrete slab. Various connection upgrade schemes were considered, based on previous research results and retrofit designs. The scheme considered and tested included a single-welded haunch (WBH), a double-welded haunch (WTBH), a double haunch on one side of the column and a double gusset plate on the other, and a bolted bracket (BB). The BB was considered because its installation could be performed without welding. This would shorten the construction sched-



Dampers are visible in the interior spaces of the building.

Owner
California Department of General Services and California Department of Transportation

Structural Engineer
Degenkolb Engineers, San Francisco, and Crosby Group, Redwood City, Calif.

Steel Fabricator
Mountain States Steel, Lindon, Utah (AISC Member)

Steel Erector
Bragg Crane & Rigging, Long Beach, Calif. (TAUC Member)

General Contractor
Arntz Builders, Oakland, Calif.

Damper Supplier
Taylor Devices, North Tonawanda, N.Y.

ule and reduce welding fume containment issues. The tests were conducted at University of California, San Diego (UCSD) under the direction of Professor Chia-Ming Uang. The size of the specimens did lead to upgrade connection performance that differed from previous testing of both the WBH and BB approaches. As a result, the WTBH scheme was selected for the connection upgrades. A final test that simulated the application of damper gusset plates into the moment connection confirmed that these plates could meet the project's drift demands. (More details on the testing portion of the project can be found in a 2006 report by Uang and Newell: *Cyclic Testing of Steel Moment Connections for the Caltrans District 4 Office Building Seismic Upgrade, Report No. SSRP-05/03*, Department of Structural Engineering, University of California, San Diego, La Jolla, Calif.)

Lessons Learned

The simplified analysis used to estimate the performance of the proposed retrofit scheme was reasonably successful in estimating the overall extent of strengthening work required to achieve the desired performance. However, this analysis substantially underestimated the drift in the lower stories and overestimated the drift in the upper stories. This resulted in a significant revision to the damper and connection strengthening scheme configuration.

The extra steps taken beyond typical engineering practices in both the analytical techniques and the full-scale testing were intended to provide better assurance that the project's performance goals would be met during the design-basis seismic event. They also helped to produce an economical scheme (approximately $50 per sq. ft for construction) that will allow the building to remain operational during the entire construction process.

Currently, construction is underway at Caltrans District 4, with little disruption to the agency's operations thanks to the extensive planning that the team undertook to establish an orderly phasing program to orchestrate the work. MSC

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