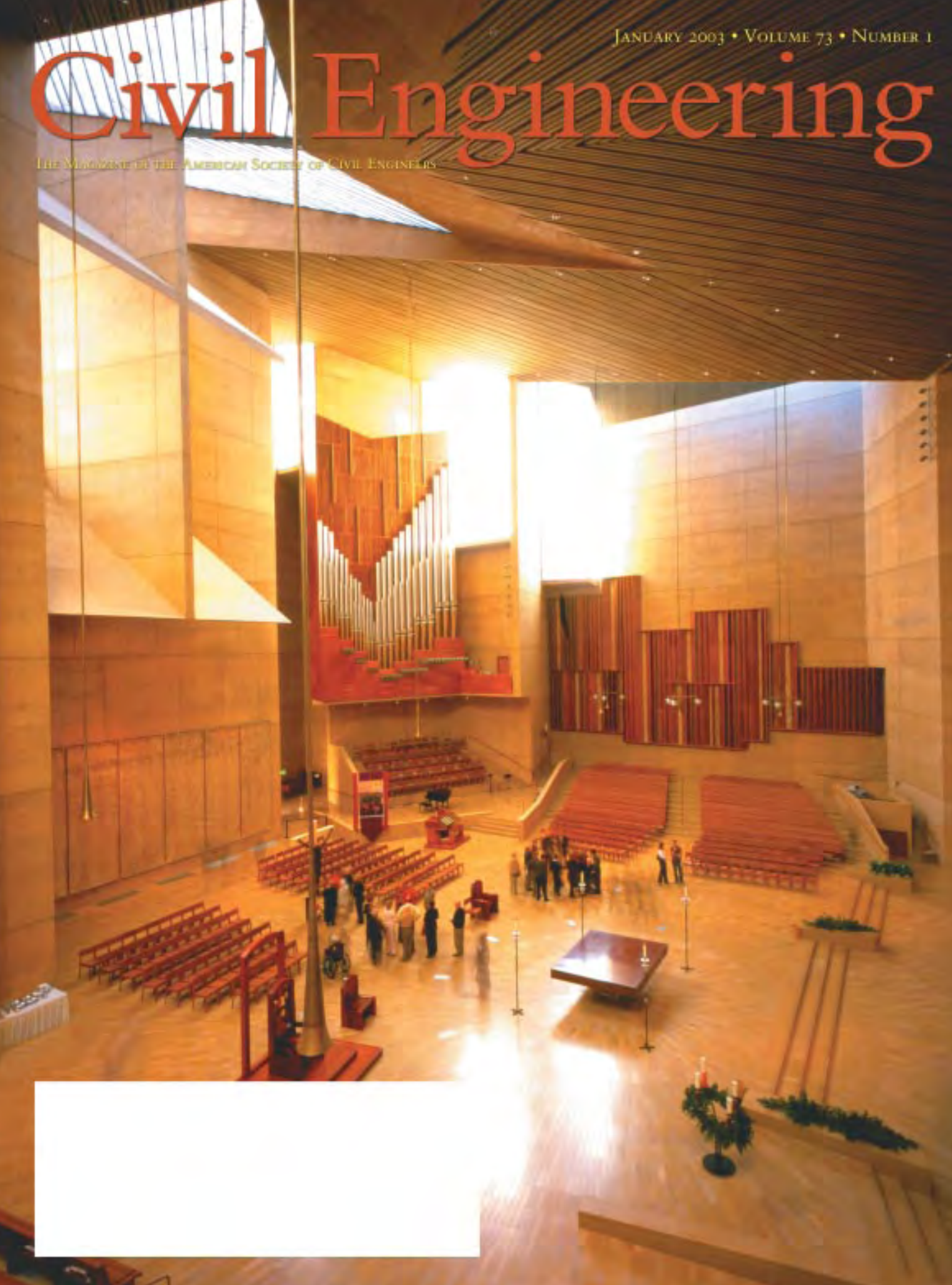
JANUARY 2003 • VOLUME 73 • NUMBER 1

Civil Engineering

THE MAGAZINE OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS



Light of L.A.

A masterful marriage of architecture and structural engineering, the new Roman Catholic cathedral erected in Los Angeles stands as a welcome spiritual and cultural beacon. **By Anne Elizabeth Powell**

Photography by Andy Ryan

It has arisen in the heart of the most secular of cities, a magnificent Roman Catholic cathedral erected in downtown Los Angeles—at the corner of Grand Avenue and West Temple Street and adjacent to the Hollywood Freeway. Conceived as edifice and icon, worship space and refuge, the Cathedral of Our Lady of the Angels, as it has been christened, speaks eloquently through architectural and liturgical vernaculars that define it "as a vibrant symbol of God's habitat in our city," as Cardinal Roger M. Mahony, the archbishop of Los Angeles, described it on September 2, 2002, in his homily during the Mass dedicating the cathedral.

Vital symbol and splendorous structure, the cathedral is a masterful work, a structure designed to celebrate the Roman Catholic faith by referencing a central gospel of Saint John (John 8:12): "Again, therefore, Jesus spoke to them, saying, 'I am the light of the world. He who follows me does not walk in the darkness, but will have the light of life'" (*Saint Joseph "New Catholic Edition" of the Holy Bible,* New York: Catholic Book Publishing Company, 1962). The design concept that emerged from a dialogue between Cardinal Mahony, who from the outset assumed an exceptionally active role in the creation of the cathedral, and the Madrid-based architect José Rafael Moneo employs numerous allusions to the light of God—especially as it is revealed through Jesus Christ—and to the spiritual journey that gains direction from an individual's evolving relationship with God.

Perhaps the fact that Moneo had not previously designed a religious structure enabled him to take an entirely fresh approach to church design—an approach reflected in a unique configuration and plan. Moneo devised a dramatic composition of essentially nonorthogonal planes that envelops 3.3 million cu ft (934,560 m^3) of space and rises to a height of 128 ft (39 m) above street level. The inventive layout he conceived for the cathedral's interior effects an unexpected—and resplendent—"journey" that beckons worshipers into the structure and then urges them forward, bathing them all the while in channels of gossamer light.

Although cathedrals are often immensely scaled and ornate in design, the term "cathedral" does not in fact refer to an elaborate sacred structure; rather it is derived from the Latin word *cathedra* (throne). A cathedral is a church presided over by a bishop. In 1994 it became clear that the archdiocese of Los Angeles would need a new cathedral. The Northridge earthquake had seriously damaged the late-19th-century mission-style Saint Vibiana's—a masonry structure situated in a rundown part of downtown Los Angeles—and the city's seismic engineers ordered its closing. Cardinal Mahony began formulating plans to raze Saint Vib's, as parishioners referred to it, and erect a new cathedral on the site, but preservationists sued to save the church and ultimately prevailed. However, because the archdiocese had long before outgrown Saint Vibiana's, Cardinal Mahony proceeded with his plans to build a new cathedral, and the archdiocese sold Saint Vibiana's to a local developer. After being refurbished and seismically upgraded, the building will open as a center for the performing arts as part of California State University at Los Angeles.

Cardinal Mahony limned quite a vision for the new cathedral: It would reflect California's mission heritage while abiding by the liturgical dictates defined in the mid-1960s by the Second Vatican Council, which held that a church structure was to speak to worshipers in their own idiom. The cathedral, he said, would have to be able to survive essentially unscathed an earthquake of magnitude 8 (the "big one"), which seismologists predict will strike the Los Angeles area in this century; it would have to

One of the most dramatic elements of the cathedral's nave—an element that is visible for miles—is the immense crucifix incorporated into the alabaster window behind the altar, *opposite.*

serve as a place of refuge during disasters; and it would have to have a service life of 500 years. *This* cathedral, the cardinal was determined, would serve the Roman Catholics of the archdiocese as both a spiritual and a temporal haven for many generations.

A key starting point in the cardinal's dialogue with Moneo was the requirement that the cathedral speak to worshipers in their own idiom—that it connect with them on a personal level. To a large extent contemporary design forms have been used in carrying out the Second Vatican Council's dictate. These forms have emphasized open church plans that "speak" to worshipers by underscoring togetherness, conveying to them the notion that participation in the Mass is an act of spiritual fellowship. Cardinal Mahony wanted to create a spiritual fellowship that would be powerful, memorable, and easily embraced by worshipers of all ages and cultures. Thus was born the design concept of the spiritual journey guided by God, the "light of the world." On a more basic level Moneo honored the tradition of California's Spanish mission churches by specifying a light tan pigment for his geometric concrete forms. But the reference is subtle: His cathedral is clearly contemporary in expression, a point he underscored by means of the shingled effect he used in defining many of the walls.

Moneo also wanted the cathedral to serve as "a beacon of light" for the city of Los Angeles, a work of architecture that would draw residents and visitors alike on the merits of its aesthetic strength. He viewed the commission as an opportunity to create a new visual landmark for the city of Los Angeles—a landmark that would, however, very clearly be a sacred space. That was perhaps his greatest challenge.

The site the archdiocese selected for the cathedral complex—which comprises the cathedral, a free-standing campanile, a residence for clergy, an office and conference area, a 600-car underground parking garage, and a plaza—is a rectangular, 5.5 acre (2.2 ha), block-long parcel in the heart of downtown Los Angeles. It is directly above the Elysian Park Fault and next to the Hollywood Freeway. While some might have regarded the freeway as a detriment, Moneo deemed it an ideal component of the site because he sees today's highways as analogous to the rivers that flow past Europe's great cathedrals. He thus believed himself to have been provided with an ideal setting.

Moneo put the plaza at the center of the site, shaping a space that could accommodate 6,000 participants in outdoor liturgies or events. The cathedral and campanile occupy one end of the site; the clergy's residence and the office and conference area, the other. The cathedral and the 156 ft (47.5 m) campanile, however, are the focal points, and Moneo's cathedral is indeed a resplendent realization of the design outlined by Cardinal Mahony.

Moneo's cathedral manifests an exquisite juxtaposition of the allusions to the light of God and the individual's spiritual journey, and it is precisely this juxtaposition that effects the unifying message Cardinal Mahony ordained. All who pass through this structure are immersed in the experience of the spiritual journey and in the extraordinary play of light Moneo engendered. The cathedral's signature features are its alabaster windows, which Moneo incorporated throughout to texture interior spaces with varied channels of light. The light is diffused, soothing—a tangible allusion to the light of God.

The alabaster installation—which includes 27,000 sq ft (2,500 m^2) of windows—is the largest installation of its kind in the United States. The panels, which range in width from 2.5 to 6 ft (0.7 to 1.8 m), were cut to a thickness of 0.6 in. (1.5 cm). The panels are protected by layers of glass, which in turn are covered with a protective film that filters ultraviolet light and heat. In keeping with tradition, the cathedral faces east—toward Jerusalem and the Holy Land—and the rising sun.

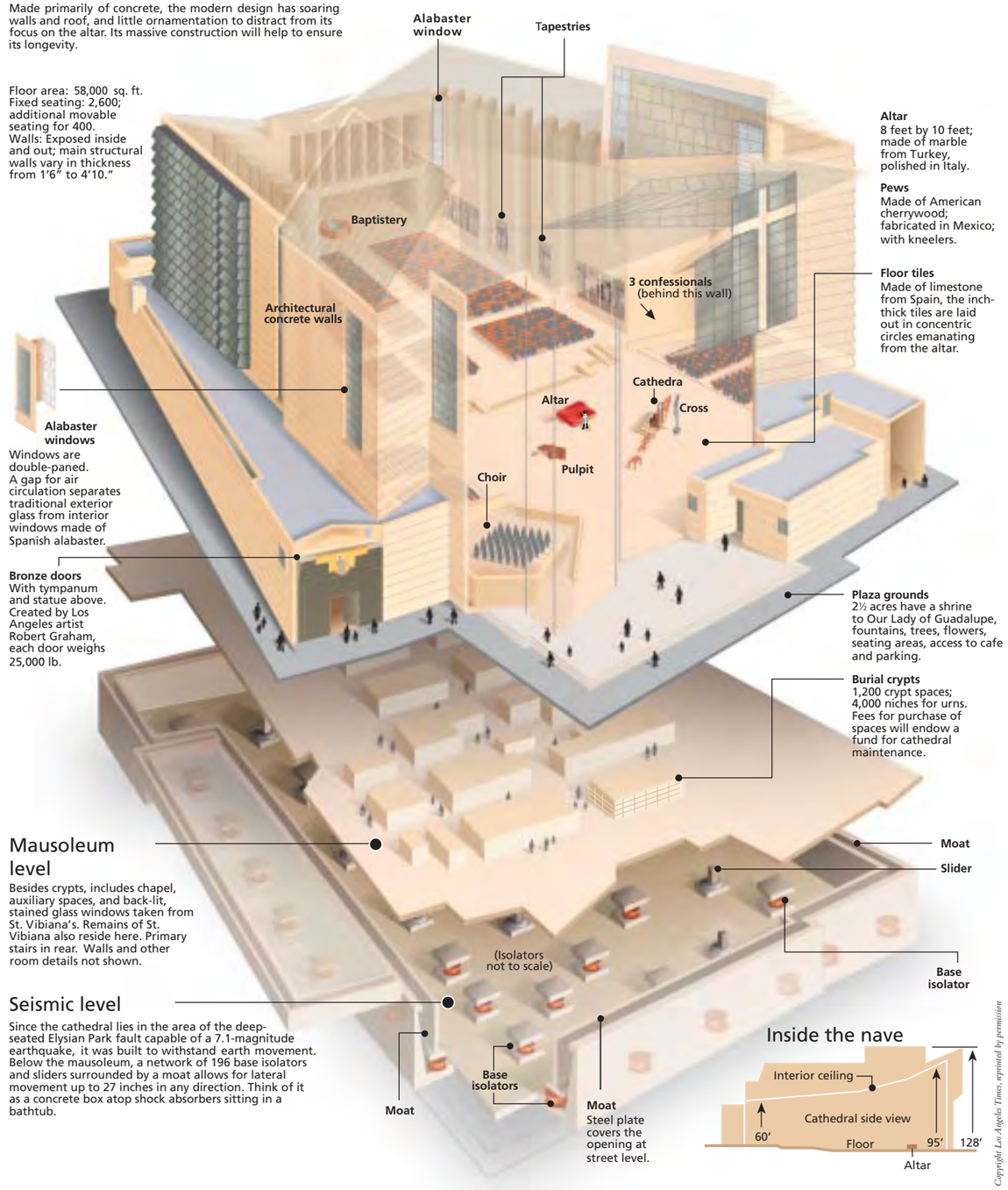
Worshipers enter the cathedral through immense bronze doors crowned by a stunning contemporary sculpture of the Virgin Mary, *Our Lady of the Angels.* The doors open into an ambulatory, which encircles the interior of the cathedral. Moneo conceived the ambulatory as embodying a spiritual progression and

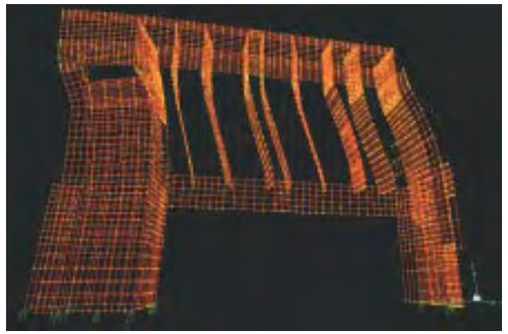
Cathedral of Our Lady of the Angels

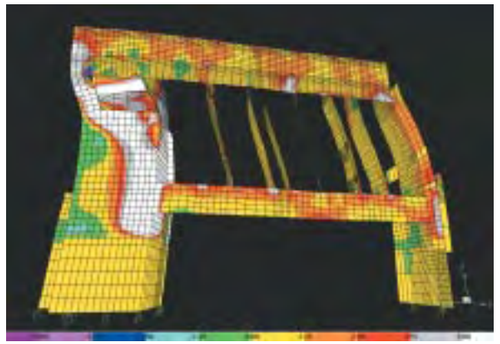
Cathedral level

Made primarily of concrete, the modern design has soaring walls and roof, and little ornamentation to distract from its focus on the altar. Its massive construction will help to ensure its longevity.

Floor area: 58,000 sq. ft.
Fixed seating: 2,600; additional movable seating for 400.
Walls: Exposed inside and out; main structural walls vary in thickness from 1'6" to 4'10."







Nabih Youssef & Associates, both

The baptistery fin walls and beams were coupled to form a Vierendeel truss, *opposite and above,* that spans the width of the nave and provides lateral stability to the rear of the cathedral. The truss concept was developed by Nabih Youssef & Associates to provide greater visual and auditory transparency.

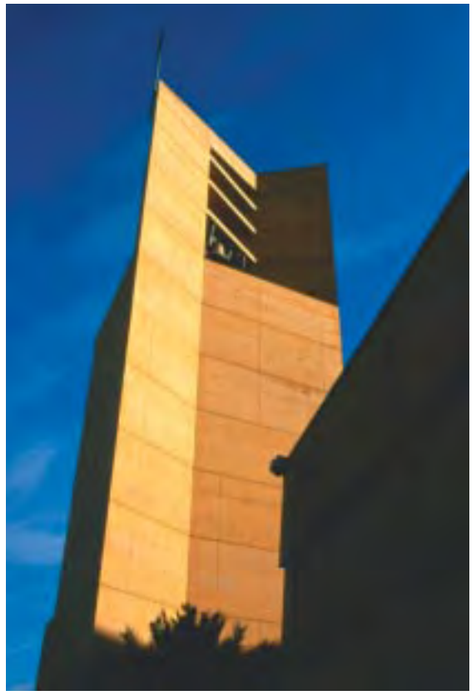
executed it to have a slight incline in its initial reaches to suggest an upward, uplifting journey. The passageway is lit by a ribbon of alabaster above and subtly punctuated by the cathedral's devotional chapels, which are arranged along the inner walls. (There are 10 chapels: 9 on the plaza level and the other one—Saint Vibiana's—on the mausoleum level below. In a departure from custom, the tabernacle is located in the Chapel of the Blessed Sacrament, not behind the altar.) Positioned asymmetrically, an ornate, 17th-century altarpiece marks the entrance to the baptistery and the nave just beyond. The baptistery—the place of baptism—denotes entry into a life with God.

The fin walls and beams of the baptistery were coupled to form a Vierendeel truss that spans the width of the nave and imparts lateral stability to the rear of the cathedral. Moneo's original concept called for solid walls spanning the nave, but there were concerns that sound reverberations would cause significant acoustical problems. The Vierendeel truss provides visual and auditory transparency while structurally stabilizing the rear of the cathedral.

Adjoining the baptistery is the nave, a soaring space that extends for 333 ft (101.5 m), encompasses 58,000 sq ft (5,388 m^2), can seat 3,000, and is awash in light suffused through immense alabaster windows where the people of God—those who have been baptized—are assembled, soon to make their journey forward to the altar to partake of the Eucharist, the body of Christ. From the altar area worshipers may access the ambulatory as it extends along the north side of the structure, where the confessionals are located. High on the wall behind the altar is a 50 ft (15 m) tall concrete cross centered in an alabaster window. Visible for miles—especially when the church is lit after dark—the crucifix was designed to leave a spiritual imprint on the city, to convey the idea of the transcendent.

On November 16, 1995, as he was embarking on the creation of the cathedral, Cardinal Mahony wrote, "It is my dream and fondest hope that as people first catch a glimpse of our new cathedral they will be drawn and captivated by its beauty and symbolism. Viewing the cathedral from any direction should evoke sure recognition that this is the City of the Angels' Catholic cathedral, while subtly luring the viewer by its sense of spiritual strength. As people draw nearer, the size, proportions, and external beauty of the cathedral should cast an intangible sense of peacefulness and security upon all who behold it, while continuing to draw them closer—almost irresistibly. Their hearts and souls should experience soothing comfort in the vitality and the wonder of God's house in the midst of the human community."

In Moneo, Cardinal Mahony found a kindred spirit—a man who understood what this cathedral should and could be, both for the archdiocese and for the city as a whole, and who was thoroughly committed to bringing it to fruition. There were others, however, who played very significant roles in the execution of this project—most notably the Los Angeles office of Leo A. Daly, which served as the executive architect; Los Angeles–based Nabih Youssef & Associates, the structural engineers; the Los Angeles office of Arup, the mechanical, electrical, plumbing, and fire protection engineers; and



Worshipers enter the cathedral through immense bronze doors, *opposite,* that open into an ambulatory, which encircles the cathedral. Glazed carapaces were devised to protect the nave's large expanse of alabaster windows, *above.* The structural system of the freestanding campanile, *right,* consists of cast-in-place concrete slabs and beams spanning reinforced-concrete walls.

Morley Construction Company, of Santa Monica, California, the general contractor.

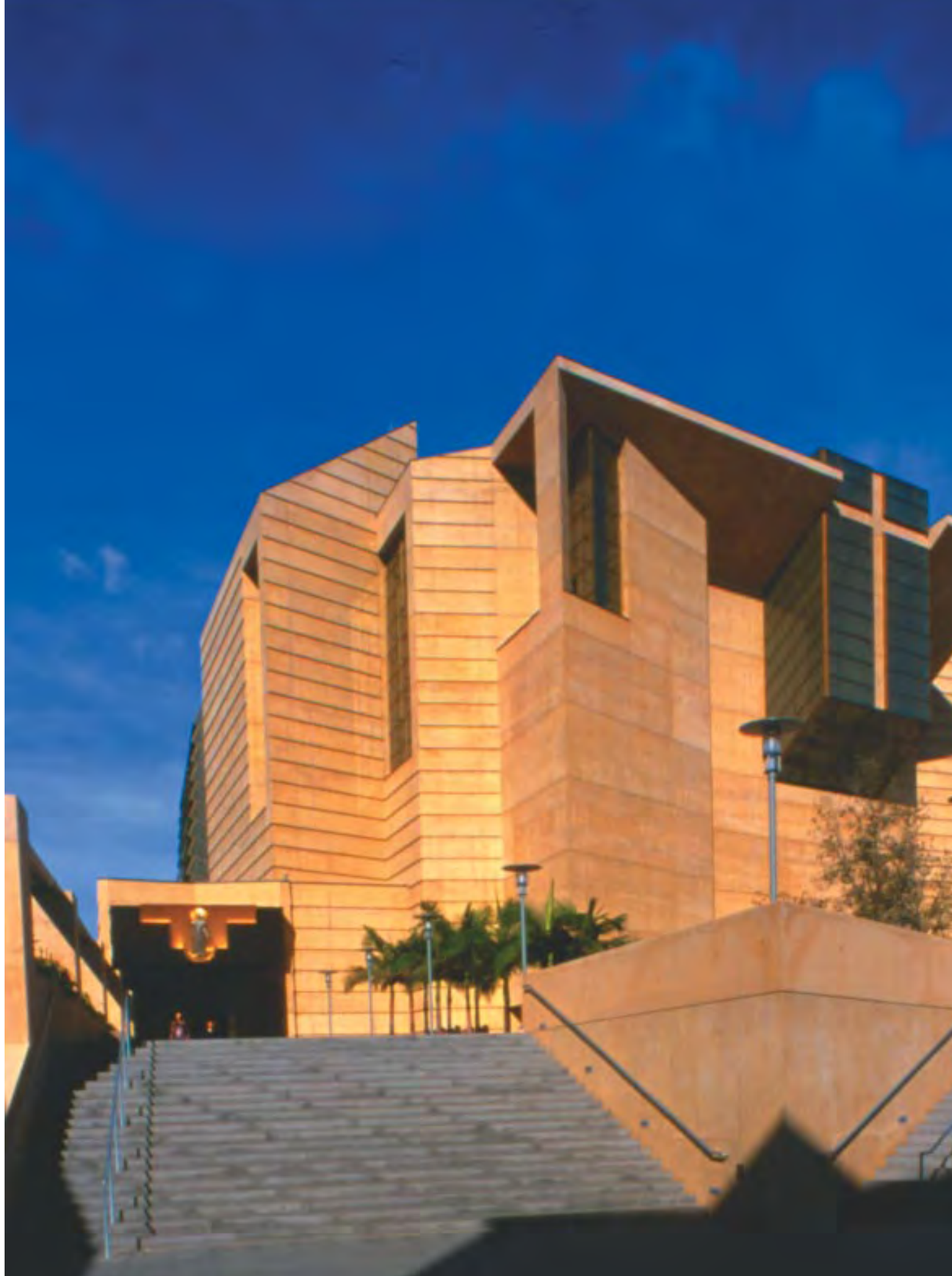
The Cathedral of Our Lady of the Angels was designed and executed to be an enduring structure. But certainly the rigorous performance standards established for the cathedral—that it withstand an earthquake of the highest magnitude essentially unscathed and that it have a service life of half a millennium—presented quite significant structural engineering challenges, especially given its location above the Elysian Park Fault, which is almost certain to produce severe ground motion in the event of an earthquake. And these demands were made all the more challenging by the three-year construction schedule—from 1999 to 2002.

The concrete work alone presented numerous technical challenges. The cathedral incorporates 454,000 sq ft (42,177 m^2) of architectural concrete, and 70,000 sq ft (6,500 m^2) of the concrete walls are shingled. The thickness of the walls varies from 1 to 5 ft (0.3 to 1.5 m), and no two walls intersect at 90-degree angles. Furthermore, there are 850 nonrepeating corner conditions, each requiring a custom form.

"Since the artistic adornment is integral to the architecture and structural framing, it was important that the exposed concrete elements be both aesthetically pleasing and durable," says Nabih Youssef, the principal of Nabih Youssef & Associates. "Thus the design of the exposed concrete elements utilizes durable materials and configurations. Additionally, special emphasis was placed on mitigating concrete cracking and increasing long-term durability." According to Youssef, minimum shrinkage and temperature reinforcement were increased from 0.0018 to 0.0025 for slabs with a close spacing of small bars to increase the effectiveness of crack control.

"Lower design yield strengths of forty kips per square inch for reinforcement were used for the design of exterior exposed concrete elements to account for the effects of long-term corrosion," explains Youssef. "Additional top steel was added above the code minimum for beams and slabs in an effort to retard long-term creep. Floor slabs were also thickened above code minimums to mitigate long-term deflections and increase durability."

It was also important to develop a concrete mix that would minimize long-term deterioration. The mix devised called for a low-alkalai type II cement with large aggregates but no calcium chloride admixtures. Youssef points out that "long-term concrete sealers will be applied to the concrete walls every ten years to further prevent environmental corrosion of the concrete." *(continued on page 96)*



(continued from page 52) Of course nothing could be left to chance with respect to the development and placement of the concrete, and to this end representatives of Morley Construction collaborated with researchers at the University of California at Berkeley to determine how to optimize mixture proportions, how to minimize the temperature of fresh concrete, and how to optimize the formwork removal interval. Ultimately, a ready-mixed concrete was used—made with white cement with a low C_3A content and formulated with chilled water and ice so that the concrete would remain below 75°F (24°C) during placement, which took place in the mornings between 3 and 9 A.M. (The cement trucks were cooled with a chilled-water spray before being loaded.) All of the forms were left in place for two and a half days after the concrete was placed. Because the exterior walls support the structure, they were fortified with increased fly ash (to prevent shrinkage), polypropylene fibers (to prevent cracking), and stainless steel ties (to prevent rust and discoloration).

The key to the structural success of the cathedral, however, is the base isolation system, which will enable the building to move independently of its foundation in the event of an earthquake. "The cathedral is a two-story, one-hundred-fifty-foot-tall structure with architecturally exposed concrete shear walls," says Youssef. "The campanile is a one-hundred-sixty-foot-tall bell tower with exposed concrete walls. From the inception of the project the archdiocese insisted on a robust design to preserve the function and integrity of the structure. But the architectural features of the cathedral—in particular the exposed concrete, the tall shear walls, and the abundance of alabaster, which is such a delicate material—placed exceptional demands on the design and construction. Therefore, structural design criteria were developed that are based on the seismic performance objective of immediate occupancy—the performance objectives for a fire station or police station following a major seismic event." The objective was to protect the cathedral, its occupants, and its contents during the major earthquakes and smaller temblors that could be expected over several centuries. The base isolation system will provide structural stability in the event of significant ground motion.

The cathedral's foundation combines mat, strip, and spread footings connected with tie beams. The structure is surrounded by a 28 in. (711 mm) wide dry moat that will allow for the maximum lateral displacement in the event of an earthquake—27 in. (686 mm). The base isolation system developed by Nabih Youssef & Associates has been designed to minimize cracking in the cathedral's concrete core by reducing the building's horizontal acceleration. (The cathedral and Los Angeles City Hall are the only base-isolated structures in downtown Los Angeles.) The load-bearing concrete walls of the cathedral are supported by 149 replaceable high-damping rubber (HDR) bearings, and lightly loaded areas are supported by 47 slider bearings. Described in the simplest of terms, the cathedral is an immense concrete structure resting atop extremely effective shock absorbers.

The campanile's structural system consists of cast-in-place concrete slabs and beams spanning reinforced-concrete walls. Horizontal steel trusses were used to brace the walls at intermediate levels. Friction pendulum bearings were used to support the campanile at four bearing points, each centered within an 80 in. (2,032 mm) diameter stainless steel saucer. The campanile moat is 36 in. (914 mm) wide and will allow the sliders on saucers to move as much as 29 in. (737 mm). "The HDR bearings, which vary in size from thirty-six inches to forty inches in diameter, have been designed to remain stable under shear stresses in excess of two hundred fifty percent," says Youssef. "The HDR bearings have a limited tension capacity and cannot tolerate a large tension displacement without sustaining damage. And so we developed a loose bolt connection that allows uplift to occur without loading the bracing in tension."

"What I find fascinating about this project is that it created a sacred space using the language of modern architecture," says Nicholas W. Roberts, the project manager for Leo A. Daly. "It's a space the city badly needs. There really was not a large sacred space in the heart of the city the way there is in New York or Washington. In New York, there is Saint Patrick's Cathedral, and in Washington there are the National Cathedral and the Shrine of the Immaculate Conception. But Los Angeles hasn't had a space like that until now. It provides a sense of the divine in the city. And it has proven to be tremendously popular. There are crowds there all the time."

Indeed, the city of Los Angeles has the "beacon of light" that Moneo so wanted to create for it. A sacred space, a place of beauty, a serene haven—a cultural as well as a spiritual anchor. ■

Project Credits:

Client: Roman Catholic Archbishop of Los Angeles, Cardinal Roger M. Mahony

Design architect: José Rafael Moneo, principal, Madrid, Spain (U.S. contact, Hayden Salter, Los Angeles)

Executive architects/engineers: Leo A. Daly, Los Angeles (Roy Follmuth, principal in charge; Nicholas W. Roberts, project manager; John Williams, senior project architect; David Arredondo, project architect)

Structural engineers: Nabih Youssef & Associates, Los Angeles (Nabih Youssef, principal in charge)

Mechanical/electrical/plumbing/fire protection engineers: Arup, Los Angeles

Construction manager/general contractor: Morley Construction Company, Santa Monica, California (C. Terry Dooley, principal in charge)

Consultants to Morley Construction Company for concrete research and planning: Paul Montiero; Reginald Hough, Larchmont, New York; SPF: architects, Los Angeles; KCJ Engineers, Los Angeles; Bovis Lend Lease, Los Angeles

Concrete ready-mix supplier: Catalina Pacific Concrete, Irwindale, California

Seismic base isolator supplier: Silvertown UK Ltd., Burton-on-Trent, United Kingdom

EDITOR'S NOTE

Cardinal Roger M. Mahony, the archbishop of Los Angeles, conceived the Cathedral of Our Lady of the Angels not just as a place of worship for Roman Catholics of the archdiocese but also as a beacon of faith and hope for all city residents. Architecturally, he desired a space that would be at once serene and moving, that would reflect man's spiritual journey, and that would acknowledge California's mission tradition. Architect José Rafael Moneo brought all of these aspirations—and more—to fruition in the form of a magnificent cathedral that has indeed become what he has termed a beacon of light for the city.

But this was not all Cardinal Mahony envisioned. Like the great cathedrals of medieval times, this cathedral, Cardinal Mahony decreed, should stand for 500 years as a symbol of the enduring power of faith. This would be no easy feat, given the fact that the cathedral was to be constructed atop an active seismic fault that could witness a 6.4-magnitude earthquake once every 700 years or so and close to the many other active seismic zones in northern California that scientists say are certain to see a "big one" eventually. To survive such a natural disaster—or disasters—the cathedral's elegant form would have to incorporate exceptionally robust and responsive structural engineering mechanisms. And it was in this area that Los Angeles–based Nabih Youssef & Associates, the structural engineers for the project, were offered their chance to shine.

As you will read in the pages immediately following, the concrete work alone presented exceptional technical challenges. The cathedral has 454,000 sq ft (42,177 m^2) of architectural concrete, and 70,000 sq ft (6,500 m^2) of the concrete walls are shingled. The thickness of the walls varies from 1 to 5 ft (0.3 to 1.5 m), no two walls intersect at 90-degree angles, and there are 850 nonrepeating corner conditions, each requiring a custom form.

But certainly the key to the structural success of this project is the base isolation system, which will enable the building to move independently of its foundation in the event of an earthquake. The objective, in fact, was that of immediate occupancy after a seismic event—the same performance objective as for police and fire stations.

It was Cardinal Mahony's goal to erect a cathedral that would endure for centuries, and it appears that his goal will be realized. Recognizing the efforts of all of those involved in this undertaking, he noted in his homily on the day of the cathedral's dedication last September that the cathedral "sinks its foundations in the very heart of the city of Los Angeles . . . where it will stand and soar for many centuries as a sign of God's enduring presence in our lives and community."

Anne Elizabeth Powell
Editor in Chief

Andy Ryan

A stunning contemporary sculpture of the Virgin Mary, *Our Lady of the Angels,* crowns the cathedral's bronze doors.