Seismic Science

BY ROUMEN V. MLADJOV, S.E., AND BRIAN M. PARDO, P.E.

Stanford's science and engineering quadrangle factors several nearby seismic faults into its new facilities.

MORE THAN A CENTURY after his death, a key element of Frederick Law Olmsted's Stanford University master plan has been realized.

The construction of the science and engineering quadrangle (SEQ-2) fulfills Olmsted's vision of a science center to the west of the school's Main Quad. The first three buildings of the four-building complex—the Environment and Energy Building (E+E), the School of Engineering Center, which is comprised of the center itself (SoEC) and a seismically separated engineering library (SoEL), and the Center for Nanoscale Science and Engineering (NSE)—are now open (E+E and SoEC were renamed the J. Yang and A. Yamazaki Environment and Energy Building and the Jen-Hsun Huang Engineering Center, respectively, at their opening ceremonies). The fourth building, the Bioengineering and Chemical Engineering Building, is scheduled to open in the spring of 2014 (and is being handled by another design and construction team).

The total built area of the three buildings, each with a unique plan configuration, is 542,000 sq. ft. E+E is 320 ft by 210 ft and has an L-shaped plan, SoEC is 236 ft by 108 ft, octagon-shaped SoEL is 99 ft by 84 ft and NSE is 236 ft by 108 ft, similar to SoEC.

The architectural style of each of the buildings, which were designed and built on overlapping, consecutive schedules, invokes

➤ Aerial view of: 1) Environment and Energy Building (E+E), 2) School of Engineering Center (SoEC) and School of Engineering Library (SoEL) and 3) Center for Nanoscale Science and Engineering (NSE).

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Framing for the Environment and Energy Building, which used 1,470 tons of steel in all.

SEQ-2 Stats

Total built area:	542,000 sq. ft
Project steel:	3,660 tons (13.5 psf)
E+E steel:	1,470 tons (12.7 psf)
SoEC/SoEL steel:	1,231 tons (14.7 psf)
NSE steel:	959 tons (13.4 psf)
Total cost:	$206,000,000 ($378 per sq. ft)

Mark DeFeo, Aerial Archives and HDCCO

Environment and Energy Building near completion of construction.

View of Center for Nanoscale Science and Engineering (which uses nearly 1,000 tons of steel) from the School of Engineering Center's second-floor terrace.

the California Mission architecture found throughout Stanford's campus, and it distinguishes itself with contemporary flourishes. The three buildings, each with a Spanish clay tile roof, are three stories tall. All three of the buildings are enclosed with precast concrete panels clad with honed sandstone of color similar to traditional stucco.

Stanford was adamant about creating an environmentally friendly addition to the campus. There are several features that minimize the development's impact on the environment, the most dramatic being the atria within each building that rise from the basement to the roof. Abundant natural light, which enters into the atria through large conservatory-like structures on the roof, diffuses into the hallways and meeting rooms at each level. As well as brightening the interior, the atria create differences in air pressure that pull the warm air out of the building during the day and draw cool air in overnight. They also serve as a visual centerpiece around which structural steel elements are exposed.

Seismic Realities

Of course, the structural design of the complex had to consider Stanford's proximity to several active seismic faults. SEQ-2 is just over two miles from the Monte Vista-Shannon Fault, four miles from the San Andreas Fault and roughly 12 miles from the San Gregorio and Hayward Faults. In addition, a seismic feature called the Stock Farm Monocline runs below E+E and part of SoEC/SoEL. Beyond the seismic requirements of the International Building Code (IBC), SEQ-2 had to comply with the Seismic Engineering Guidelines of Stanford University. These guidelines required the engineers of SEQ-2's new buildings to consider the IBC spectral accelerations and also the spectral accelerations for Basic Safety Earthquake 1 and 2 (BSE-1 and BSE-2). While BSE-1 spectral accelerations are similar to those in IBC, BSE-2 spectral accelerations correspond to a more severe event, one that is approximately equivalent to a moment magnitude of 7.5 on San Andreas Fault, with a recurrence interval of 970 years and a 10% probability of exceedance in 100 years.

The effect of the high spectral accelerations of BSE-2 was compounded by the exceptional weight of the structures. Despite the desire to use lightweight building materials in California, the engineers had to accommodate heavy precast panels and heavy clay tile roofs. To illustrate, E+E's precast panels weighed 76.5 psf more than an aluminum and glass system. Given a total enclosure area of 49,200 sq. ft, the additional dead load from the precast panels amounted to 2,860 k—a 21.5% increase on the total dead load. Deep landscaped planters on the balconies and terraces also exacerbated the issue. Naturally, these items not only increased the lateral force (see Table 1), but also created more gravity loads.

The structural design was further complicated by the landscaped quadrangle and existing site conditions. SEQ-2's master plan called for extensive subgrade laboratory and assembly space beneath large areas of the plaza. The roofs not only had to span as much as 62 ft to accommodate a columnfree auditorium, but also had to support between 3 ft and 7 ft of fill, top soil, landscaping and a fire truck lane that traversed the longitudinal axis of the site. Such heavy loads and long spans usually aren't considered concurrently. The engineers also gave special consideration to another challenge presented by the existing site conditions: two adjacent and parallel research tunnels that intersected the footprints of SoEC/SoEL and NSE. Stanford wanted to preserve the larger of the two tunnels for future use, so its structural integrity had to be steadfastly preserved. This meant that the engineers had to either design a structure that spanned over the existing tunnel or design a foundation system that didn't impart surcharge loads upon it.

▲ Steel erection for the School of Engineering Library.

Framing Selection

To address these main structural challenges, the engineers considered the following gravity and lateral force resisting systems:

1. Steel gravity framing with:
   a. Special moment resisting frames (SMRF)
   b. Eccentrically braced frames (EBF) in combination with SMRFs at the perimeter
   c. Steel-plate shear walls
2. Concrete gravity framing with specially reinforced concrete shear walls

The design team chose to frame the buildings with steel for several reasons: It would be quicker to construct, offer greater flexibility for future modifications, be more able to accommodate various architectural elements and be less expensive than concrete framing.

To resist the large base shears that resulted from the seismic criteria and the heavy dead loads, robust lateral force resisting systems were designed. Lateral force resisting systems made up of EBF cores and SMRFs, strategically placed at the perimeter to improve each building's torsional resistance (choice 1B above), are employed at E+E, SoEC and NSE. The typical column, beam (and link) and brace sections that create the EBF are W14×233, W21×111 and HSS14×14×5/8, respectively. The typical sections in the SMRF are W14×211 for the columns and W24×94 for the beams.

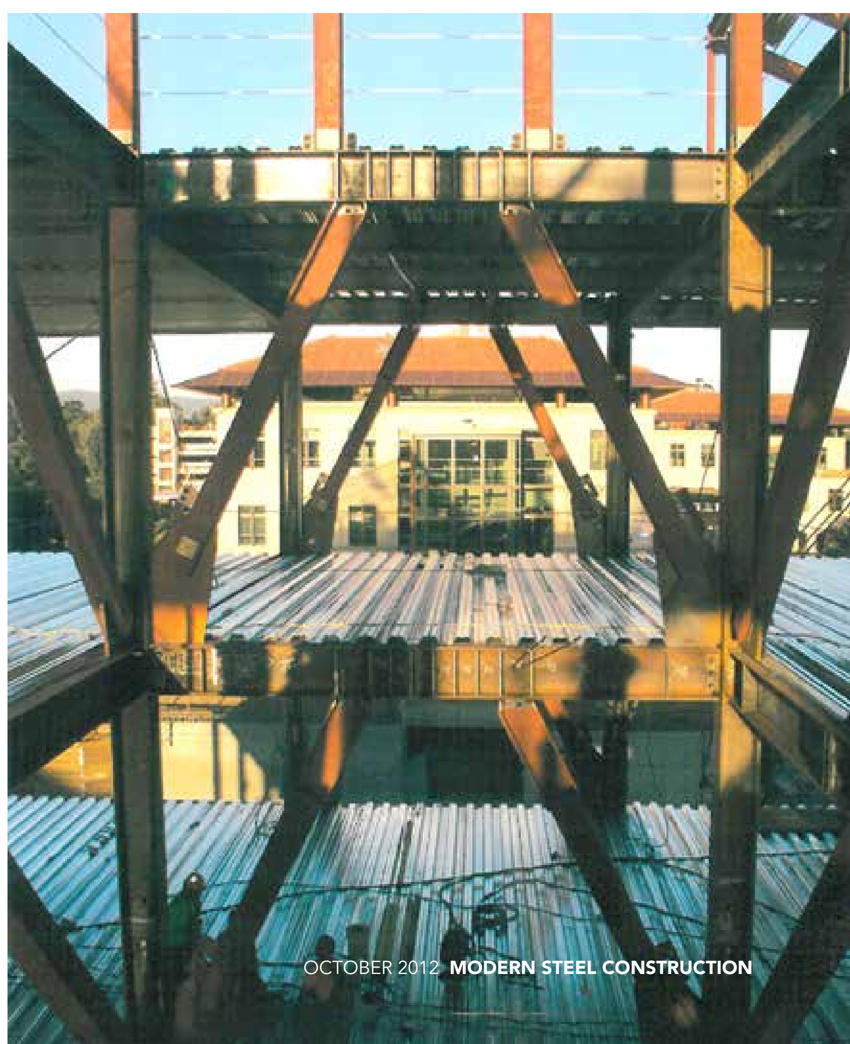
SoEL is unique in the sense that the gravity and lateral force resisting systems are one and the same. Four lines of SMRFs composed of three frames each and arranged in a grid identical to a tic-tac-toe board resist all the vertical and horizontal forces. The eight perimeter columns at each corner of the octagon-shaped building are W24×250. At the four points where the four SMRF lines intersect, cruciform columns constructed of W24×250 sections are provided; the SMRF beams are typically W30×132. Throughout SEQ-2, the engineers used welded unreinforced flange-welded web (WUF-W) moment connections, which were permitted based on the results of a successful WUF-W test program conducted in 2001 for Stanford's James H. Clark Center. The tested connections had resisted rotations of 0.045 rad, which exceeded the building code and testing protocol requirements.

The steel gravity system, which is divided into typical bays of 31.5 ft by 39 ft, supports composite floor deck, and the floor-to-floor heights vary from 15 ft to 18 ft. The steel framing typically consists of wide-flange beams and col-

Structure	Building Weight, W (kips)	Design Base Shear, V (kips)
E+E	13,329	0.179W
SoEC	12,433	0.201W
SoEL	3,835	0.128W
NSE	14,970	0.172W

Table 1. Summary of Design Base Shear for E+E, SoEC/SoEL and NSE

▼ Eccentrically braced frames at School of Engineering Center. The braces are architecturally exposed steel.



umns. The gravity beam and girder depths vary from W16 to W27; the columns vary from W12 to W14. Above the subgrade auditorium, W40×167 sections are provided 8 ft, 3 in. on center to carry the loads of the plaza and its landscaping features across a 62-ft span.

The columns of E+E, SoEC/SoEL and NSE are typically supported on single or combined spread footings; footings that support columns that are part of the lateral force resisting system are tied together with grade beams. Spread footings are not employed to support the SoEC/SoEL and NSE columns that are located above the tunnel, as they would have loaded the tunnel's wall. To safeguard the tunnel, the engineers would have preferred to span the buildings over the tunnel, thus relocating the troublesome columns farther away. Deep steel sections could have easily accomplished this span as they accomplished other long spans at other locations in SEQ-2. However, this was not an option, as SoEC/SoEL's and NSE's programs had been set; the column grids could not be adjusted. To avoid surcharging the tunnel's wall, 24-in.-diameter drilled piers were constructed on either side of the tunnel. The pier caps of the two drilled pier groups are connected by a grade beam that supports the column that would have otherwise loaded the tunnel. In this manner, the column loads are directed around the tunnel and delivered to the piers that straddle it. This detail is repeated 23 times. MSC

Owner
Stanford University, Stanford, Calif.

Architect
BOORA Architects, Portland, Ore.

Structural Engineer
Middlebrook + Louie, San Francisco (Now two separate firms: Louie International Structural Engineers and Pannu Larsen McCartney Structural Engineering, both in San Francisco)

General Contractor
Hathaway Dinwiddie Construction Company, Santa Clara, Calif.

Steel Team

Fabricator and Erector
Herrick Corporation, Stockton, Calif. (AISC Member/ AISC Certified Fabricator)

Detailer
SNC Engineering, Inc., Compton, Calif. (SoEC/SoEL and NSE buildings) (AISC Member)