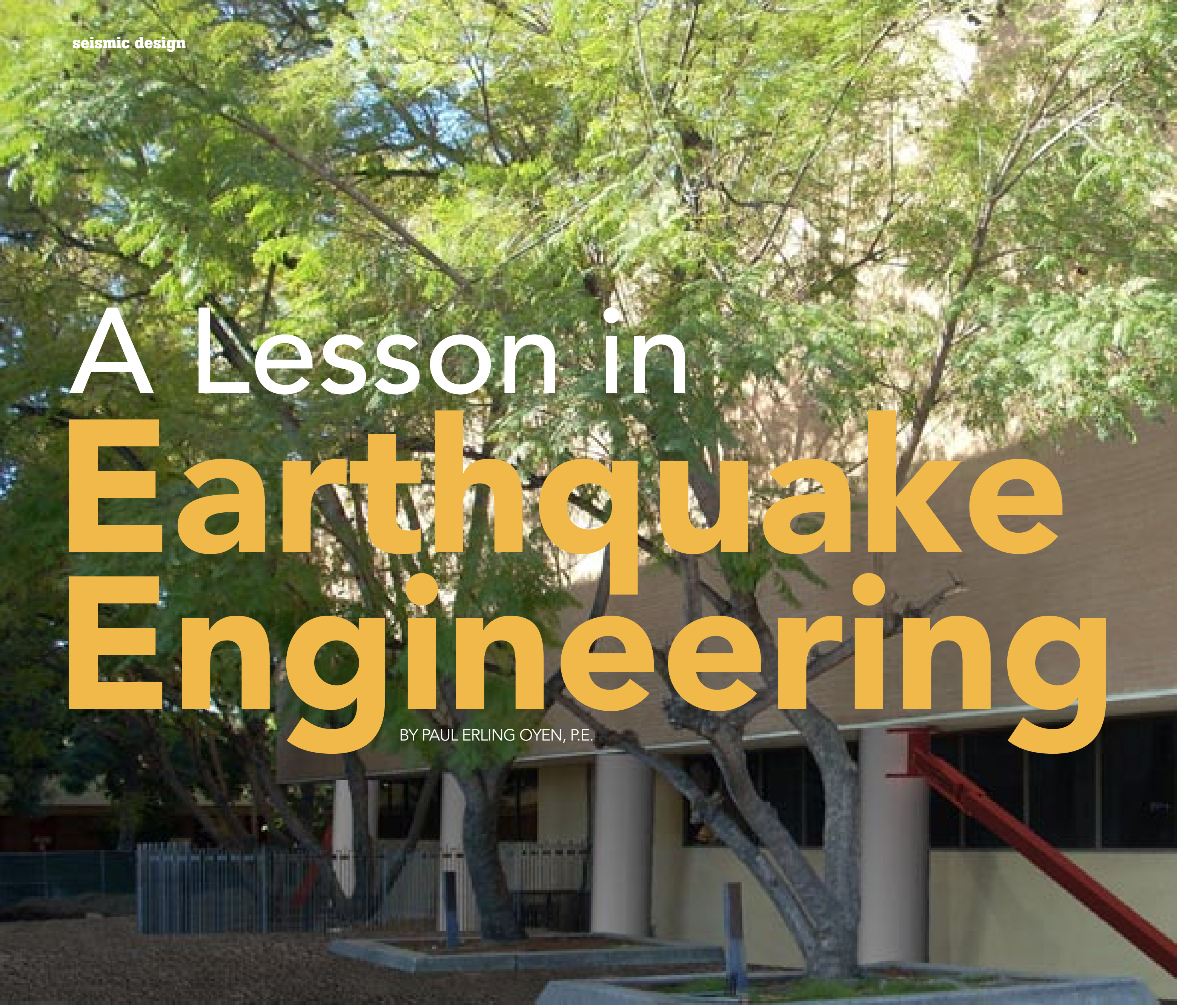


A Lesson in Earthquake Engineering

BY PAUL ERLING OYEN, P.E.

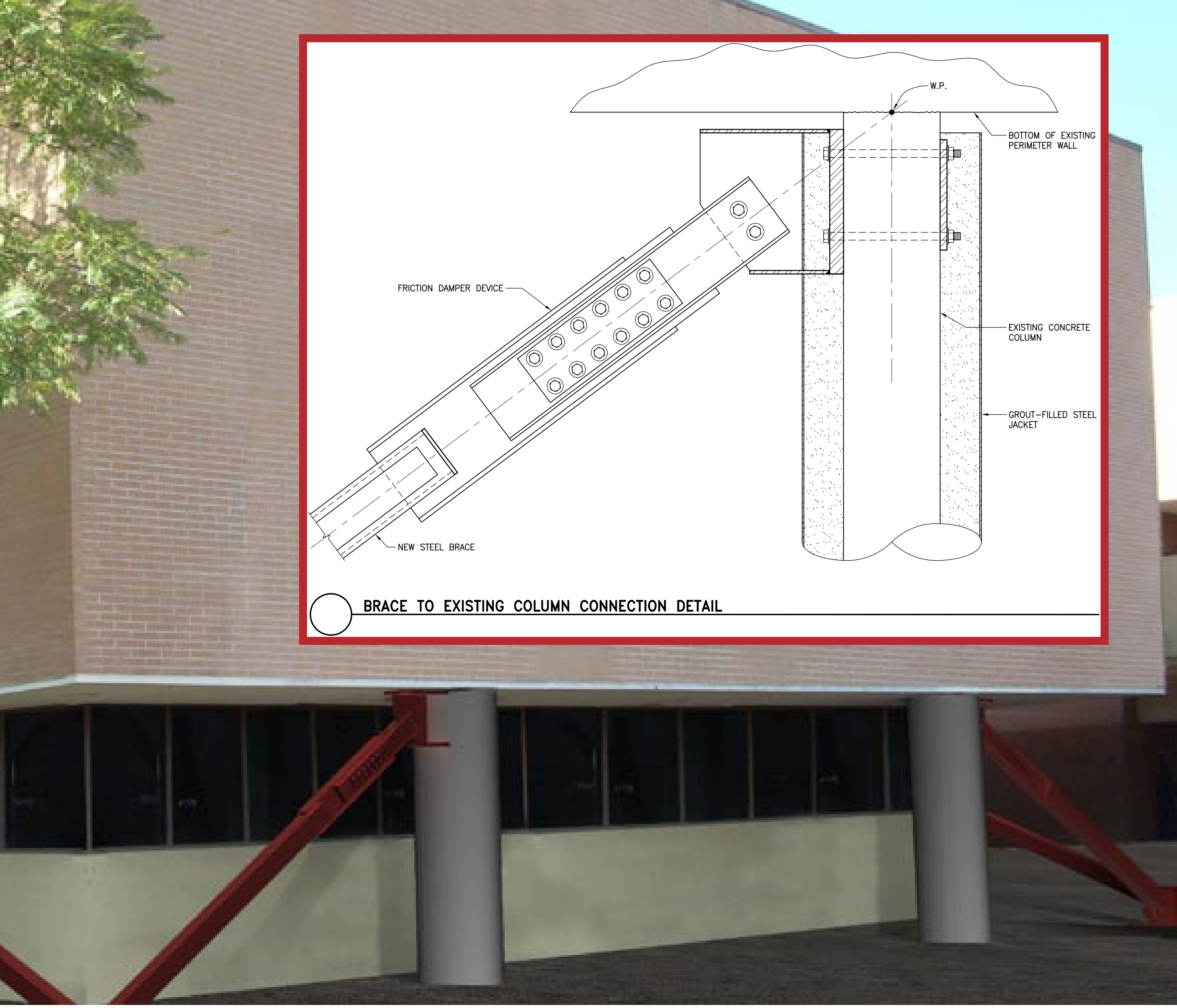
Steel bracing picks up the seismic slack for a concrete high school building in southern California.

BUILDING 1 OF THE GLENDALE HIGH SCHOOL campus (in Glendale, Calif.) is not unlike other high school buildings in the area. Built in the late 1960s, the two-story brick structure houses administrative offices and the school library. However, one element that will set it apart from others of its type is the exposed seismic bracing that will become an identifying characteristic of the building, once a seismic retrofit is completed this summer.

The roof is a cast-in-place slab over steel beams and tapered steel girders. The roof girders sit on second-story reinforced concrete and masonry bearing walls, and the second floor is a reinforced concrete pan-joist system supported by first-story reinforced concrete columns. There are no structural walls in the first story and no first-story columns at the corners, allowing the second-story walls to cantilever one full bay. The first floor is a reinforced concrete slab-on-grade, and the foundation of the structure is comprised of 18-in.-diameter, 30-ft-deep, drilled piers in groups of two to four at each column. Grade beams tie the pile caps together.

Following the 1994 Northridge Earthquake, a review of the campus identified Building 1 as seismically deficient, because of the soft story condition in the first story. Above the first story's nonductile concrete moment frames are full perimeter concrete and masonry shear walls with few openings. The second-story system is much stiffer than the first story. In the event of a significant seismic event, displacement and damage would be localized to the first story and prevent energy from dissipating throughout the structure. Non-ductile detailing exacerbates the condition.

Typical of 1960s construction, the existing concrete columns have non-seismic reinforcement ties that are not spaced closely enough to provide sufficient concrete confinement. Additionally, some of the existing concrete frame beams are shear critical under lateral loading. These details prevent the building from performing ductility and dissipating energy during strong seismic shaking. As such, the building would most likely not survive the shaking of a code-level earthquake.



Eight steel braces—HSS8x8x5/8 with two ¾-in. x 5-in. side plates—provide seismic reinforcement for Glendale High School. Images: Courtesy SGH

Eliminating Deficiency

To bring the building into the post-Northridge world, the Glendale Unified School District initially approached structural engineering firm Simpson Gumpertz & Heger with the task of eliminating the soft-story deficiency. The "obvious" solution was to add concrete shear walls to the first story. However, this option proved unacceptable, as the walls would prevent natural light from entering the building, and the overall result would not be aesthetically pleasing.

Another option we explored for eliminating the soft story was to use conventional steel braces to stiffen the first story. This solution required W14x311 braces for stiffness, adding several drilled piers to existing pier groups, and making difficult connections between the braces and the existing structure. This proved to be infeasible as well, as connections with the code-required overstrength forces could not be made to the existing pile caps.

Handling Displacement

We eventually settled on a displacement-based design approach using ASCE 41, *Seismic Rehabilitation of Existing Buildings*. This approach didn't eliminate the soft story but rather improved the structure's ability to safely handle the expected large displacements at the first story. The method determines the deformation demands at the first story from the design-level earthquake. The structural performance is predicted by comparing computed inelastic deformations to acceptable deformation limit states. The design objective for a seismic rehabilitation is to make the imposed seismic deformations stay within the limits. This can be done by decreasing the deformations (stiffening the structure) or increasing the limits (adding deformation ductility). Both were done to Building 1.

We reduced the displacement demands on the structure by stiffening the first story, though not enough to eliminate the code-defined soft story. This was accomplished by adding steel braces—HSS8x8x5/8 with two ¾-in. x 5-in. side plates—at each of the end bays (eight total). The weight of each brace frame was reduced from 8,000 lb to 1,500 lb. Accounting for the additional steel in the column jackets, the total steel weight went from 64,000 lb to 30,000 lb.

We increased the building's displacement capacity by selectively cutting existing interior column reinforcement bars, jacketing all first-story columns with grout-filled steel shells, and incorporating friction dampers in each new steel brace.

Though counterintuitive, cutting existing reinforcement bars in the concrete columns protects the concrete frame beams from catastrophic shear failure. The weakened columns act like a fuse. Under lateral loading, the columns will now hinge plastically prior to exceeding the shear capacity of the beams. The grout-filled steel shells provide confinement at these plastic hinge locations to considerably increase the rotational capacity of columns, thus increasing the displacement capacity of the structure.

Dual Functionality

In this design the friction dampers have two functions. They allow the braces to deform axially for the full design target displacement of the structure without buckling, and they limit the amount of force that can be imparted on the foundation and the connection to the existing structure. Friction dampers are essentially two plates of steel sandwiched together by pretensioned bolts in long slotted holes. The tension in the bolts and the faying

Friction dampers provide a seismic segue between the new steel braces and the extisting columns.

surface between the plates is calibrated to allow the plates to slip under a specified load. The friction dampers in this rehabilitation are designed to slip at 200 kips, providing +/- 4.5 in. of displacement capacity. They are attached to the top of the existing concrete columns by through-bolted steel gusset plates. Each brace sits on new concrete pile caps over drilled piers at each corner. These pile caps are tied to the existing pile caps with new grade beams, and no additional foundation work was necessary.

Again, the rehabilitation design was performed to the ASCE 41 standard, which uses the concept of performance-based engineering. The performance objective for this building is the "Basic Safety Objective," which corresponds to the implied performance of a code-based design for an ordinary building. We performed nonlinear pushover analysis to evaluate the seismic demands using CSI's PERFORM-3D. We modeled existing concrete moment frames with steel shells as nonlinear frame elements and braces with friction dampers as elastic perfectly plastic axial springs with a yield force equal to the specified 200-kip slip load. Second-story shear walls were elastic shell elements, and the forces in the walls showed that they remain elastic under seismic loads. MSC

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