AN INCLINATION FOR INNOVATION

After 30 Years, Dallas City Hall Is Still an Architectural Triumph and an Engineering Milestone

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Innovative architecture often requires equally innovative engineering and technologies in order to execute it successfully. An outstanding example of this interdependence can be seen in the Dallas City Hall, a landmark building completed in 1977, designed with daring vision by one of the world's leading architectural teams, I.M. Pei and Partners.

The building is a fascinating amalgam, equal parts raw truth and magic. The 560-ft long structure is a cast-in-place monolith of exposed concrete, unabashedly checkered with the imprints of the resin-coated plywood panels used to form it. The long north façade, however, leans forward at a 34-degree angle, each floor 9 ft-4 in. farther into space than the one beneath it, seeming to hover weightlessly despite the obvious massiveness of the structure. Its appearance is often described as "gravity defying."

The architectural aspects of the famous ‘inverted pyramid‘ have been written about at great length. The technology that makes it seem to contravene the laws of nature is an untold story of bold science and engineering. It is an early example of post-tensioning used for large-scale construction, and its innovative post-tensioning system was crucial to executing the building’s unique shape. The building also employed another then-new technology, shrinkage-compensating concrete, to achieve the beauty and "truth" of its concrete.

Fig. 1 - Dallas City hall

Photo courtesy of the City of Dallas, TX

Dallas City Hall, designed by I.M. Pei & Partners in 1966, is a monolith of 60,000 cu yd of buff-colored shrinkage-compensating concrete, plus an additional 24,000 cu yd of portland cement concrete in the foundation. Its dramatic, sloping north facade nonetheless appears to defy gravity. An innovative form of post-tensioning was used to help achieve this seeming weightlessness.

CONCEPT

"You guys are crazy," said Dallas mayor Erik Jonsson to the architects, upon seeing an early model of the building. "People will think it's going to fall over." Theodore Musho, AIA, Pei's lead designer on the project, still remembers the conversation well, because Jonsson's opinion was important. The mayor was closely involved with the project, the prime mover in the drive to build a new city hall and in the selection of the Pei firm to create it.

The project was conceived in the aftermath of the assassination of President John F. Kennedy. Dallas was reeling from the tragedy, grieving and simultaneously under attack from around the world as a "City of Hate." When Jonsson took over as mayor, he made it a priority to reinvent the city's image, and created the "Goals for Dallas" program to accomplish this transformation. One of goals, Design of the City, was summarized by the statement, "We demand a city of beauty and functional fitness that embraces the quality of life for all its people." That was the impetus to build a new city hall to replace the small and outdated structure that had served Dallas since the early 20th century.

Musho relates that a study of the space requirements of city government concluded that a great deal of square footage was needed for the functions of the bureaucracy, but much less was required for the specific activities that interfaced with the public. "Dallas had an outreach mentality, though," recalled Musho in a recent interview. "People still came to City Hall to pay their water bill." Musho and Pei recognized that the building had to welcome the public, so they wanted to concentrate the offices and counters where the public came to conduct its business at ground level. This suggested a small space at the bottom of the building, with increasing floorspace higher up to house the offices that ran the government. As they began to play with sketches, the inverted pyramid profile took shape.

Pei intended the inclined facade to welcome visitors and, on the grander scale, to create a visual dialogue with the growing downtown area to the north of the site. He persuaded the city to acquire an additional six acres in front of the building – two full city blocks – as a plaza and buffer zone for his grand public structure.

The cost of construction and the extra land proved a challenge for the city. It took six years to raise the money, during which time the project was scrapped and then revived by a new mayor, Wes Wise. Funding was eventually supplemented by income from the 1325-car parking garage that was built beneath the plaza.

DESIGN

The Pei firm subscribed to a creed of "honesty of materials." Jonsson described Pei as a purist. "Pei… doesn't like to see a thin coating of marble on the outside that makes you think you're looking at an honest marble building. He wants it solid marble or something of a single material that's homogenous … and won't be a source of worry… for the first hundred years anyway." Jonsson recalled that Pei chose concrete because it was the only thing that the city could afford that met the design criteria.

When Jonsson reacted to the apparent top-heaviness of the building's shape, Pei and Musho created the three cylindrical pillars that appear the hold up the structure. These are, in actuality, stairwells that had originally been concealed within the design, but were brought forward to lend visual support; they do not bear the load of the building.

The cantilevered floors are supported by fourteen large bearing walls, 18 in. thick, arranged in seven pairs. The pairs describe a width of 14 ft, except in instances where they flank the staircase towers. The 11-ft wide areas enclosed by the pairs are used to house mechanical and electrical services. Between the pairs are 65 ft-4 in. spans of office space. The north edges of the bearing walls slope outwards flush with the façade. The south edges terminate in sheer verticals at the interior atrium. The floor-to-floor height is 14 ft-0 in.; 3 ft-8 in. of this height is occupied by a coffered concrete ceiling, raised floor deck, and integral air-duct system.

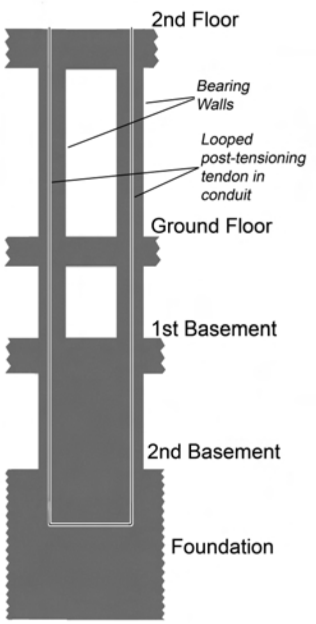

Fig. 2 – Looped tendons in the bearing walls

Illustration by Steven H. Miller. Used courtesy of CTS Cement Mfg.

The pairs of bearing walls were vertically post-tensioned in tandem. Tendons ran down one wall, looped through the foundation under the space between the walls, and ran up the other wall. The illustration shows the post-tensioning at the 2nd floor as a typical example; a separate set of tendons were tensioned at each floor. In the above-ground levels, the space between the walls is used for access to utility systems. Below ground, there is no separation, but a 14-ft thickness of solid concrete. This mass concrete was subject to high heat-buildup during the early stages of curing.

The task of engineering the daring design was given to Jack Rosenlund, P.E. of the Dallas firm of Terry-Rosenlund & Associates. Rosenlund brought in additional engineering assistance from Weisskopf and Pickford, New York.

The structural strategy was an innovative implementation of vertical and horizontal post-tensioning. The bearing walls are post-tensioned vertically through the portion directly over the wall's narrow footprint. Bonded post-tensioning was used, in which tendons are fed through steel ducts and then grouted in place after stressing. The ducts ran down one wall of each pair, into the foundation, looped across the bottom of the 14-ft gap and came up the other wall of the pair. Thus, each tendon applied compressive force to both walls of the pair (see Fig. 2). Each floor had its own separate set of tendons. As the building rose floor by floor, tendons were fed through the ducts, anchored in one wall and stressed from the other.

The horizontal post-tensioning ran from the front of the sloped façade, where the tendons were anchored, back to the edge of the interior atrium (see Fig. 3). Openings for doorways penetrating the bearing walls were limited to 6 ft-8 in. in height, leaving more than 7 feet of solid wall height at each floor for post-tensioning.

The horizontal tendons carry the over-turning force of the cantilever back to the vertical tendons, which then transfer it down to the foundation. The foundation and basement levels are considerably wider than the apparent footprint of the structure, extending out beneath the inclined facade. The cantilevered roof is 200 ft wide, the ground floor is 126 ft wide, and the basement 230 ft wide. The footing beneath the second basement is also post-tensioned, with a force of 4 million pounds.

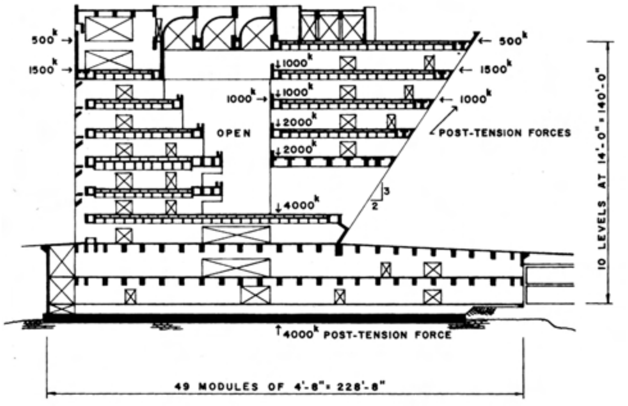

Fig. 3 – Building wall elevation showing cantilever construction

Illustration courtesy of the American Concrete Institute

The floors along the north side of the building cantilever outwards, each extending 9 ft-4 in. further than the one below, forming a 34-degree angle inclined façade. The basements and footings actually extend even further north than the projected roofline.

The interior atrium is 96 ft of unbroken height. Across the top, 14-ft high box-beams tie the sloping front structure to the more orthodox shape of the rear half of the building, providing balance and additional stability.

Throughout the building, post-tensioned concrete coffered ceilings span the 65 ft-4 in. distance between bearing walls. The ceilings are three feet deep and configured in 4 ft-8 in. squares. Above the ceilings are 8 in. high voids that function as integral HVAC ducts. Cast concrete curbs on the top side of the ceiling coffers support the floor above.

MATERIAL

Since concrete was both the primary structural and finish material, close attention was paid to every aspect of its mix and placement. "We had learned more every time we did a concrete building," remembered Ted Amberg, AIA, in a recent interview. Amberg was an Associate Partner of the Pei firm and ran the company's Dallas office during the construction of the project. "In Dallas City Hall, the use of concrete and care of concrete was stretched to its limit. To build formwork and place concrete that would let the structure speak for itself, let structure speak to the architecture, that was very satisfying."

Pei wanted the building to feel like an organic product of the region. He felt this would be achieved by using a buff-colored concrete that resembled the local earth tones.

"Color of the concrete was *the* issue," recalls Musho. "You can't put a block of concrete that big on the Earth without doing it in the right color. That buff color was the rose for the lady."

Another important issue, both aesthetically and structurally, was to minimize shrinkage cracking in the concrete. The design team toured the region observing large cast-in-place buildings, paying attention to cracking characteristics. Then, different aggregates and mix designs were tested, casting more than 50 sample panels, but none were entirely satisfactory.

Rosenlund had some previous experience with shrinkage-compensating concrete and believed it would provide the needed control of drying-shrinkage cracking and reduce loss of post-tensioning force due to drying shrinkage. Local cement producer Texas Industries was a licensee of the patent for Type K cement used to make shrinkage-compensating concrete. They had already produced buff-colored portland cement, made by oxidizing the clinker in the kiln. For this project, they developed a buff-colored Type K cement. Amberg recalls that the Pei firm felt it was not "buff enough" and induced the producer to enhance the color by reprocessing the clinker with an extra burn in the kiln.

Consistency of color was the focus of a great deal of effort, because concrete color is affected by many variables including the batch-to-batch variations of cement and aggregate properties, placement temperature, water-to-cementitious-material (w/cm) ratio, and curing conditions. Texas Industries was also ready-mix supplier for the project, and made a commitment to keep the concrete consistent over the period of 18 months needed to finish the building.

"If the project were being done today," explains Louis Valenzuela, Type K Product Manager for CTS Cement Mfg, the current producer of Type K cement, "the buff color of the shrinkage-compensating concrete would be created by adding integral pigments to the mix at the batch plant, a technique that gives a wide range of available colors."

ERECTION

The formalism of design is echoed in the regulated way it was constructed. The formwork, for instance, was not simply specified: the orientation of every sheet of plywood was designed with an eye towards the final pattern the wall would present.

Pei's firm used repetition of structural elements as a way of making a demanding design more affordable. The coffered ceilings were formed on fiberglass domes that could be reused numerous times without deterioration. The walls were originally specified as board-formed, but this was changed to a phenolic resin-coated plywood that was extremely dense and smooth, and also extensively reusable. The 4 ft x 8 ft sheets were held in form guides to keep alignment uniform and joints tight. Musho comments that the surface texture produced by those forms was extremely smooth.

The temperature extremes in Dallas over the course of a year posed a challenge to concrete color-consistency. "Aggregates were stock-piled in the blistering Texas sun," recalls Amberg. "and you could fry a chicken on them." There was also concern that built-up heat of hydration within the massive concrete walls would cause cracking. A placement-temperature of 85° F was specified. According to Bob May, who was then Texas Industries' Vice President of Concrete, extraordinary measures were required to meet that specification, including heating the aggregate in winter, and cooling the mix water and aggregate in summer using liquid nitrogen.

The Pei firm insisted on building a small mock-up before embarking on construction. This was a regular practice of the company, intended to allow all the workers to become familiar with the specific practices demanded by the project, and how they all functioned together. Pei would then request that the same crews perform the same tasks throughout construction. The mock-up was a freestanding structure 14 ft-0 in. wide, 23 ft-4 in. long and one story in height, comprising three typical sloped windows and nine ceiling coffers. It was complete with lighting fixtures, so that as many trades as possible could see how their work fit into the whole. It also gave the architect an opportunity to work out methods with the contractor. It cost $100,000, just 0.3% of the total cost of the building, which Amberg considers well worth the price.

Crack-control was a priority. Close attention was paid when the basement levels of the bearing walls were placed. Since that area would not ultimately be seen by the public, it was considered a good test-location to observe the performance of the shrinkage-compensating concrete and work out any final adjustments in its mix. Concrete was much more massive below grade level, however: it was solid across the 14-ft width of the wall-pairs. Small cracking was noted, and adjustments were made in mix design, placement and curing techniques. Valenzuela explains that proper curing is critical with shrinkage-compensating concrete: it must be kept wet for seven days after placement, the expansion-phase of the material.

There is evidence that the cracking in the basement was caused by heat build-up creating a level of stress that could not be compensated. Below ground, the walls are not separated by a gap; they are 14-ft thick masses of concrete, which were subject to high buildup of the heat generated by the chemical reaction of cement hydration. Thermocouples placed in a wall on a hot day showed a temperature differential between the concrete interior and exterior of 50° F (100° F on the wall surface, 150° F in the concrete interior). Professor Milos Polivka, an expert on expansive concrete from the University of California, was

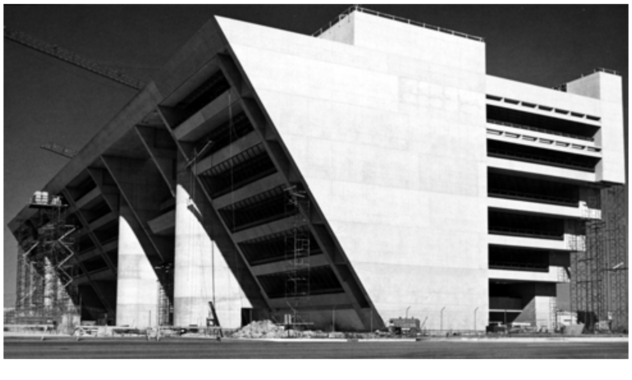

Fig. 4 – Dallas City hall during final stages of construction

Photo courtesy of the City of Dallas, TX

The building is supported on 14 slender bearing walls structured in pairs, which are post-tensioned both vertically and horizontally. Horizontal post-tensioning transfers the overturning force of the cantilever to the interior edge of the wall. Vertical post-tensioning on the interior end transfers it to the foundation. An unusual system of looped vertical tendons joins the two walls of each pair.

consulted. He calculated the internal stress as 175 psi, significantly higher than could be counteracted by the shrinkage-compensating cement available at that time. Advances in shrinkage-compensating technology now make it practical to compensate for tensile forces of 175 psi or more. Computing the cumulative width of the cracks, Polivka found that they were half as much as could be expected with conventional concrete, and concluded that the shrinkage-compensating concrete was performing properly.

Polivka's conclusion was proved correct as construction progressed. In the above-ground levels, where the walls are not as thick, there was little or no cracking. The crack control effect was judged satisfactory by Rosenlund, and even satisfied the notoriously exacting standards of the architect. Thirty-five years later, the above-ground levels of the building remain largely crack-free.

At the point where the bearing walls met grade level, there was a dense forest of steel reinforcement bar to help transfer load to the extending "foot" of the foundation. Concrete placement was especially tricky there, and even with careful vibration, consistent distribution was difficult. Eventually, superplasticizer was added to make the concrete flow more readily into the tangle of steel.

Forms were kept in place an unusually long time, according to Amberg, and were covered with wet blankets to cure the shrinkage-compensating concrete. The concrete was specified as 4000 psi compressive strength, with post-tensioning stress to be applied when the concrete achieved 75% of its target strength, or 3000 psi. Shrinkage-compensating concrete is documented to achieve approximately 20-25% greater compressive strength than portland cement concrete of similar mix design, so 3000 psi was reached in as little as four days in parts of the City Hall, and in no case longer than six days.

Construction took five years. The building was dedicated with great ceremony in 1977.

THE TESTIMONY OF TIME

More than 30 years after construction was completed, the building stands as proof of the structural soundness of its design. Methodical control and consistent practices paid off with highly uniform color and texture of the structure's finish.

Contemporary architectural criticism of the building was generally positive, and inspired terms like "monument" to describe it. It had its intended effect on the city, beginning a series of important structures in Dallas that brought a sense of pride and dignity.

Fig. 5 – Construction site

Photo courtesy of the City of Dallas, TX

As the building (at the far side of the plaza) rose, post-tensioning was applied to vertical tendons, floor by floor, to support the increasing overturning force of the cantilevered façade.

Fig. 6 – View of the central interior gallery with the post-tensioned bearing walls that support the North Facade (on right)

Photo courtesy of the City of Dallas, TX

The pairs of post-tensioned bearing walls are architecturally expressed as single massive columns at the interior atrium. (on the right in the photo)

Fig. 7 – View of the cantilevered box beam

Photo courtesy of the City of Dallas, TX

14-ft high box-beams traverse the atrium, tying the north side of the building to the south side and helping to balance the load of the cantilever. Imprints of the formwork can be clearly seen in this photo, a carefully designed mosaic pattern of large rectangles.

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