Sustainability through Strength

Integrating post-tensioned lateral systems and slag cement concrete for a model of environmental architecture

BY MARK STEVENSON AND LEO PANIAN

Situated in downtown Berkeley, CA, within 0.6 mile (1 km) of the Hayward Fault, the new David Brower Center (Fig. 1) will provide offices and meeting space for environmental advocacy and nonprofit groups. The project, named after one of the preeminent environmentalists of the twentieth century, incorporates many features of sustainable design in the structural, mechanical, electrical, plumbing, and lighting systems and is expected to be LEED® Platinum certified by the U.S. Green Building Council.

To protect the building against a highly likely major earthquake, the structure integrates a unique combination of post-tensioned concrete walls and frames that make efficient use of construction materials and will improve performance and limit damage. The defining feature of this system is its unique self-centering behavior that virtually eliminates permanent post-earthquake deformations. The hybrid system combines the elasticity of high-strength, unbonded tendons with the energy dissipation capacity of mild steel reinforcement to control the inelastic response of the structure.

Specialized concrete mixtures, with large volumes of portland cement replaced with slag cement, were also integrated into the design to reduce the embodied energy and carbon footprint of the structure.

PROJECT DESCRIPTION

The project is a combination of the four separate elements shown in Fig. 2: the four-story David Brower Center containing office space and a conference center, a multi-unit residential structure, ground floor retail space, and an underground parking garage. This article is focused on the David Brower Center.

With its distinctive elongated bullet shape, the Brower Center forms the northern boundary of the complex. With plan dimensions of approximately 62 x 196 ft (19 x 60 m), the Brower Center comprises roughly 50,000 ft^2 (4650 m^2) of the 225,000 ft^2 (20,900 m^2) complex. The construction cost of the entire project is about \$50 million, and the cost of the Brower Center alone is estimated to be around \$15.3 million.

Floors consist of post-tensioned concrete flat slabs supported by uniformly arrayed columns. The perimeter columns are architecturally exposed. The seismic force-resisting system shown in Fig. 2 is a dual system of two centrally located, C-shaped, vertically post-tensioned core walls acting in conjunction with transverse post-tensioned moment frames at the ends of the building. The entire structure is supported by a mat foundation.

For both cost and environmental reasons, concrete was the material of choice for the structural system. The thermal mass is a key factor in reducing operational energy usage, and the slabs were integral to the installation and functioning of the radiant heating and cooling systems. The mechanical systems were run under a raised-floor system rather than hanging from the bottom of the slab. This allowed the slab soffits to remain exposed as a finished ceiling and allowed the hydronic tubes to be located at the bottom of the slabs, which simplified installation (Fig. 3).

Other nonstructural strategies to minimize energy and water use included operable windows to allow natural ventilation, a basement cistern system to store rainwater runoff from the roofs and plazas for landscape irrigation, rooftop-mounted solar water heaters, and a 60 kW photovoltaic trellis crowning the Brower Center roof.

Fig. 1: Design and construction of the David Brower Center in Berkeley, CA, exemplified the missions of the environmental advocacy and nonprofit groups that will lease its office and meeting space

SEISMICITY AND SUSTAINABILITY

The site is near a major fault system that is likely to produce a 7.0 or greater magnitude earthquake within the service life of the structure. A typical code-compliant building would be considered well-performing if it remained standing and allowed safe evacuation of the inhabitants after a major seismic event, even though residual drift and widespread damage to nonstructural components may render it unfit for continued use. In such buildings, permanent offsets can interfere with the functioning of doors, windows, elevator shafts, and other nonstructural components to such an extent that repairs are not economically feasible.

In this setting, a major aspect of sustainable construction is continued functionality of the structure after the occurrence of a large earthquake. In other words, protection of the investment in energy and materials is a key “green” construction goal.

POST-TENSIONED CONCRETE SEISMIC SYSTEMS

To best meet the cost and environmental goals for the project, the seismic force-resisting system incorporates post-tensioned cast-in-place concrete structural walls and post-tensioned moment-resisting frames that are seamlessly integrated with the building architecture.

The flexural behavior of a post-tensioned structural system is ideal for this application. The mild steel reinforcing bars yield to dissipate energy during a seismic event, while the unbonded tendons remain elastic to provide a positive restoring force that centers the structure following the event.[1,2] The elastic restoring component is proportioned to be somewhat larger than the yielding component, which means that slightly more than half the total resistance is derived from post-tensioning and contributes to the recentering effect.

Key aspects of the design approach include:

- Basic strength design to meet seismic design criteria as defined in ASCE 7[3] and ACI 318[4] for special reinforced concrete walls and moment-resisting frames;
- Structural walls proportioned so that the overall flexural strength attributable to post-tensioning alone is more than 55% of the total flexural strength;
- Walls and frame elements designed with sufficient concrete area and strength to minimize crushing strains and maintain stable compression zones at ultimate response; and
- The use of capacity design principles for shear design.

Properly proportioned, the system provides improved ductility and is less prone to physical damage during earthquake shaking. Moreover, the post-tensioning provides significant strength enhancement, substantially reducing conventional reinforcement in flexural members and resulting in more compact dimensions and improved constructibility.

To predict forces in critical elements, eliminate nonductile failure modes, and ensure a stable flexural mechanism, nonlinear response history analyses were used in conjunction with capacity design principles.[5,6] Interstory drifts under the design basis earthquake were kept well below the maximum prescribed by code to limit potential damage. Residual drifts and permanent deformations turned out to be negligible. Strains in the unbonded post-tensioning strands were limited to the elastic range, while the reinforcement was anticipated to experience significant yielding.

A critical aspect of seismic detailing for structural concrete is confinement. Section ductility and good hysteretic behavior require that core concrete retain its integrity under high compressive strains and repeated load reversals. This becomes even more critical in post-tensioned seismic-resisting systems, where the added imposed compressive forces push concrete close to its ultimate crushing strain. Figures 4 and 5 show typical reinforcing details at critical regions of the walls and frames, respectively.

Given the large No. 14 (No. 43) vertical flexural bars at the bases of the structural walls and No. 11 (No. 36) bars at the hinge regions combined with the functional need to minimize overall core dimensions, traditional hooked bars and crossties were not practical in the first two stories of

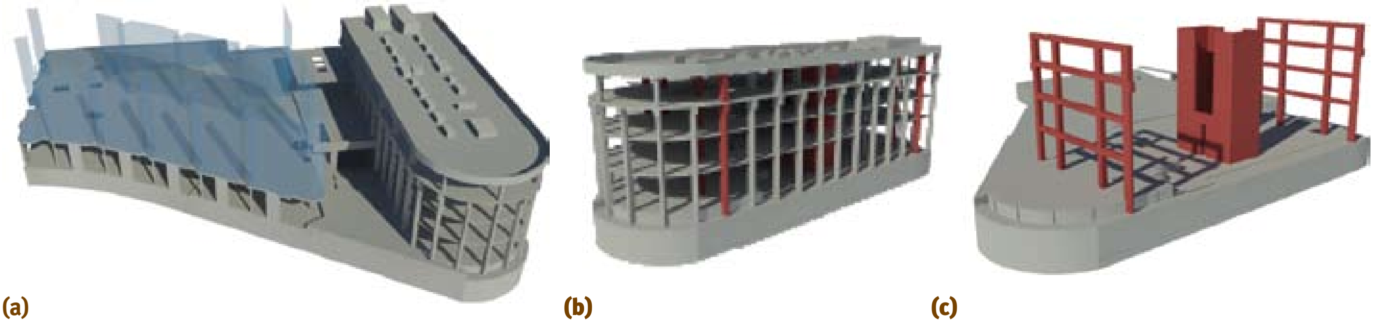

Fig. 2: Models of the David Brower Center: (a) the project included spaces for a multi-unit residential portion (upper left), with retail space below, office and conference space (upper right), and below-grade parking (basement); (b) overall structure of the office center; and (c) the lateral force-resisting system of the office center, consisting of vertically post-tensioned structural walls and post-tensioned frames

the cores. Headed bars were used at the most congested sections where anchorage of longitudinal or transverse reinforcement was critical. Their compact shape allowed them to be closely spaced while effectively engaging the horizontal and vertical bars. Confinement above the third floor was through the use of traditional hooked crossties.

The post-tensioning tendons used in the walls and frames consist of bundles of 0.6 in. (15 mm) diameter, individually sheathed and greased strands in corrugated metal ducts. This approach allowed the ducts to be cast in place and the strands to be installed after the concrete was placed. Tendons typically contained 11 to 17 strands and terminated in multi-strand anchorage devices.

CONCRETE AND CARBON FOOTPRINT

The project design goals emphasized efficiency in resource use, reduced embodied energy, and reduced life-cycle cost. Minimizing the amount of portland cement used in the concrete—typically a major component of embodied energy and carbon footprint for a concrete structure—was a key aspect of attaining this goal. The carbon footprint was minimized by using slag cement to replace large portions of the portland cement in the concrete. This saved an estimated 5000 tons (4500 tonnes) of CO_2 emissions for the project. Low-impact mixtures were used throughout the project, with typical portland cement replacement values of 50% for slabs, columns, and walls, and 70% for the mat foundation. The mixtures used for the Brower Center typically had portland cement contents of 200 to 400 lb/yd^3 (120 to 240 kg/m^3). This is very low by traditional standards, as commonly available 3000 psi (21 MPa) concrete can have a portland cement content around 500 to 600 lb/yd^3 (300 to 360 kg/m^3), and typical shotcrete mixtures can contain up to 850 lb/yd^3 (500 kg/m^3).

Fig. 3: Although much of the mechanical and electrical systems were located under a raised floor (instead of hanging from the ceiling), the floor slabs contained lighting conduit and tubing for the hydronic heating and cooling system in addition to the prestressed and mild reinforcement

GREEN MIXTURES

Although in many ways they are similar to conventional concrete, mixtures containing large amounts of slag cement have some unique properties that affect design and construction. These include rate of strength gain, finishing behavior, and ability to form fine details.

The rate of strength gain can have a significant impact on the construction schedule. Because the elevated slabs were post-tensioned, the time between concrete placement and slab stressing was a critical-path item. Typically, a 5000 to 6000 psi (34 to 41 MPa) post-tensioned slab is

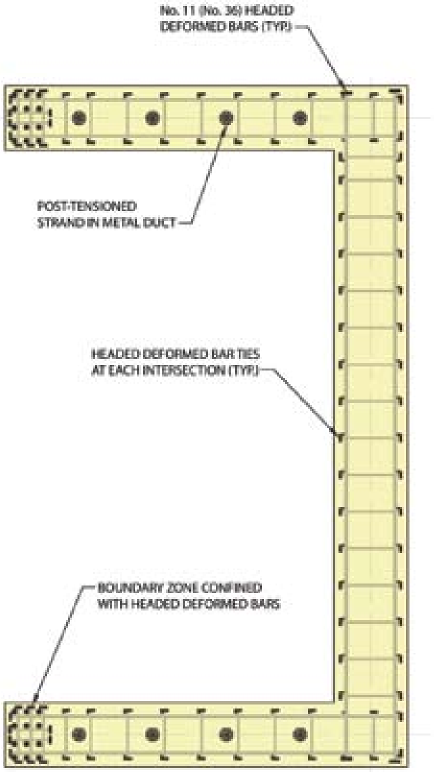

Fig. 4: Reinforcement for a typical structural wall at the level detailed as a plastic hinge region

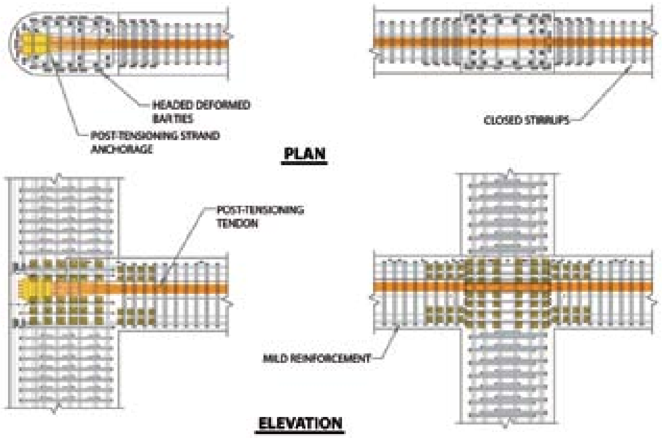

Fig. 5: Typical reinforcement details at the intersection of the columns and the post-tensioned beams for the two lateral force-resisting frames

required to reach 3000 psi (21 MPa) before the strands can be stressed. Most conventional mixtures, under typical conditions, can meet this criterion in 3 to 5 days. The 50% slag cement mixtures used in the Brower Center often reached stressing strength within 5 days, but in a number of instances required 7 to 10 days. Because construction continued from late autumn through late spring, a wide range of temperatures was encountered. Placements during colder weather were typically slower to reach strength. As the Brower Center has only four elevated decks and the adjacent plaza portion was on a separate construction track, the net impact on the construction schedule was minor.

Some mixtures that did not contain slag cement were used when slag cement was temporarily unavailable or in miscellaneous applications such as stair pan fill. This allowed comparison of the effects of slag cement inclusion under field conditions. Strength gain beyond the initial 7 to 10 days was similar for mixtures both with and without slag cement for values of f'_c between 3000 and 6000 psi (21 and 41 MPa). The initial 8000 psi (55 MPa) mixture containing 50% slag cement replacement that was used in the structural walls, however, was found to be particularly slow in achieving strength. Some samples required as much as 90 days to reach the full design strength. For the uppermost structural wall placement, slag cement was reduced to 40% of the total cementitious materials to speed strength gain. This mixture produced an average strength of 8600 psi (55 MPa) at 56 days. Figure 6 shows typical strength gain characteristics for the different mixtures used on the project.

NONSTRUCTURAL ISSUES WITH SLAG CEMENT CONCRETE

There are additional considerations related to the use of slag cement beyond structural concerns. Material availability on the West Coast of the U.S. is sporadic. Most slag available in California is imported from China. The amount and quality of this slag have not been consistent, so many producers have not made provisions for its use. Hanson Asphalt & Ready Mix, the Brower Center supplier, had to erect a temporary slag cement silo to service the project. Growing demand for slag cement, however, will perhaps lead to increased availability.

Slag cement mixtures also required modified finishing operations. Initial set is somewhat delayed, and more bleed water rises during floating; more time must be allowed between floating and troweling. Additionally, control of evaporative moisture loss is important, so use of curing compounds can be helpful. Despite these issues, reports from the field indicated that finishing of slag cement concrete is relatively less difficult than finishing high fly ash content mixtures. The contractor also reported that the slag cement mixtures pumped and placed well, showing improved workability.

Another characteristic of the high slag cement content mixtures was a tendency for formed surfaces to have rounded corners and edges. Bleed water expelled during form vibration appeared to rinse out the cement paste at form joints, corners, and snap ties, leaving a sandy residue with a radius of 1/16 to 1/8 in. (1.5 to 3 mm). This was problematic where reveals, sharp corners, or other fine features were required in exposed surfaces. Patching provided a good final appearance, but further investigation is needed to determine how to adjust the mixtures to correct this behavior.

High-volume slag cement concrete offered advantages in the interior environment as the whiter color of the concrete was included in the interior lighting design. The light color of the concrete walls and painted ceilings, with the long, narrow building footprint, allowed a 100% daylight design—no interior lighting is required under normal conditions. Exterior sun shades enhance this effect and are designed for optimal sun exposure, creating shade in summer months and allowing light infiltration in winter months.

TEAMWORK

Sustainable design requires a systems design approach. If a building must be constructed where extreme events are highly likely, the structural system must be robust enough to ensure the building remains functional and not part of the recycling or waste streams. The structural material must be selected to reduce energy demand and carbon footprint. If it can also help optimize thermal and lighting systems, then the architectural and engineering teams must work together to achieve those efficiencies. The David Brower Center exemplifies these concepts. Though not yet widespread in practice, the advantages offered by these concepts and systems are being increasingly recognized and used.

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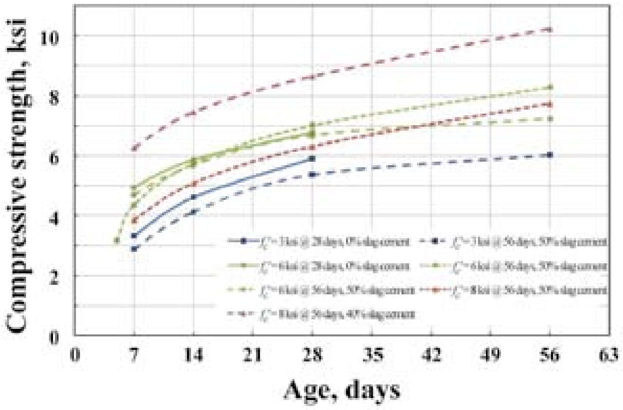

Fig. 6: Comparison of strength development characteristics for concrete mixtures used in the Brower Center (1 ksi = 6.9 MPa)

PROJECT CREDITS

Architect: Solomon E.T.C., San Francisco, CA
Owner/Developer: Equity Community Builders, San Francisco, CA / RCD, Berkeley, CA
Contractor: Cahill Contractors, San Francisco, CA
Concrete Supplier: Hanson Asphalt & Ready Mix, Berkeley, CA

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