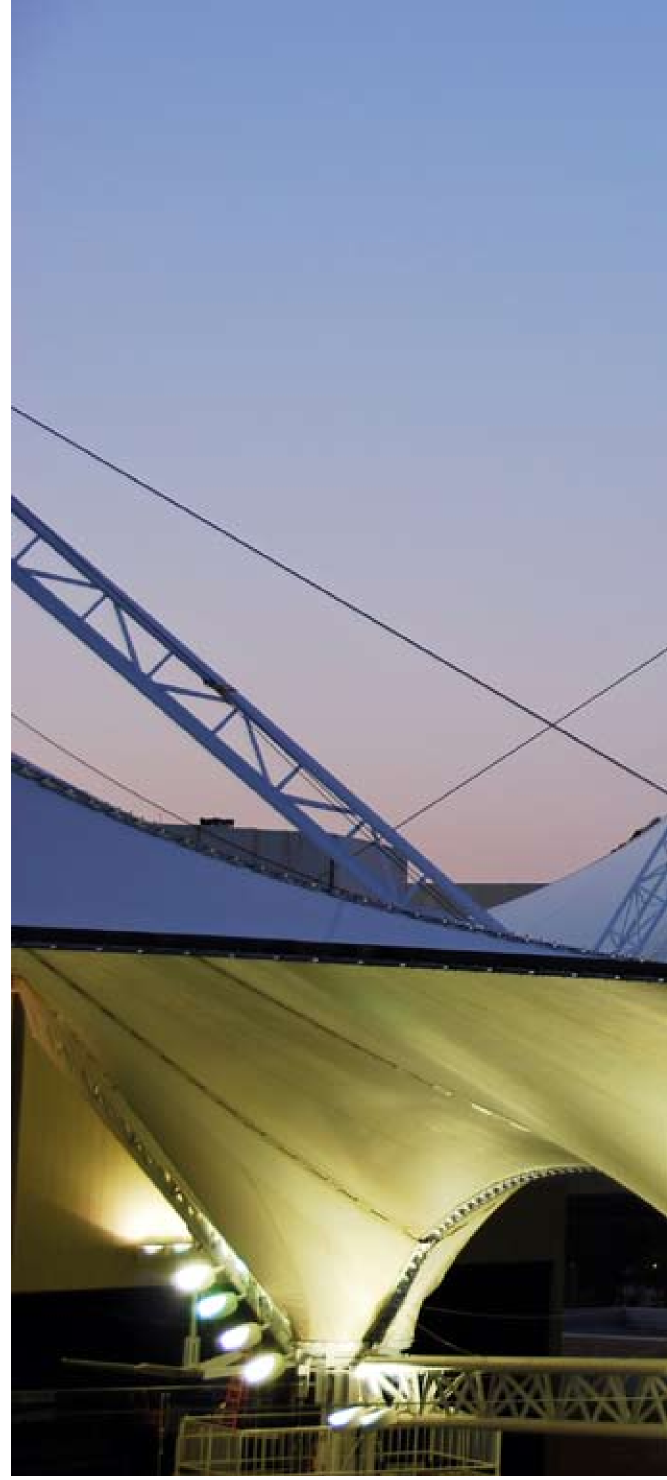
photos this page courtesy of Jeff Young

On September 13, 2008, winds and debris from Hurricane Ike shredded the 20-year-old fabric roof of the Cynthia Woods Mitchell Pavilion north of Houston. The supporting steel survived intact.



The flexibility of structural steel and tensile fabric combine to allow the rapid replacement and expansion of a landmark amphitheater.

Just 7½ months after Hurricane Ike came to town, the storm-ravaged Cynthia Woods Mitchell Pavilion was once again ready for opening night but with more than double its original capacity.

**WHEN HURRICANE IKE** ravaged the Texas Gulf Coast on September 13, 2008, it left more than 3 million households without power for up to several weeks. As the storm moved northward out of the Houston area, it continued to carve a path of destruction. When Ike finally cleared the area, after almost 15 hours, it left the fabric roof of the Cynthia Woods Mitchell Pavilion in shreds. Thanks to the dedication of a multi-disciplinary design and construction team, the venue was reconstructed twice as large as—and more hurricane-resistant than before—after only a five-month reconstruction and expansion project. This compressed timeframe enabled the Pavilion to launch its 2009 season on time with the scheduled May 1 opening concert by the Dave Mathews Band.

For the three years prior to the storm, the 20-year-old Cynthia Woods Mitchell Pavilion had been ranked by *Pollstar* magazine as one of the top six amphitheaters in the world. Located 27 miles north of downtown Houston in The Woodlands, Texas, the outdoor venue has hosted a steady stream of events that range in style from the Houston Symphony to Kenny Chesney and Aerosmith.

More than $3 million in damage resulted from a combination of Ike's strong winds and windborne debris. Although the durable steel substructure survived intact, the venue's fabric roof was irreparably damaged. The Pavilion's board of directors took advantage of the opportunity to expand the structure during the reconstruction process by more than doubling the facility's covered seating capacity from 2,479 to 6,387 seats. After the $9.5 million renovation and expansion, the total capacity of the venue, including lawn seats, has grown to 16,040.

# Steeling the Show

BY TAREK AYOUBI, P.E. AND RACHEL CALAFELL

Installation of the 13 fabric panels was completed over a 51-day period ending less than a week before opening night. Total weight of the 82,000 sq. ft of fabric: 25,000 lb.

## The Steel Skeleton

The requirement of creating a large open space using members with long spans made structural steel an ideal material for both the original and expanded structures. Laced steel struts and masts were used to ensure the feeling of openness under the canopy, to minimize impact on the sightlines, and for acoustical purposes. In addition, the use of structural steel improved constructability of the project, as members were fabricated in the shop and lifted into place in the field using a tower crane. With the complex geometry of the structure, the construction process was like putting together the pieces of a puzzle—everything had to fit together perfectly.

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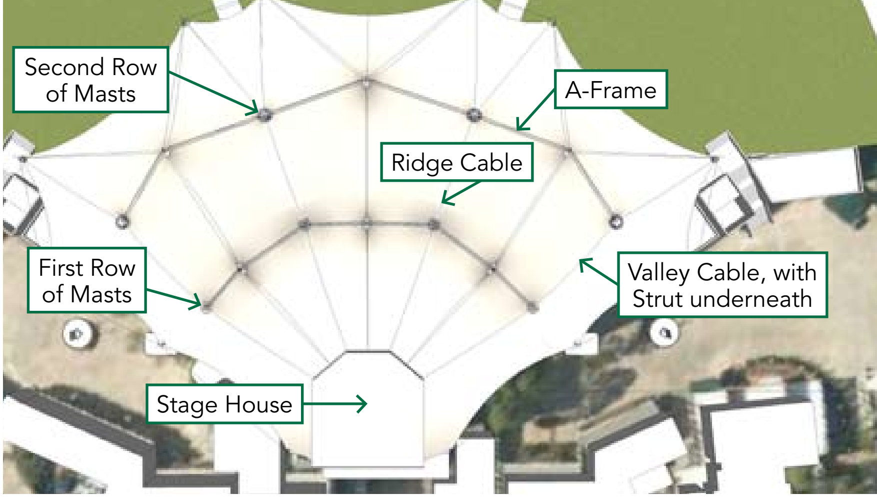
At one point, as many as 13 personnel lifts were being used simultaneously to erect the steel and cable framework as quickly as possible.




This plan view of the expanded structure, with the structural components identified, is from the Sketchup model.

The structure's gravity system involves compressive loads being transferred to spread footings through A-frames, struts, and vertical masts, while tensile loads are transmitted through a network of cables. Lateral loads are transferred through the compression and tension members to the stage house, where they are resisted by braced frames, and through diagonal cables anchored to new foundations. ASTM A586 structural strand cables of ⅝- to 1⅝-in. diameter with Type A inner and outer coating and breaking strengths of 48,000 to 324,000 lb were used throughout the structure.

The original structure consisted of one row of A-frames and masts, and a series of struts and cables. The expansion of the roof area required adding a second row of A-frames and masts with connecting struts and cables, while using as much of the existing structure as possible.

The vertical masts are laced members with a square cross-section comprising four ASTM A53 vertical pipe members and smaller pipe members acting as lacing between the vertical pipes. The four existing masts, which consist of four 6-in. diameter ASTM A53 vertical pipes in a 2 ft by 2 ft square cross section, were reused. The increased height, wind pressures, and tributary area of the roof resulted in larger sizes and cross sections for the new masts supporting the new, outer row of A-frames. The two interior masts were constructed using four 8-in. diameter pipes in a 2 ft by 2 ft cross section. The two exterior masts use four 10-in. diameter pipes in a 3 ft by 3 ft cross section.

Membrane structures achieve load carrying capacity in various directions through curvature, and saddle surfaces are formed by introducing supports that are not in a single plane. The A-frames, which are trussed elements between the masts, create external supports for

Walter P Moore

The masts consist of four ASTM A53 structural steel pipes ranging from 6-in. to 10-in. diameter arranged in a square cross section. The connecting struts and A-frame members use three pipes, 3-in. to 6-in. diameter, in a triangular cross section.

saddle surfaces of the fabric roof. The struts are nearly horizontal laced members in compression that offer support points at the perimeter edge of the structure and transfer load to the braced frames located at the stage house. All three of the existing A-frames and several of the existing struts were reused in the expanded structure.

The new A-frames, spanning up to a projected horizontal length of 130 ft, were constructed using 3- to 6-in.-diameter ASTM A53 pipes as continuous trunks, laced together with 1½-in.-diameter ASTM A53 pipes in a 2 ft by 2 ft triangular cross section. The new struts, which span up to 85 ft, have a 2-ft to 2-ft 6-in. wide by 2-ft to 3-ft deep triangular cross section, with 6- to 8-in.-diameter ASTM A53 trunk pipes and 2- to 3-in.-diameter ASTM A53 pipe lacing.

The stage house was extensively retrofitted to allow it to provide much of the lateral load resistance for the expanded structure, as it did for the original structure. The retrofits involved adding steel side plates to many wide flange members, adding bracing members, and strengthening several of the existing steel connections. In addition, existing footings were exposed and retrofitted by expanding their size and adding anchor rods to resolve higher uplift and lateral forces. The stage house retrofits were redesigned as needed during the construction process as existing conditions were discovered that differed from the 1989 design drawings.

### The Fabric Membrane

Horst Berger, architect of both the original and the expanded roof structures, designed the new canopy to retain the same signature look as the original structure. Because of its ability to both withstand design wind loads and transmit light without the heat gain of traditional glazing, Sheerfill II fabric produced by Saint-Gobain Performance Plastics was used in both the original and expanded structures. The fabric is a composite material made of fiberglass and polytetrafluoroethylene (PTFE) with a Teflon coating. It is designed to maintain its original prestressed shape throughout its typical lifespan of 25 or more years.

The expanded roof of the Pavilion incorporates the use of 13 panels of fabric totaling an area of approximately 82,000 sq. ft, compared to the original 30,000 sq. ft. The fabric panels weigh approximately 25,000 lb in total.

Several aspects of the expanded fabric structure make it more resilient to hurricane wind loads now than when it was first constructed. These features include reinforcing the fabric with surface cables to act as rip stops and providing triangular fabric panels at the outer edges to avoid terminating ridge cables in edge catenary cables. The expanded structure also was designed for higher wind loads, including hurricane force winds of up to 110 mph, with a gust of three seconds.

### The Effect of Fast-Track

On November 6, 2008, Walter P Moore structural engineers first visited the site to assess the structure's damage resulting from Hurricane Ike. Only 164 days remained before the grand re-opening concert when the first meeting of the design team was held on November 18. To succeed, the project team had to compress the entire design and construction schedule into those precious 164 days, demanding that some tasks often taking months or weeks be completed in days. Determining the effect of high winds was one such challenge.

Although a wind tunnel analysis was performed for the original structure, another was required to accurately predict wind loads on the new structure due to geometrical differences between the structures. However, because the fabric panels, structural steel, and cables had to be ordered before the full wind tunnel analysis could be completed, the design was carried out on the basis of preliminary desktop studies. The wind loads resulting from the preliminary studies performed by the wind engineering consultant were later confirmed by the final wind tunnel test results and required only modest changes.

The construction drawings were issued in several packages to speed up the project delivery schedule. After receiving the fabric interface geometry and details from the fabric engineer, the structural engineer issued foundation, steel trunk, cable, connection, and stage house retrofit drawings in separate packages to allow timely procurement of long-lead materials while permitting construction to proceed at full-speed as design was being completed.

A specialty membrane and cable-net program was used for analysis of the fabric roof, with a separate program employed to pattern the fabric for installation purposes. SAP 2000 was used to design the structural members. Although AutoCAD 2009 was used for documentation, the creation of a 3D model of the steel structure and fabric using Google Sketchup was useful in detailing the complex geometry and facilitating discussions between consultants. The model was particularly helpful in determining potential interferences between the fabric and the steel structure, especially at the interface between the fabric and the A-frames.

Construction began on December 1 with seven-day work weeks, although crews later worked around the clock. As many as 13 lifts were used on the site at one time to erect 75 tons of steel in three weeks. During the first week of February, 2009, the reused masts, pipe columns, and A-frames for the first row were installed, along with new struts and tension cables. Over the next two weeks, the second row members were erected. Retrofitting the stage house was performed after the steel structure was in place.

Installation and tensioning of the fabric occurred during a 51-day period ending April 26, a mere five days before the opening concert. This left just enough time for the seating, handrails, landscaping, and final painting to be completed.

The Cynthia Woods Mitchell Pavilion opened on time for the sold-out May 1 concert and its 20th season. It is back, bigger and better than ever—and the structure indeed "steels" the show. MSC

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**Steel Detailer**
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**Fabric Patterning & Installation**
FabriTec Structures, a brand of USA Shade & Fabric Structures, Inc., Dallas

**Wind Tunnel Consultant**
Rowan Williams Davies & Irwin, Inc., Ontario, Canada