2021 AWARD OF TPROJECT HE YEAR: THE PHILLIP AND PATRICIA FROST MUSEUM OF SCIENCE'S GULF STREAM AQUARIUM TANK

POST-TENSIONING INSTITUTE ®

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2021 PROJECT OF THE YEAR: THE PHILLIP AND PATRICIA FROST MUSEUM OF SCIENCE'S GULF STREAM AQUARIUM TANK

PROJECT OVERVIEW

In 2011, the Phillip and Patricia Frost Museum of Science embarked on an ambitious relocation and expansion project at Miami's downtown waterfront that opened to the public in May 2017. The new energy-efficient home for the museum features an aquarium and planetarium with state-of-the-art interactive exhibits. The award-winning museum offers visitors exhibits centered on science, technology, engineering, and math while emphasizing South Florida's culture and ecosystem.

One of the highlights of this $305 million project includes a one-of-a-kind 120 ft wide x 30 ft deep (37 m wide x 9 m) 600,000 gallon (2.3 million L) seawater aquarium with a cornerless design that allows open-water marine species to swim continuously as they would in the actual Gulf Stream (Fig. 1). This structure is at the heart of the site, and thanks to its innovative elevated conical-shaped design that includes a 30 ft (9 m) diameter acrylic oculus at the bottom of the basin, museum visitors are amazed by the view of Gulf Stream marine life from below. The extraordinary three-story tank design offers a variety of views for the visitor from shoreline to greater depths of the aquatic ecosystem while enhancing the museum's interactive aquarium experience. The unusual tank has the appearance of a tilted martini glass suspended above the museum's viewing gallery. Visitors can view marine life through large round acrylic viewing windows built into the walls of the tank (Fig. 2).

The tank was constructed with post-tensioned concrete, as opposed to structural steel, to dampen the interference with the sharks' sensory system. This innovative engineering design incorporates bonded post-tensioning (PT) reinforcement oriented in three directions throughout the tank walls with no construction joints.

Aside from meeting all code requirements in ACI 318 and ACI 350, it was important to the design team to have concrete that was in a state of compression when subjected to the water load. In areas of high demand, extreme fiber

Fig. 1—Top view of Gulf Stream Aquarium.

stresses were not allowed to exceed the cracking limit. Post-tensioned concrete provided an elegant solution for reducing concrete tensile stresses throughout all portions of the tank. The tank consists of 1200 yd^3 (917 m^3) of concrete and was placed monolithically in 25 hours.

DESIGN CRITERIA AND LOADING

Kline Engineering & Consulting (Kline) was engaged as the specialty structural engineer responsible for design of the tank. DDA Engineers, P.A., as engineer of record for the project, provided a schematic design for the tank and delegated the final design to the contractor. The construction team included Skanska USA as general contractor; Baker Concrete Construction, Inc. as concrete subcontractor; and Structural Technologies as the PT supplier/installer.

The design considerations for the tank are summarized as follows:

- Provide a sleek and efficient tank wall design that meets the aesthetic requirements prescribed by the architect.
- Develop the design to accommodate functional features such as the adjoining acclimation tank and circular acrylic oculi that allow for viewing of marine life within the tank.
- Design the tank wall to minimize the potential for cracking and eliminate construction joints.
- Design the tank to meet ACI 318 and ACI 350 requirements for strength and serviceability.

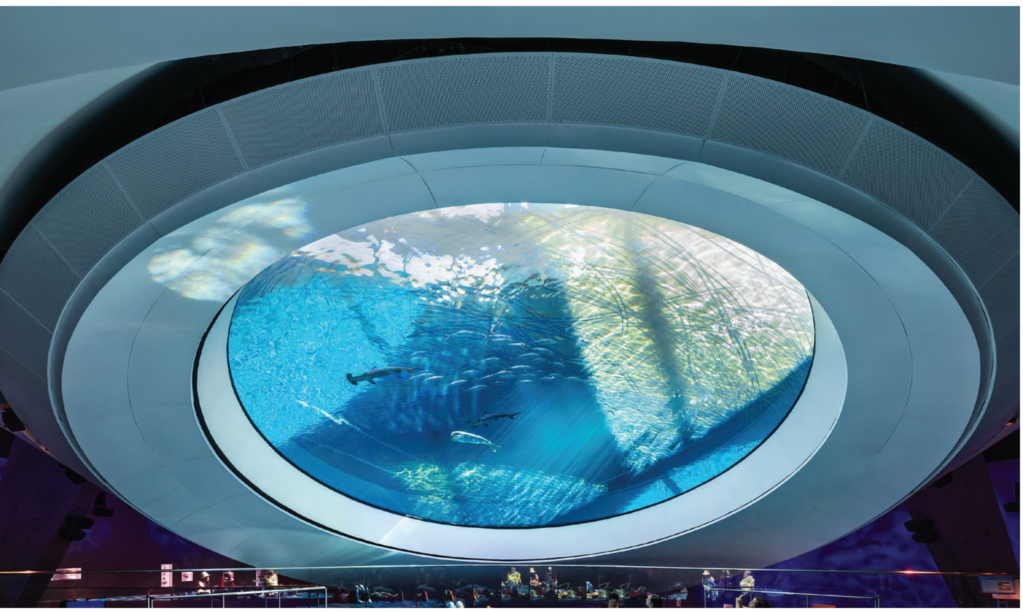


Fig. 2—30 ft (9 m) diameter acrylic viewing oculus at bottom of tank wall.

Tank loading consisted of self-weight as dead load, and seawater at a density of 65 lb/ft^3 (0.10 kg/m^3) as live load. It was decided to consider the water pressure as a live load as opposed to a fluid load to slightly increase the factor of safety for strength design consideration. Figure 3 illustrates how water pressure was applied in five discrete depth zones within the finite element model.

The tank is supported by a ring beam, which is supported on a series of columns (Fig. 4). These supports, when combined with the tremendous water pressure from within the tank, create complex load effects in the tank wall including flexural stresses and hoop stresses. Unlike a conventional tank design where the walls are designed for horizontal pressure, the walls of this tank had to be designed to resist lateral pressure and the vertical load of 4.5 million pounds (2 million kg) of saltwater within the tank. The acrylic viewing windows (or oculi) interrupt the

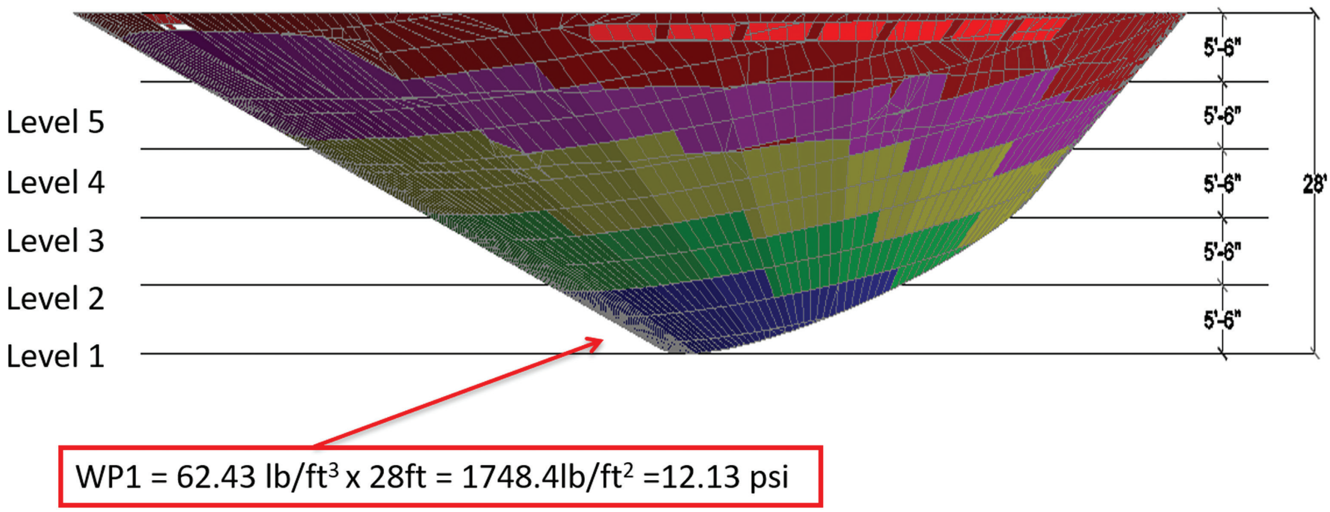


Fig. 3—Water pressure at discrete depth zones.

continuity in the tank walls. All of these factors resulted in extraordinary structural complexity.

To reduce the potential for cracking in the tank wall, Kline developed the following design criteria:

- Design the prestress for a residual average precompression of 200 psi under service loading.
- Design the prestress to achieve maximum extreme fiber tensile stresses of $6\sqrt{f_c'}$ under service loading.
- Provide supplemental non-prestressed reinforcing steel to satisfy strength requirements.

DESIGN DESCRIPTION

The tank walls are 28 in. (710 mm) thick, supported by a single 56 in. (1420 mm) deep post-tensioned ring beam. The ring beam is supported by six cast-in-place concrete columns. The design team considered various tendon layout options for the tank walls, including a radial/circumferential layout and a two-way distributed layout. Due to the complex geometric shape with discontinuities created by the acrylic panels, the engineer selected a unique tri-directional tendon layout (Fig. 5). This layout was selected because it provided the most elegant solution for evenly distributing two-way prestressing forces throughout the tank wall and allowing sweeping of the tendons between features such as skimmers, panels, and openings.

An encapsulated bonded PT system was used due to the high prestressing force requirements and to ensure robust corrosion protection for the prestressing steel. Tank wall PT consisted of 45 tendons with twelve 0.6 in. (15 mm) diameter strands within corrugated high-density polyethylene (HDPE) ducts with VSL ECI6-12 anchorages. Acclimation tank floor PT consisted of 19 tendons with four 0.6 in. (15 mm) diameter strands within corrugated HDPE oval ducts with VSL VSLAB6-4 anchorages. Tank wall tendons are chaired at wall middepth in three layers. The specified 28-day concrete strength was 5000 psi (34 MPa), and the PT was stressed when field-cured concrete breaks exceeded 3500 psi (24 MPa). All tendons were stressed in two stages—first, all tendons were brought up to 50 percent of the jacking force. Then all tendons were stressed to 100 percent of the jacking force. In each stage, the interior layer of tendons was stressed prior to the two outer layers.

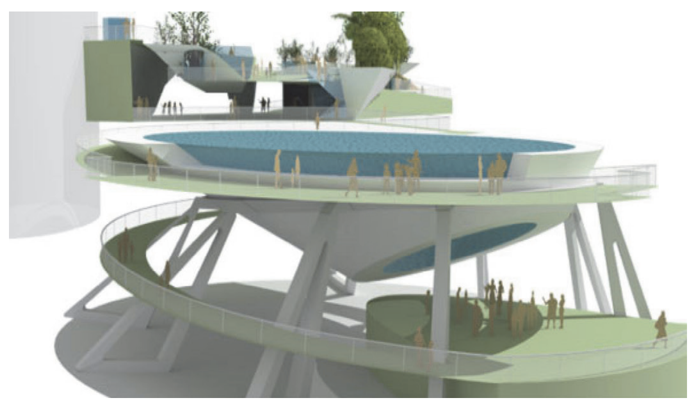


Fig. 4—Tank suspended by series of columns and ring beam.

DESIGN AND CONSTRUCTION CHALLENGES

The complex geometry of the tank precluded the use of off-the-shelf PT design software. The engineer chose to use SAP 2000 to model the tank using the finite element method. SAP 2000 allows the user to input PT tendons, but the software had limited capability when inputting tendon elements. To import the tendons into the model, they were first mapped to the inside face of the tank wall as individual short tendons at each wall segment. Then, the user had to assign profile points to each tendon segment. The average number of sections required to model a tendon from anchor to anchor was approximately 75. Although this was tedious work, it ultimately proved to accurately model the prestress forces in the tank wall.

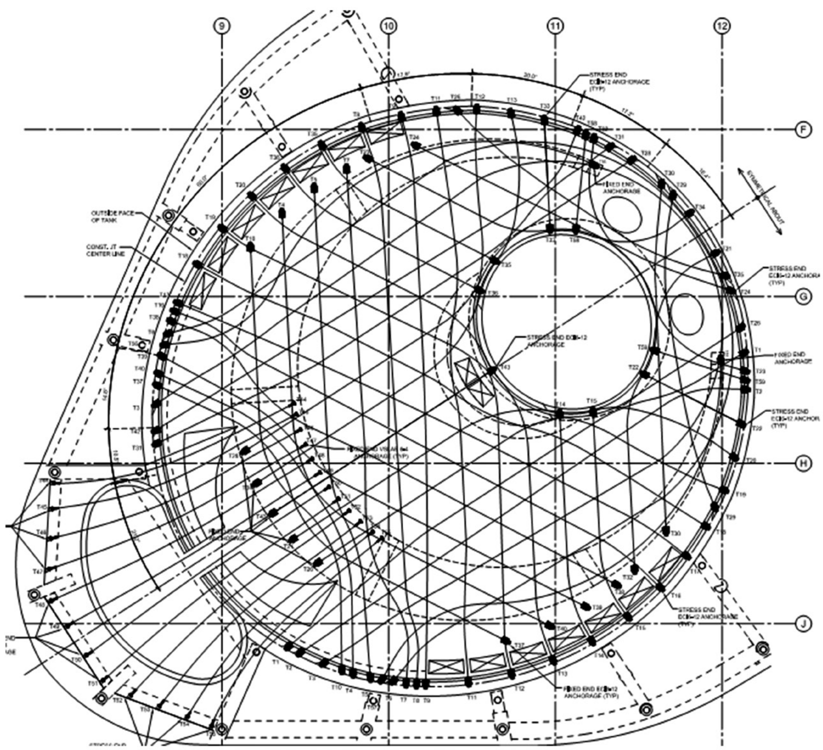


Fig. 5—Tri-directional PT tendon layout in tank wall.

Fig. 6—Stress end anchorages and formwork.

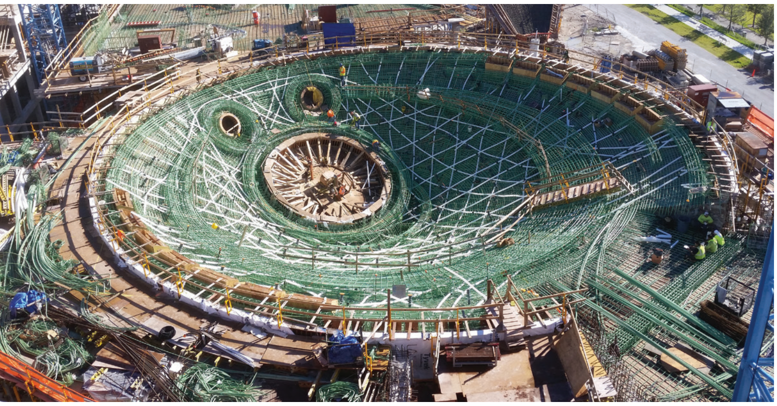
Construction of the blockout forms supporting the stressing end PT anchorages was a challenge. Imagine a curved edge of wall and almost every PT tendon anchoring at the wall edge with different vertical and horizontal angles. Construction of this formwork would have been extremely challenging. To simplify construction of the blockout forms, the engineer provided the contractor with blockout drawings and geometry for every unique anchorage condition using the 3-D tank model extracted from SAP 2000 (Fig. 6).

A high level of coordination for tendons and plumbing lines and sleeves was required to assure no conflicts existed. An overlay was developed using AutoCAD 3D, which allowed the design/construction team to make adjustments prior to construction.

Concrete placement was also a challenge due to the complex geometry. Most of the tank walls were formed using single-sided forms. However, on one side of the tank, the walls are at a steep incline of over 60 degrees from horizontal. This required the use of double-sided forms at this portion of the tank. Approximately 1200 yd^3 (917 m^3) of low-slump concrete was placed in a single monolithic pour over a duration of 25 hours (Fig. 7).

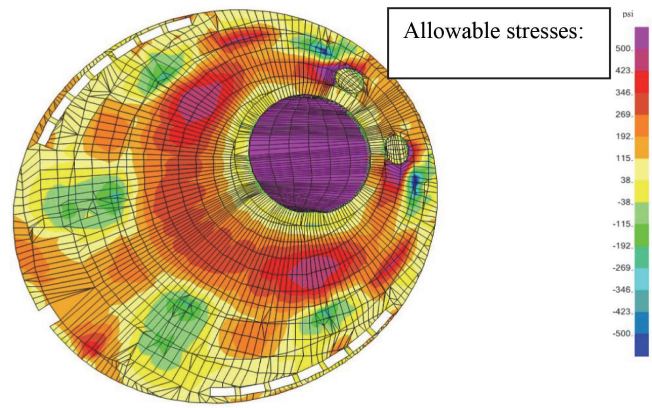
STRUCTURAL ANALYSIS

The SAP 2000 FE model was used to analyze the tank walls under

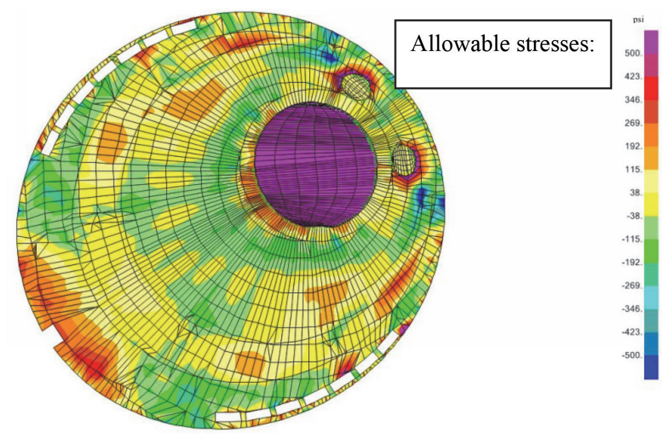


a. PT duct and reinforcing bar placement.

b. Concrete placement using single and double-sided wall forms.
Fig. 7—Tank under construction.



a. Service load combination with DL + LL.



b. Service load combination with DL + LL + PT.
Fig. 8—Bottom fiber concrete stress diagram – SAP 2000.

various service and strength load combinations. To illustrate how PT enhanced the service load performance of the tank, Fig. 8 provides a comparison of the bottom concrete stresses under full dead and live load with and without PT. Without PT, large areas of the tank walls are in tension, and some areas have stresses that exceed $6\sqrt{f_c'}$. When PT is added into the service load combination, bottom stresses are significantly reduced, and no areas have stresses above the $6\sqrt{f_c'}$ limit. Although not shown herein, top stresses are also significantly reduced when PT is included in the load combination.

CONCLUSIONS

Design and construction of the Phillip and Patricia Frost Museum of Science's Gulf Stream Tank was a collaborative effort between all parties including Baker Concrete, Structural Technologies, Kline, and the EOR. The design team delivered an efficient yet robust design that minimized project costs and complexity. The tank combines elements of form and function in a way that can only be realized using post-tensioned concrete. The Gulf Stream Tank is an extraordinary example of how post-tensioned concrete enhances the human experience and improves the built environment.

Owner: The Phillip and Patricia Frost Museum of Science
Location: Miami, FL
Architect: Grimshaw Architects
Executive Architect: Rodriguez and Quiroga Architects Chartered
Engineer of Record for the Museum: DDA Engineers, P.A.
Structural Engineer: Kline Engineering & Consulting, LLC
General Contractor: Skanska
Concrete subcontractor: Baker Concrete Construction, Inc.
PT Supplier: Structural Technologies, Inc.
Other Contributors: Don Kline – article author