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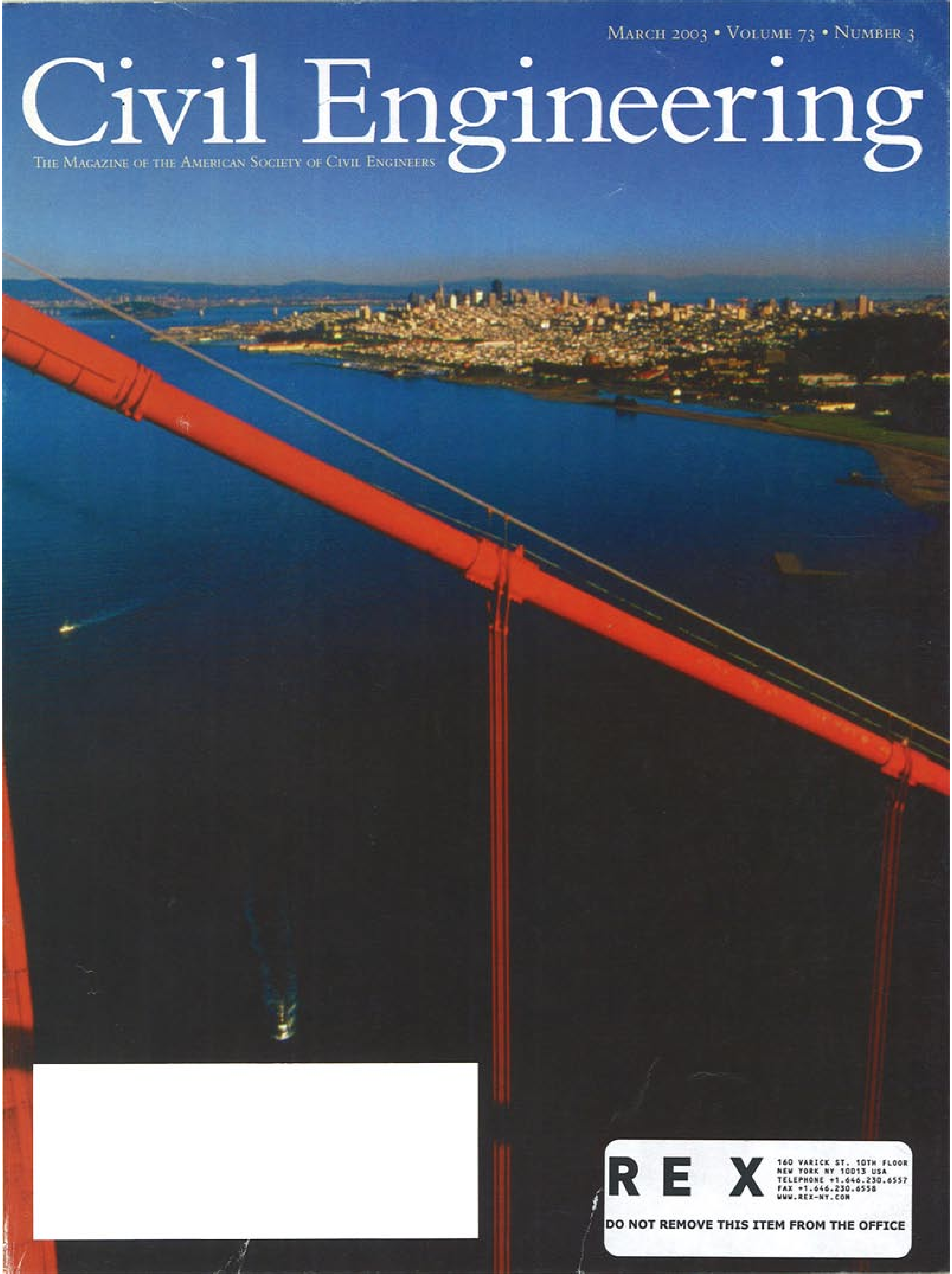


Pushing The Envelope

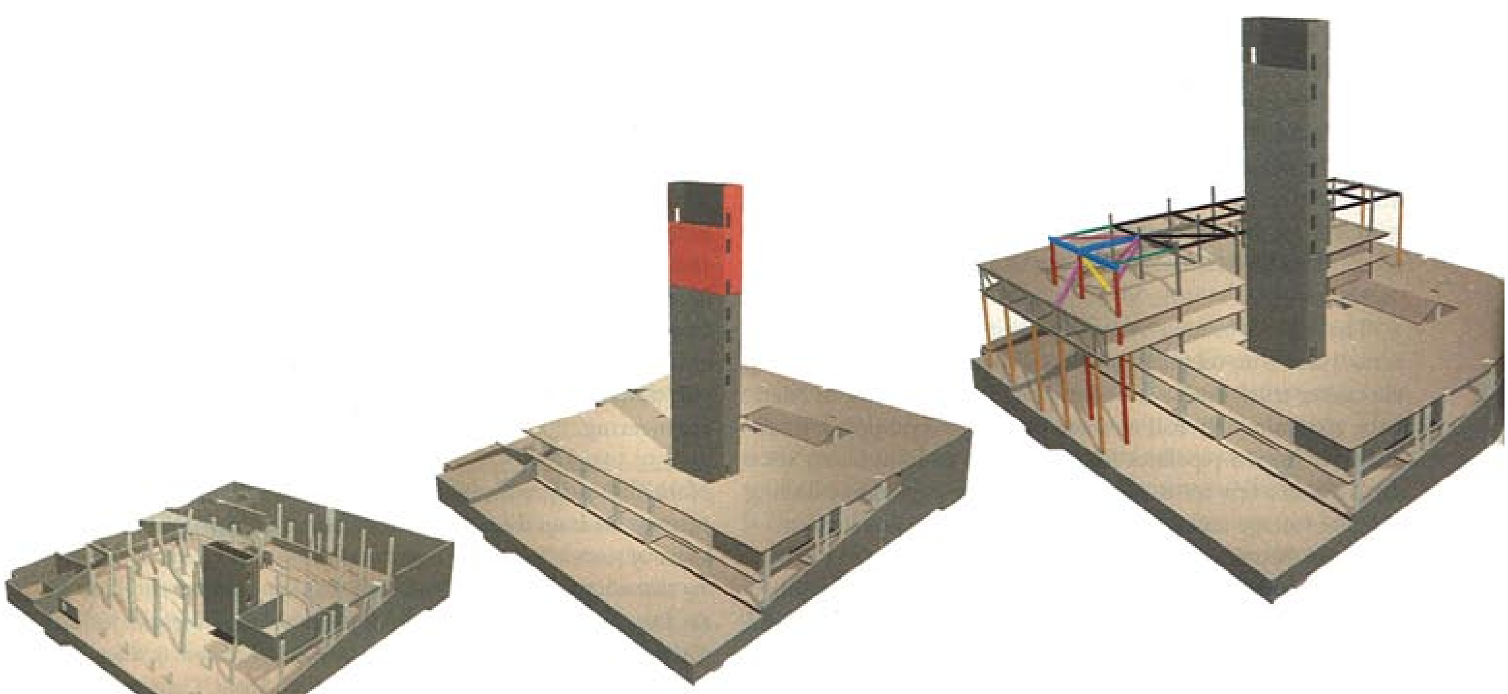
The engineering solutions devised to address the challenges posed by the bold architecture of Seattle's Central Library effect a remarkable amalgam of form and function that places a strong emphasis on sustainability. **By Bruce McKinlay, P.E., Derek Beaman, P.E., and Anders Carlson, P.E.**

The Seattle Central Library has its origins in an ambitious desire to re-create the entity we know as the library. When the Dutch architect Rem Koolhaas unveiled his schematic for the building, nearly four years ago, his expressed goal was "to redefine/reinvent the library as an institution no longer exclusively devoted to the book—as an information store, where all media, new and old, are presented under a regime of new equalities. In an age when information can be accessed anywhere, it is the simultaneity of all media and the professionalism of their presentation and interaction, that will make the library new."

Rather than create one more library that would serve primarily as a repository of books—a place where reading areas and public spaces would inevitably be crowded out by an ever-increasing inventory of titles—Koolhaas conceived the Seattle Central Library as a series of independent but connected spaces that would house a variety of media—as a structure divided into efficient compartments dedicated to and equipped for particular functions.

The result of international collaboration on the part of architects and engineers, the library is a remarkable amalgam of form and function—a 12-story structure divided into five overlapping platforms, each of which, according to Koolhaas, is "a programmatic cluster that is architecturally defined and equipped for maximum, dedicated performance." The library also incorporates sustainable systems and is one of the largest structures under consideration for certification by the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) program. The $155-million project is scheduled for completion later this year.

The design collaboration involved Koolhaas's Office for Metropolitan Architecture (OMA), in Rotterdam, the Netherlands; LMN Architects, of Seattle; the Los Angeles, London, San



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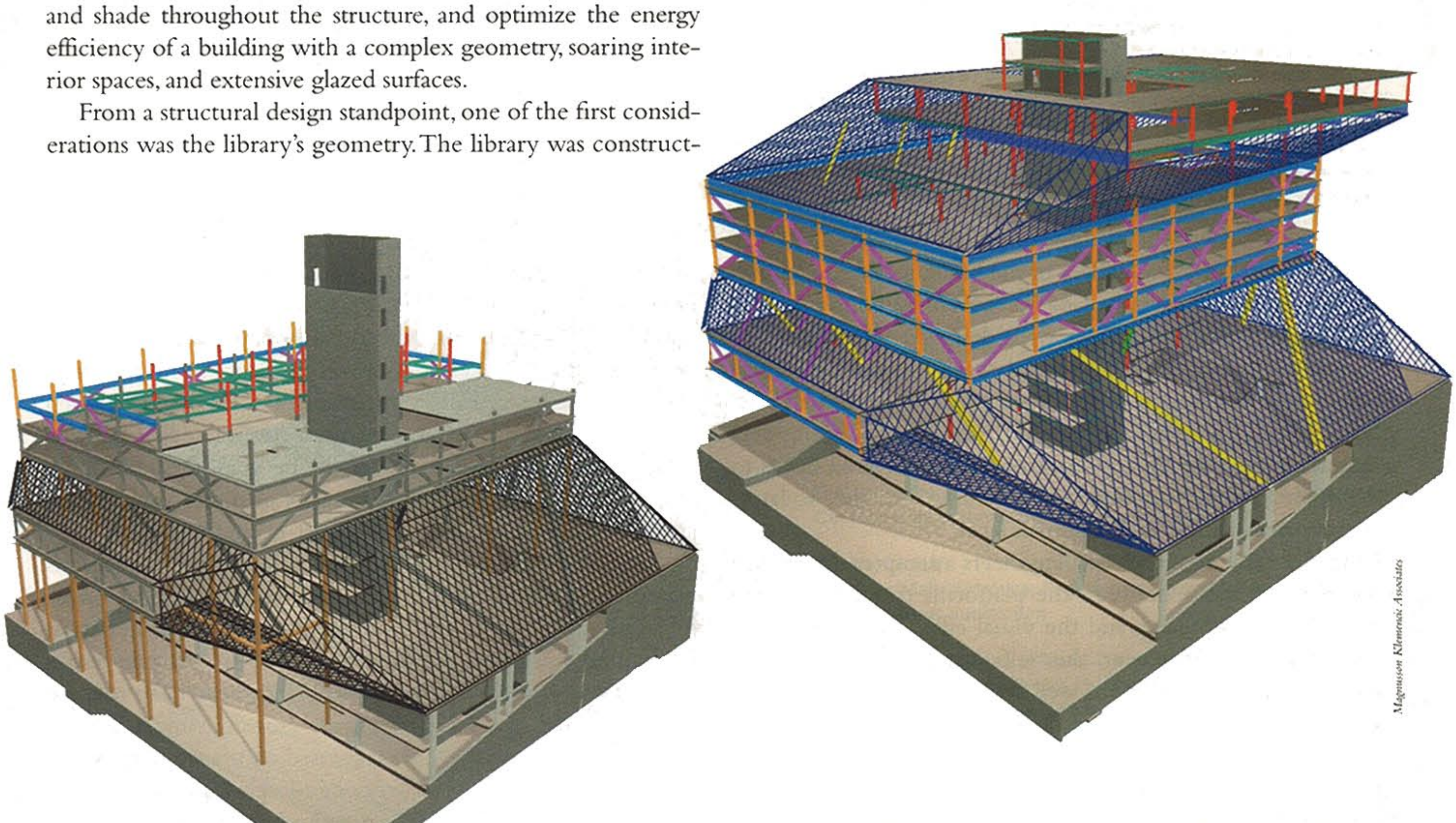
Francisco, and New York offices of Arup; and Magnusson Klemencic Associates (MKA), of Seattle (formerly Skilling Ward Magnusson Barkshire). Arup led the design of the integrated mechanical, electrical, and plumbing (M/E/P) systems, while development of the building's unique structural scheme was a joint effort between Arup and MKA. The engineers worked closely with the OMA and LMN to optimize the structural, facade, and energy performance systems as a whole, not as isolated parts. During schematic design, Arup led the analysis and documentation efforts for the structure, with each firm advancing various structural concepts. As the engineer of record, MKA further refined the structure during the design development and construction document phases, with Arup providing peer review.

The library's unique layout posed a full range of challenges for engineers—from the design and implementation of the structural system to detailed sunlight and airflow studies intended to maximize the building's efficiency. Among the issues addressed were the most effective ways to minimize the number of columns between and within platforms, use the structure's envelope as its primary resistance to lateral loads, optimize the transparency and position of the envelope to manipulate light and shade throughout the structure, and optimize the energy efficiency of a building with a complex geometry, soaring interior spaces, and extensive glazed surfaces.

From a structural design standpoint, one of the first considerations was the library's geometry. The library was constructed on the site of its predecessor, which had been razed to make way. Within a site footprint of 235 by 243 ft (72 by 74 m), the new building's five platforms are displaced vertically and horizontally with respect to one another to create ample public spaces and to maximize views of Elliott Bay to the west and Mount Rainier to the south. Each platform is designed for a particular purpose. From bottom to top they address needs in connection with parking, staff, assembly (public spaces), books, and administration, and each differs in size, density, and opacity.

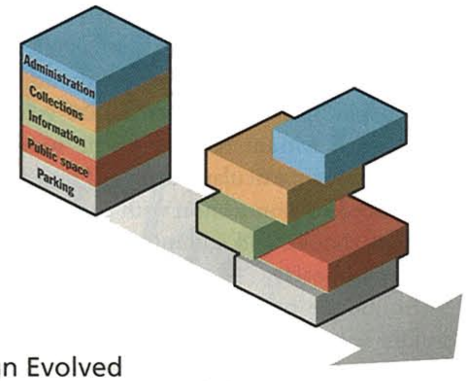
The unique massing of the building led the engineers to consider several structural challenges. Providing the structure with seismic integrity, resistance to torsion, and a secure path for its gravity load had to be achieved with minimal intrusion into the platforms and the public spaces between them. It would have been too expensive to design platforms rigid enough for the space between them to be devoid of columns; at the same time, traditional framing between the units would have turned the public space into a forest of steel.

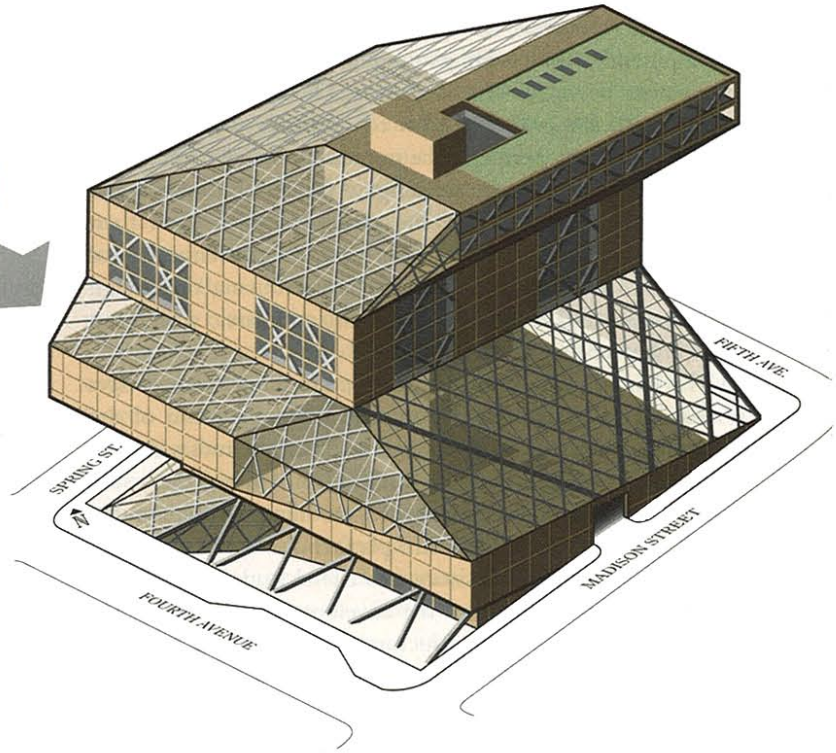
Instead, engineers devised a structural scheme that uses the fewest possible interplatform columns and intraplatform trusses and pushes the gravity and lateral forces of the enormous



The new Seattle Central Library comprises five "platforms" displaced horizontally and vertically with respect to one another and supported by a complex system of interior and exterior trusses and straight and sloping columns. Two platforms are in the building's concrete substructure, and the three above them are framed in steel. A 213 ft (65 m) concrete core climbs through each for the height of the building. The platforms are connected at their perimeters by an envelope of steel latticework that functions both as the building's facade and as its primary resistance to lateral loads. Engineers used airflow and sunlight studies to maximize the energy efficiency of the building's expansive glazed surfaces and open spaces.

Seattle's Central Library





How the Design Evolved

At first glance, it is easy to miss the logic of this coppery crisscross of a building. But the design started from practical considerations: What type of activities will this building be required to handle and how can similar functions be grouped together?

A tour of new big-city libraries showed a tendency toward generic spaces that, depending on changing needs, serve as, for example, reading rooms or book stacks. The problem, as architects saw it, is that storage space can crowd out public areas, and few rooms are designed with a distinctive feel.

The goal in Seattle is to create distinct areas for each function. After analyzing functions and space requirements, five broad categories emerged: administration and staff, collections, information, public space, and parking. The architects visualized the space as five stacked boxes and used that as a starting point for the building's design.

The boxes, or sections, were repositioned to provide better views and more natural light. The headquarters, on top, was pushed east to face Fifth Avenue, toward Mount Rainier, and the area containing the main book stacks was nudged north to offer views of Elliott Bay from the reading rooms. Moving those upper floors also let more sunlight into the lower floors.

floating platforms to the edges of the building, thus maximizing the torsional resistance of the eccentric configuration. Full-length perimeter trusses were designed for the face of each platform to create peripheral spaces devoid of vertical columns, enhancing the architectural effect of the distinct platform masses. The trusses serve a dual structural role, transferring as they do the gravity loads of the cantilevered floors to the sloping support columns and providing resistance to lateral movement within each platform level.

In the early design phases, engineers attempted to provide column-free space between the platforms to maximize the flexibility of the spaces and the visual effect of the independent platforms. However, this self-supporting scheme was found to be impracticable as well as prohibitively expensive. It would have required the use of significantly more structural steel in both the seismic grid and the platforms, and the internal bracing would have disrupted the layout within the platforms. The final design required the placement of several large columns between the platforms, located just behind the seismic grid, to transfer gravity loads from the trusses to the platform edges below.

Because the seismic grid is so critical to the building's structural performance—linking the various platforms—it was one of the primary focuses of the early design process. Analyses were performed to determine a framework that could mitigate the lateral movement of the platforms, and numerous studies were conducted to find a material for the grid's mullions that would optimize both light and shade.

The grid was designed in a rigid diamond pattern conceived to resist wind, gravity, and seismic forces. The challenge was to establish a grid that would maintain its integrity given the long spans and large areas it had to cover. The first task was to assess the nonlinear behavior of the grid—broken down into various panels oriented at a variety of angles—when subjected to shearing, vertical, and out-of-plane forces.

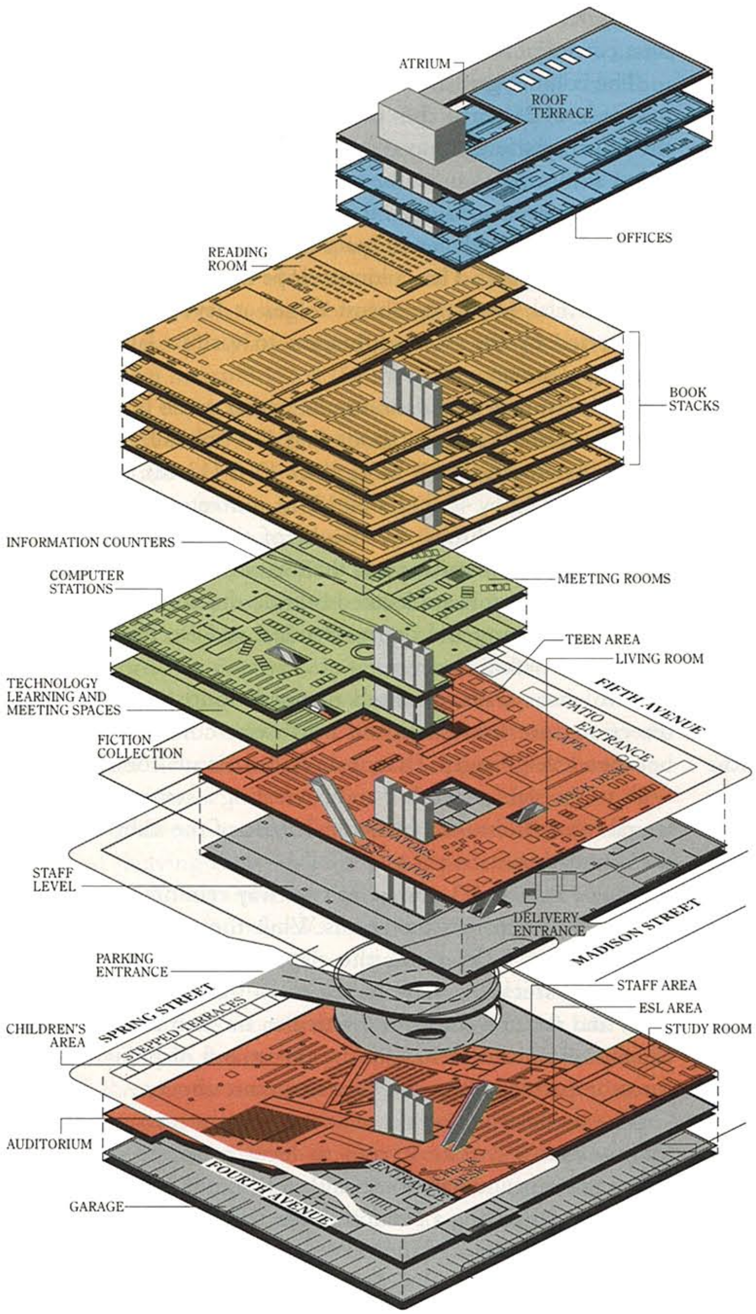
Given the large number of slopes and spans and the various diamond sizes that were being considered, Arup in Los Angeles and London performed multiple analyses—sharing data at the beginning and end of their workdays—to provide results as quickly as possible. The global working partnership resulted in an extended workday, effectively crossing time zones. In parallel with these efforts, MKA assessed constructibility issues, including the possibility of weaving the grid members. These efforts helped keep the design moving forward on budget.

Because the unique structural system was untested, the engineers performed buckling analyses on various diamond sizes to determine the limits of the grid's capacity for both in-plane and out-of-plane loading. To minimize the time and expense of nonlinear analysis, the engineers "tricked" the SAP2000 structural analysis program, developed by Computers & Structures, Inc., of Berkeley, California, into performing a pushover analysis for gravity loading by tipping the model on

What Will Be Inside

The 12 floors and garage of the 412,000 sq ft (38,300 m²) building will be connected by three passenger elevators and one freight elevator, as well as escalators connecting the sections and running through the book stacks.

The central, glass-covered atrium will create an opening from the roof to the Fourth Avenue level, 10 floors below.



Graphics and reporting: Phil Loubere
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Seattle Times Staff
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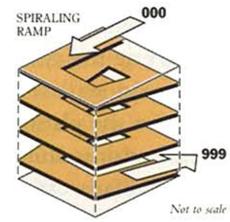
Headquarters

Function: Offices for the staff of the citywide public library system.

Features: Two floors of offices and meeting rooms; views of Mount Rainier from the southeast corner; and a grass-landscaped terrace on the roof with a garden open to the public as a future possibility. Government publications also will be stored here. This collection is expected to shrink as it is converted to a digital format, gradually yielding more space for offices.

Collections

Function: Housing for nonfiction collection. This will require 118,000 sq ft (11,000 m²), or 28 percent of the building's total space, and 6,200 shelves.



Features: Shelves on a continuous ramp that spirals down through four floors. This system keeps the collection intact by allowing individual categories to expand or contract as needed. The ram angle of 2 degrees will be gentle enough both for staff members pushing book carts and for patrons in wheelchairs. Aisles between shelves remain flat, as does the center space of each floor, where members of the collections staff will work.

Elevator stops will be labeled with Dewey decimal numbers to designate the books contained on each floor. A large reading room with a view of Elliott Bay will be located on the upper floor.

Mezzanine

Function: Information and research. Architects call it the mixing chamber because of its gateway position between the public spaces and the collections.

Features: Two floors. The upper floor's central information area will house help-desk staff; other areas will have computer stations and reading and work spaces. The lower floor will offer meeting spaces and technology-based learning services.

Entrance levels

Fifth Avenue

Function: Building entry; public space; fiction collection; area for teenagers.

Features: Large, informal area with seating, called the Living Room. The Fifth Avenue entrance will open into this space. Escalators lead both up to information areas and down to the Fourth Avenue level. The fiction collection is stored in the area under the mezzanine. The teen area occupies the Fifth Avenue side.

Fourth Avenue

Function: Main entrance; English as a second language (ESL) area; children's area; auditorium.

Features: Drop-off lane in front. The ESL area can be accessed directly through front doors; the children's area and auditorium are located to the left of the entrance, sloping down beneath Spring Street. A study room and more staff area are located in back.

Staff level; garage level

Function: Staff work spaces; shipping and receiving; parking.

Features: Staff floor between Fourth Avenue and Fifth Avenue levels will have delivery bays with an entrance on the Madison Street side and a staff entrance on the Spring Street side. The garage on the bottom level has 177 spaces; the entrance ramp will spiral down from Spring Street.

A series of stepped terraces with grillwork in the flooring on Spring Street will allow light to filter through into the Fourth Avenue level below.

its side. Various combinations of gravity and lateral loading could then be combined to assess the benefits and limitations of the diamond grid system. The results of these studies revealed that the grid had excellent in-plane shear strength to resist seismic forces but relatively weak resistance to such out-of-plane loads as wind and axial gravity forces.

To maximize their efficiencies, the engineers decided that the diamond grid and the megatrusses at the edges of the platforms would be designed as localized systems to carry respectively lateral forces and gravity forces. However, they were also able to tie the systems together for further cost-effectiveness. The grid will serve as the lateral-force-resisting system between the platforms. The platforms themselves will be protected against lateral movement by the megatrusses, and the gravity loads carried by the trusses will be transferred via perimeter megacolumns—and in some cases internal trusses—to various points below.

By separating the seismic and gravity systems within the building, engineers were able to avoid the use of fireproofing on the grid's steel members. (The city of Seattle requires fireproofing only on systems resisting gravity loads.) They were also able to establish a greater number of unobstructed views and to maximize the amount of daylight channeled into the structure.

The depth of the framework and the size of the openings in the grid will influence the amount of solar radiation and natural light that pass through the building. The engineering team worked with the architects and with Dewhurst Macfarlane & Partners, a New York City–based facade consultant, to consider the grid parameters and helped keep the project on budget by recommending that the steel grid double as the mullion support system. In this way the more economical mullions can span the length of a grid unit rather than the entire distance between platforms. Once the decision was made to use the lateral-force-resisting structural framework to provide support for the glazing system, the design team optimized each system accordingly.

Before construction began, engineers modeled the entire structure with SAP2000, including more than 18,500 frame elements. The analysis was performed using three modeling assumptions: a "complete building" model including all of the structural elements and two "special consideration" models to evaluate the effects of partial and complete removal of the building's seismic grid.

The special studies were undertaken to ensure that the building would have sufficient structural capacity to support gravity loads without the seismic grid. They proved that the structure would remain stable under such conditions. The steel and concrete elements were subsequently designed for the worst-case loading conditions presented in the three models.

From a structural standpoint the building can be defined as two distinct segments: the concrete substructure and the steel superstructure. Occupying a hill in downtown Seattle, the project site slopes down approximately 31.5 ft (10 m) from Fifth Avenue to Fourth Avenue. The concrete substructure begins at Fifth Avenue (level 3) and descends to the subgrade parking level located one story below Fourth Avenue (level 0). The steel superstructure rises from level 3 to the roof, which is at level 12.

The building is founded on spread footings up to 30 ft (9 m) square and 7.5 ft (2.3 m) thick, with an allowable bearing pressure of 10,000 psf (49,000 kg/m^2) over most of the site. A mat foundation measuring 44 by 65 ft (13.4 by 20 m) was used under a stairway core that rises the full height of the building, and a 28 ft (8.5 m) wide combined footing was used to support two shear walls and a column located in the northwest corner of the site.

The column grid at level 0 does not align with the column grid at level 2, which rises continuously to the book stacks in the fourth platform; thus most of the columns between levels 1 and 2 slope to connect the two grids. While this discrepancy could have been accounted for with transfer beams, the sloped columns create a dynamic space that will be used as a children's reading area. The columns slope as much as 33 degrees from vertical, imparting thrust forces at levels 1 and 2 that are carried by the slab diaphragms to various lateral-force-resisting elements.

The perimeter foundation walls, which are 28 in. (710 mm) thick in some areas, are about 9 ft (2.7 m) tall at the site's Fourth Avenue side and more than 43 ft (13 m) tall at Fifth Avenue. The 12 by 40 ft (3.7 by 12 m) concrete core surrounds a stairway that climbs the height of the building—213 ft (65 m) from the foundation to the top of the elevator machine room. The elevators are located outside the core, but the primary exit stairway and the mechanical and electrical systems are located within the core.

Two shear walls, oriented in north-south and east-west directions, are located in the northwest corner of the site between levels 0 and 1. Diagonal concrete struts connect these walls to the slabs at levels 2 and 3, creating a system to deliver lateral forces from the northwest corner of the slabs down to the foundation.

Levels 1, 2, and 3 consist of two-way reinforced-concrete slabs with drop panels and beams. While the typical slab thickness is 10 in. (250 mm), the slabs are more than 15 in. (380 mm) thick in many locations so that they can handle shear and flexural forces. In particular, the slab at level 3 was heavily reinforced to handle the thrust and diaphragm shear forces imparted by the steel superstructure above.

The foundation wall is crucial to the substructure's lateral-force-resisting system. It rises to level 3 on the structure's entire east side and half of its south side, and it is connected to the level 3 slab along a portion of the north side via a terrace. The stair core—located in the western half of the site between the north and south sides of the level 2 and 3 slabs—also provides lateral resistance. And the concrete struts and shear walls located in the northwest corner deliver lateral and thrust forces from the steel superstructure above—as well as forces associated with the sloping site's unbalanced earth pressures—to the foundation.

The steel superstructure is divided into three distinct platforms, which are primarily framed with steel beams and girders and covered with a concrete slab 2.5 in. (64 mm) thick over a 3 in. (76 mm) thick metal deck. For the most part, the interior of each platform frame is supported by vertical steel columns, and the perimeter is supported by the steel megatrusses that transfer lateral forces between the platform floors.

Platform 3, which contains levels 4 and 5, is framed with single-story trusses on its north and west sides. The west truss is hung from two interior trusses that span levels 5 and 6 in an east-west direction, and the north truss is supported by three interior trusses that span levels 4 and 5 in a north-south direction. The thrusts imparted by these sloping structural elements are carried by a horizontal truss in the plane of the floor framed between the stair core and a braced frame that descends from level 5 to the foundation wall at level 3.

Platform 4, which includes levels 6 through 10, is a key architectural element of the building. It is framed with sloping floors to create a continuous spiral that is four blocks long and will house a collection of books that will be seamlessly organized to prevent even a single break in the Dewey decimal cataloging system. The platform features three-story trusses on all four sides that measure 176 ft (54 m) in the north-south direction and 200 ft (61 m) in the east-west direction. With chords as large as W40X593, diagonals as large as 4L8X8X1$^1/_8$ and W14X342, and verticals as large as W14X605, these are the hardest-working trusses in the building.

The trusses on the north and west faces are each supported by three sloping columns. The east truss is supported by two built-up box columns, and the south truss is supported by a built-up box column and a sloping column extending from the stair core. The sloping columns are oriented in a variety of directions and impose tremendous thrusts on level 6. The thrust forces are carried by a horizontal truss system in the plane of the floor that is connected to opposing elements and to the stair core.

The southern portion of the platform—which will contain staff and shelving areas—is level and is penetrated by a 40 by 40 ft (12 by 12 m) opening, enabling the building's atrium to extend vertically from level 3 to a skylight at level 12.

Platform 5, which will contain levels 11 and 12, has perimeter trusses at the east and west sides, each supported by two interior trusses incorporating Vierendeel panels that form corridors. While the majority of platform 5 is conventionally framed, the interior trusses were linked with tension and compression struts to resolve the truss forces. Braced-frame diagonals on the north and south sides between levels 11 and 12 transfer lateral forces between floors and ultimately to the building's seismic grid, which connects with level 12 on the north and west sides and level 11 on the south and east sides.

The diamond-shaped grid, which will interconnect the platform trusses and carry lateral forces down to level 3, is being constructed from W12X22 members oriented in two directions. The diamonds will measure 4 ft (1.2 m) per side and will be oriented at 60 degree angles, making them almost 7 ft (2 m) high.

The grid will be directly fitted with mullions, which will support diamond-shaped glass panels. The panels will be oriented from 21 to 45 degrees from horizontal and will span as much as 84 ft (26 m), and the framing system will therefore be subjected to its own weight, the weight of the curtain walls, and wind loads. Where necessary, one of three different stiffening solutions will be used to control the stress and deflection of particular panels. In some areas, additional W12X22 members will be added to the main grid to impart stiffness. In other areas, columns will be added transverse to the grid to prop up a panel, or connections will be made between the grid and parallel sloping columns.

One of the OMA's primary objectives in designing a building enveloped in glass was to maximize its transparency. Through extensive use of natural lighting, the design will connect visitors inside the building with the outdoor urban environment. To this end, engineers carefully analyzed the transparency of the structure and then balanced it with requirements for occupant comfort and energy efficiency.

Arup conducted a detailed study of the sun's path over the building site to determine the shade provided by adjacent buildings. With these data they were able to design an envelope that would maximize energy efficiency and natural light within the building while minimizing glare. The solar study determined the percentage of direct solar radiation on the facade surfaces at different times of the day during the month of June. The envelope was then designed with high-performance glazing on the sunlit facades to improve energy efficiency and with glazing of greater transparency on the shaded facades to increase the amount of natural light in the building.

The OMA and Arup began analyzing the glazing system for the diamond grid almost immediately after Koolhaas conceived the idea for the library's unique geometry and netlike skin. Early design decisions were based on such factors as construction cost and feasibility, heat gain, quality of light, and the appearance of the building from the outside. The design team experimented by altering the shape of the seismic grid and perforating it for visibility. They also explored the idea of using a membrane facade. Ultimately, though, they decided to use a glazing system that consists of metal mesh sandwiched between two planes of high-performance glass.

The metal mesh is angled in such a way that each module provides a unique perspective into and out of the library. The angled mesh will also lessen the amount of direct sunlight that reaches the interior—providing a balance of natural light that is important for visual comfort and for reducing glare on the envelope's exterior.

The building envelope is made up of approximately 140,000 sq ft (13,000 m^2) of transparent glazing and skylights. With an eight-story central atrium and high floor-to-floor heights, natural light will penetrate deep into the interior of the building. To extract the full benefit of energy savings from this design scheme, the building's lighting control system was designed with photocells that will automatically shut off artificial lighting when natural light levels are adequate.

To meet the energy efficiency requirements of the LEED program, as well as those of the city of Seattle, Arup designed the building to have a highly efficient *(continued on page 87)* *(continued from page 67)* air-conditioning system—not an easy task in view of the structure's unique geometry, lofty interior spaces, and extensive glazed surfaces. While minimizing energy consumption and maximizing indoor air quality, engineers had to account for the stratification and recirculation of air in immense open spaces and still meet the stringent acoustical requirements of the library when sizing ducts, fans, and outlets. Once the system and envelope design was complete, Arup developed a model to simulate building energy using DOE2, a program developed by the U.S. Department of Energy, to demonstrate compliance with Seattle code and qualify for LEED certification.

Additional computer modeling was necessary to develop the building's system for managing smoke. Standard calculations proved impractical because of the building's full-height atrium and open floor plans. Therefore Arup Fire developed a computer fire model to predict the temperatures and volumes of smoke and fire gases that would be generated by a fire in the atrium to calculate the required building exhaust and pressurization necessary to ensure that occupants would have adequate time to leave the building.

The air-handling systems serving the building can be separated into various distribution categories. All large-volume areas that open into the central atrium will be serviced by a displacement system supplied by a plenum beneath a raised floor. This type of system is ideal for tall spaces in which only the occupied zone, or lowest 6 ft (1.8 m), needs to be air-conditioned. The air is provided at low levels and low velocities through floor and wall displacement diffusers. If the use of an area in the library is altered slightly, the floor displacement diffusers can be easily changed to meet the new needs of the space.

In addition to the diffusers, high-velocity jet nozzles will distribute conditioned air directly onto the building's large expanse of glazing. This system has been expressly designed to offset the facade's heat gains and losses in the atrium and other vast spaces. Because the air-handling system serving the glazing is separate from the system serving the interior spaces, it can respond much more efficiently to varying solar loads and external temperatures.

All of the air-handling systems serving the building have been designed to provide approximately 15 cfm (0.4 m^3/min) of outside air per person for the maximum predicted occupancy. When occupancy levels are low, carbon dioxide monitoring systems—which ensure that carbon dioxide levels in the building are below 530 ppm by volume—will feed back to a building energy management system and modulate outside air dampers, reducing ventilation and, in turn, energy consumption.

The library will also conserve energy by means of an atrium economizer cycle—a system that draws air from throughout the building to the top of the atrium, where it is vented to the outdoors. Thermal energy from the air will be extracted and recovered by the system and then used to precondition the atrium by cooling or heating its glazed surfaces. The speed of the exhaust fan at the top of the atrium will be controlled by the building management system and will respond to the amount of outside air introduced into the building by individual air-handling units. This fan is also designed to expel air from the atrium as part of the building's system for managing smoke.

The building's cooling plant will consist of two 500 ton (450 Mg), high-efficiency electrical centrifugal chillers that do not use chlorofluorocarbons and that have matching cooling towers and a variable primary chilled water distribution system. The two high-efficiency chillers have a full-load coefficient of performance of 7.229 and an integrated partial-load value of 10.275, exceeding the values of a standard chiller by respectively 39 percent and 94 percent. Cogenerated high-pressure steam provided by the locally based Seattle Steam Company will be used to generate hot water.

To achieve a comprehensive water conservation plan, the library has been designed with low-flow plumbing fixtures, a system for collecting storm water, and a landscape architecture program that emphasizes drought-tolerant plants and trees. A 20,000 gal (76 m^3) concrete retention tank will collect and store water from the building's roof that will be treated and used to irrigate the building's landscape. Any water not used in this way will be allowed to overflow into the municipal storm system. If more water is needed for irrigation, it will be obtained from the tempered condensate produced from the utility steam used to heat water, which is typically discharged into the municipal sewer. Based on weather data and rainfall predictions, the building is expected to retain and use about 1.3 million gal (4,900 m^3) of water annually that would normally come from the municipal system.

With its various energy conservation measures, the Seattle Central Library will exceed the standard LEED building in energy performance by approximately 40 percent. By establishing the priority of a LEED "silver" rating early on, the city of Seattle raised the standard for its new library and gave the design team enough time to integrate strategies for sustainable development into a remarkable architectural vision and a unique structural design. The result is a building where sustainability and design are inextricably linked and where information will know no boundaries. ■

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PROJECT CREDITS

Owner/client: Seattle Public Library

Architecture: A joint venture of the Office for Metropolitan Architecture, Rotterdam, the Netherlands, and LMN Architects, Seattle

Engineering: Arup/Magnusson Klemencic Associates

Arup: Structural, M/E/P, fire protection, information technology, and audiovisual

Magnusson Klemencic Associates: Structural

Landscape architecture: Jones & Jones, Seattle, and Inside/Outside, Seattle

Facade consulting: Dewhurst Macfarlane & Partners, New York City

Facade design/build: Seele GmbH, Munich, Germany

Acoustics: Michael Yantis Associates, Seattle