Mast Swap

By Paul A. Gossen, P.E., F. ASCE and David M. Campbell, P.E., M. ASCE

In 1982, Tennessee hosted the World's Fair (EXPO '82) in Knoxville. As is customary, the host state built a pavilion designed to represent itself. Unlike most World's Fair structures that are demolished after the fair, this pavilion was to remain as a legacy facility. The structure was conceived as an open-air theater/concert venue, with a stage and seating, covered by a tensile fabric roof. The facility remains in use today, surrounded by a man-made lake in World's Fair Park, adjacent to the "sun sphere," another legacy structure from EXPO '82.

After 25 years, the masts of the Tennessee Pavilion showed signs of deterioration and structural deficiencies. Replacement of the masts, while keeping the fabric membrane in place, created a challenge for the engineer and erector.

The Tennessee Pavillion.

Structure Description

The dominant feature of the pavilion, or Tennessee Amphitheatre as it is known, is a fabric membrane canopy roof. This was unique in 1982 and remains so today. The main canopy consists of a twin cone tent-like tensile structure spanning 220 feet (67m) over the amphitheater seating, covering an area of 50,000 sf (4,645 m^2). A separate arch supported tensile structure covers the stage. Each cone section of the main canopy is supported by two masts that form an "A-frame." These frames straddle the seating, allowing an unobstructed view to the stage. A tie-back cable, anchored behind the seating area, holds these masts in place and prevents them from tipping. The configuration essentially forms a tripod with two compression elements: the masts, and a tension element: the tie-back cable. The masts are tri-chord trusses composed of pipe-chord sections with angle sections used for diagonals.

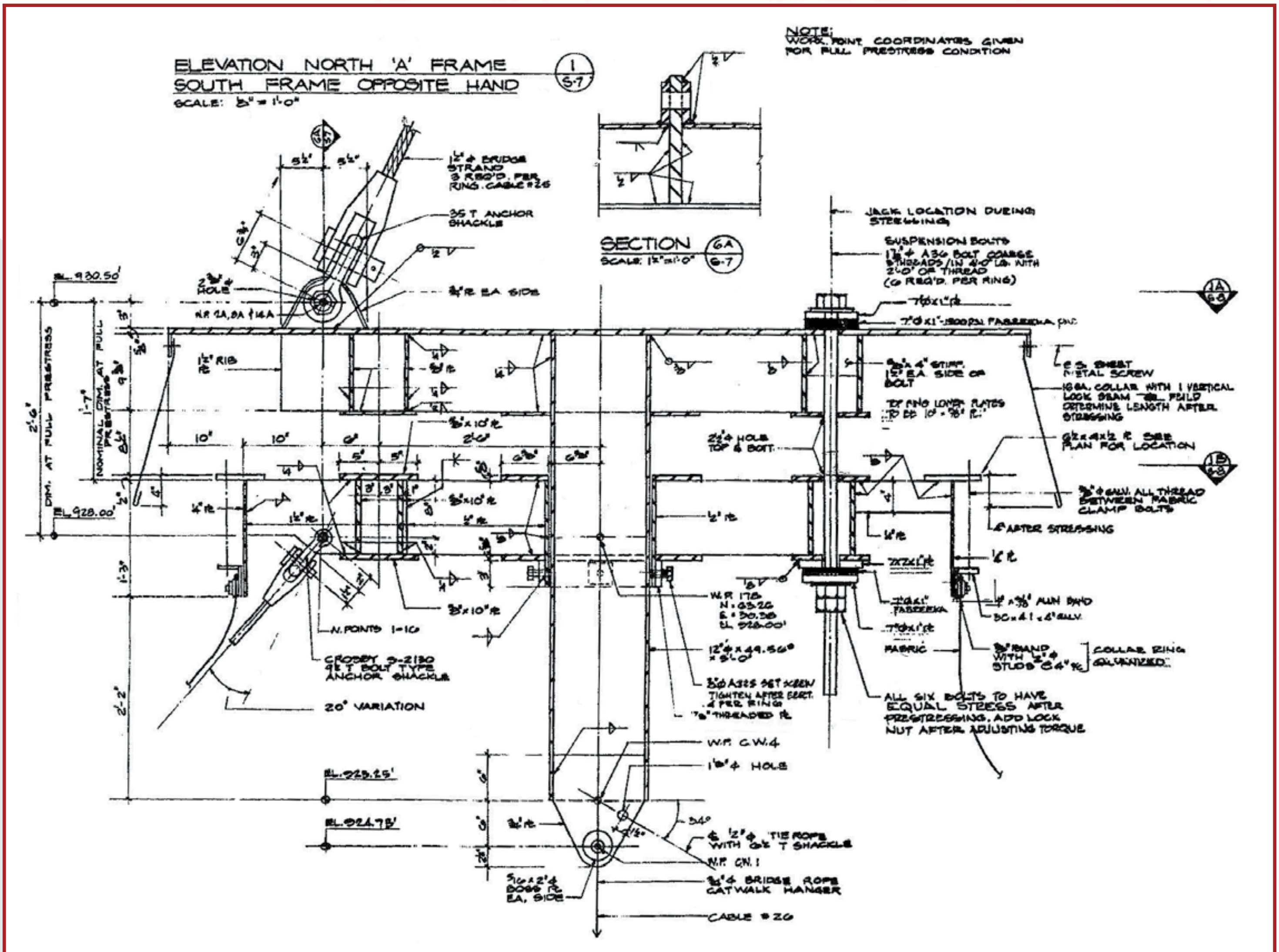
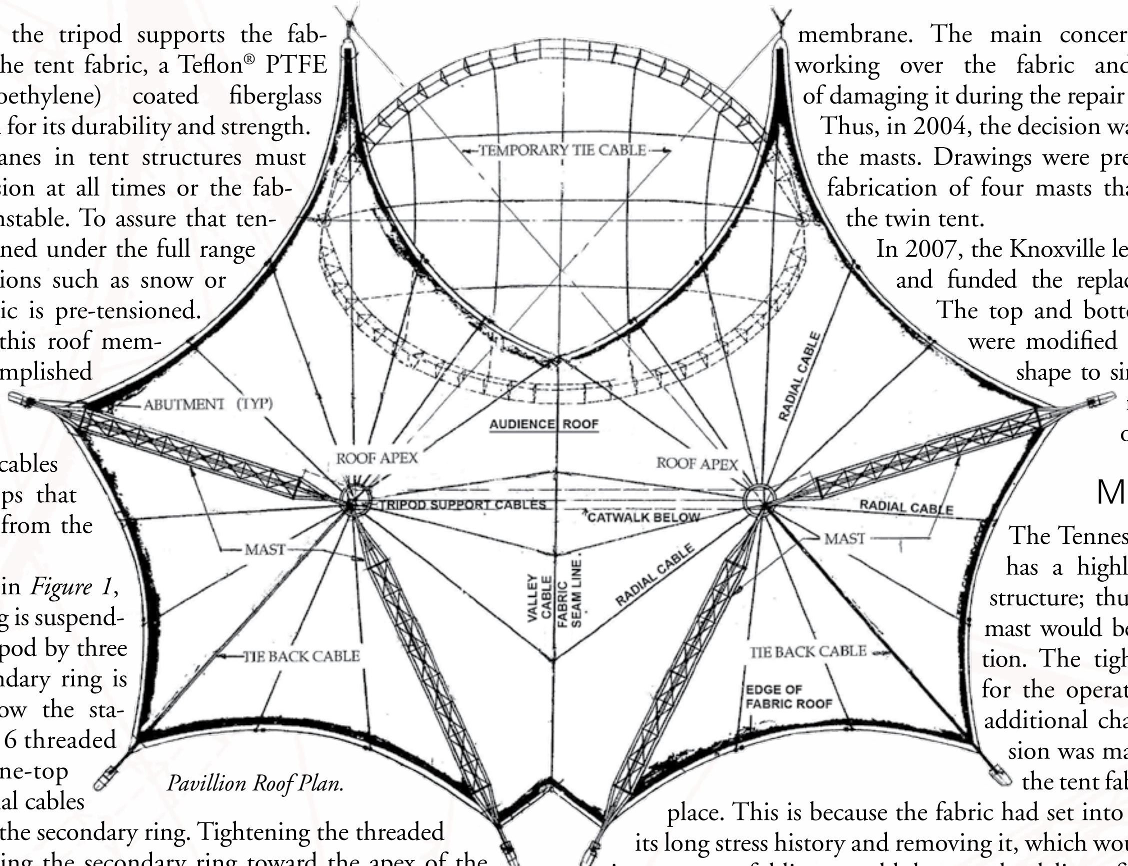


Figure 1: Roof Tensioning Ring – Section.

The apex of the tripod supports the fabric cone. For the tent fabric, a Teflon® PTFE (polytetrafluoroethylene) coated fiberglass weave was used for its durability and strength. Fabric membranes in tent structures must remain in tension at all times or the fabric becomes unstable. To assure that tension is maintained under the full range of load conditions such as snow or wind, the fabric is pre-tensioned. Pretensioning this roof membrane was accomplished by jacking the fabric and attached radial cables at the cone-tops that are suspended from the tripod.

As illustrated in *Figure 1*, a stationary ring is suspended from the tripod by three cables. A secondary ring is suspended below the stationary ring by 6 threaded rods. The cone-top fabric and radial cables are fastened to the secondary ring. Tightening the threaded rods, thus pulling the secondary ring toward the apex of the tripod, tensions the system since the fabric and radial cables are anchored to perimeter foundations. Tensioning the radial cables causes them to lose their sag, thus introducing radial stresses in the fabric. At the same time, this introduces lengthwise stresses through jacking of the fabric at the "neck" of the tent. This operation stresses the fabric in two directions at once. Stressing the fabric in only one direction would result in wrinkles.



Pavillion Roof Plan.

Observations

In 2002, during a periodic inspection, rust patterns were observed that suggested cracks had formed in the mast pipe chords – the mast steel had corroded. There was also a desire to refurbish the venue with a new paint coating. Subsequent testing (magnetic particle and ultrasonic) revealed cracks of up to 30 inches (760 mm) long in the chords. These defects were not at welds but in the base material, suggesting that previously undetected lamination cracks had opened over time. Water infiltrated the cracks and corrosion opened them further. As a result of this discovery, the venue was declared unsafe and not to be used for public events.

Rehabilitation

In contemplating the future of the structure, several options were considered. The obvious one was to tear the building down. However, since the structure was unique and the fabric was still in very good condition after 20 years of life, the decision was made to rehabilitate the structure. Another factor that influenced the decision was the fact that the amphitheatre is located next to the recently built Convention Center and would serve as a valuable attraction in the planned revitalization of the City's World's Fair Park.

Alternatives considered in repairing the structure included field repair of the mast chords. This would have required gouging of the cracks in the mast chords in place and significant field welding. The approach was deemed difficult, as the work would be performed on a highly stressed member even though the load could be relaxed by de-tensioning the membrane. The main concern, however, was working over the fabric and the possibility of damaging it during the repair operation.

Thus, in 2004, the decision was made to replace the masts. Drawings were prepared for the re-fabrication of four masts that would support the twin tent.

In 2007, the Knoxville legislators approved and funded the replacement operation. The top and bottom mast sections were modified from the original shape to simplify fabrication, resulting in savings of $30,000.

Mast Swap

The Tennessee Amphitheatre has a highly integrated roof structure; thus, exchanging the mast would be a delicate operation. The tight space available for the operation presented an additional challenge. The decision was made to not remove the tent fabric, but leave it in place. This is because the fabric had set into its shape through its long stress history and removing it, which would involve rolling it up or even folding, would damage the delicate fiberglass yarn.

The proposed procedure would require de-tensioning the fabric to release the pre-stress load on the masts and disconnecting each mast from the apex of the tripod. The fabric would still need to be under some nominal tension, so that a mild wind would not cause it to flutter and thus be damaged. The emphasis would be for a speedy operation to minimize exposure of the membrane in its vulnerable condition (i.e. low pre-stress). As part of the operation, close monitoring of the weather would be required.

Base plates of the masts that were removed also anchored radial and edge tent catenaries that needed to be temporarily tied to abutments that support the masts. Configuration of the tripod apex incorporated a detail that made exchanging the masts challenging (*Figure 2, page 40)*. The mast tops had bearing plates that butt against each other. Sandwiched between these bearing plates is a plate that anchors the 2½-inch ø (56 mm) tie-back cable. Load from the tie-back cable is transferred into the masts through (10) 1⅜-inch ø (35 mm) SC bolts. Unbolting this connection would release all three components simultaneously. Another consideration was to avoid disconnecting the tie-back cable, since it would

Temporary anchorage of cables.

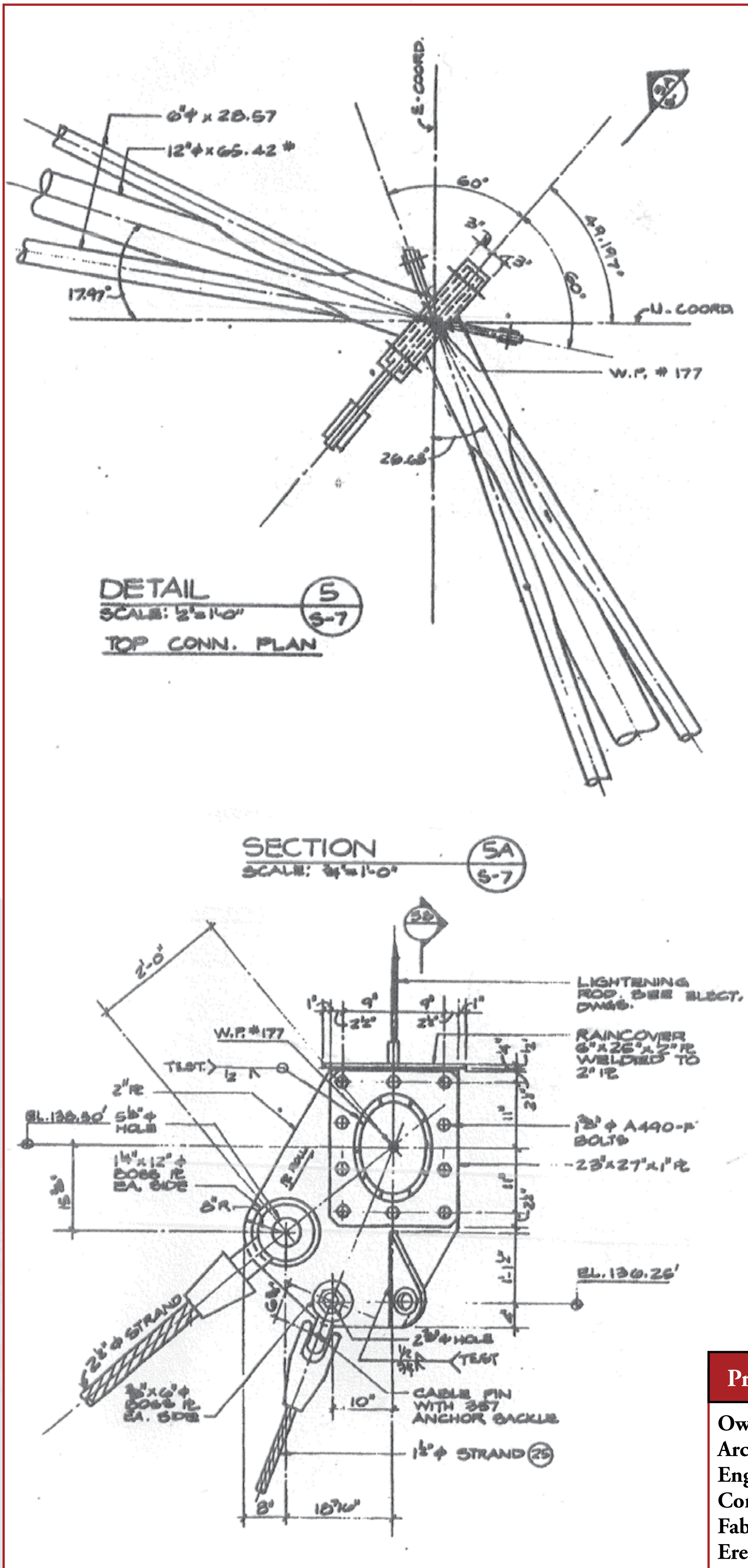


Figure 2: "Tripod" Top Detail.

have been very hard to reconnect the cable at the tripod apex. A procedure was devised to support the tent from a crane while exchanging the old masts for the new. In all, three cranes were required: one 190-ton crane supported the tent and with its secondary hook, the top of the mast to be removed; a second crane picked-up the mast near its center of gravity, and; a third crane hoisted the work crew.

With this set-up, the following procedure for the mast swap was executed:

* The first tent was de-tensioned by threading down the nuts on the six rods that connect the stationary ring to the fabric support ring. A temporary anchorage was installed on the mast abutments and the edge catenaries. Radial cable anchors were transferred from the base plates of the masts to the temporary anchorage. The 190-ton crane was hooked up to the ring supporting the fabric and the fabric was re-tensioned slightly. The weight of the tent to the crane was 30,000 pounds (133 KN), but was increased to 40,000 pounds (178 KN) to retain some pretension of the fabric. Re-tensioning also provided space for rotating the masts back, which relaxed the load in the tie-back cable. This made it easier to detention the cable at the abutment. The purpose of this operation was to reduce the horizontal load component of the tie-back cable at the tripod apex as much as possible. At this point, the only forces in the apex connection were from the weight of the masts and the tie-back cable.
* A temporary weld was used to connect the sandwiched tie-back anchor plate to the bearing plate on the mast that would remain in place while the other was removed.
* A cable was fastened behind the bearing plate of the remaining mast and was strung to an existing tent anchor that lay in line with the tie-back cable. The purpose of this cable was to resist the horizontal component of the tie-back cable once one mast had been removed.
* By lifting the top of the mast that would remain, pressure at the mast's butt connection was reduced enough for bolt removal. A second crane was now able to swing the other mast away and set it aside. The mast with the tie-back cable attached remained in place for the time being. The replacement mast was then swung-in and set on the existing anchor abutment. Space was very tight at the apex connection, since the top of the mast had to be needled through tent support cables. The assembly was lifted slightly to line-up the mast top with the tie-back cable anchor plates.

Project Credits

Owner: City of Knoxville, Public Building Authority
Architect: MHM Architects, LLC
Engineers: Geiger Engineers, PC
Contractor: Johnson & Galyon
Fabricator: Quality Machine & Welding Steel Fabricators
Erectors: Powell Construction Company

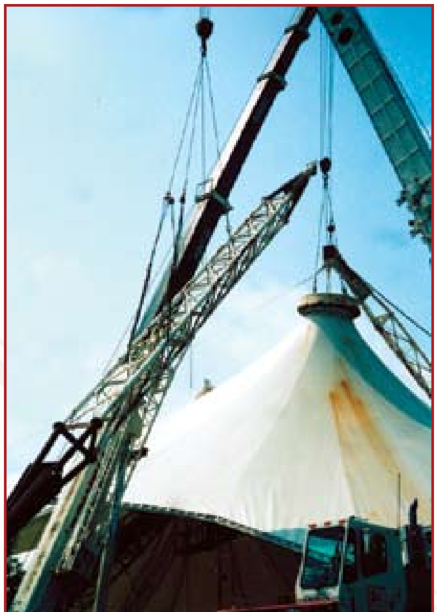
* Once the plates lined up, drift pins were used to align bolt holes. A 3-inch (75mm) long fillet weld was applied to fasten the new mast bearing plate to the tie-back anchor plate. The cable that had been installed behind the old mast bearing plate was disengaged and reinstalled behind the new mast bearing plate. The temporary weld between the old mast bearing plate and the tie back anchor plate was removed after a crane had been hooked to the center of the mast. This then enabled removal of the other old mast and installation of the second new mast. New $1\frac{3}{8}$-inch ø (75 mm) ASTM A 490 SC bolts were installed to clamp the assembly together.

* Where bolts could not be installed due to misalignment, they were substituted with fillet welds around the perimeter of the plates.

Completion

Mast exchange for the first pair took 3 days of preparation and 2 days for the actual exchange. Replacement of the second pair took only 2.5 days. Experience gained, as well as preparation that commenced while replacement of the first set of masts was executed, allowed for this speedy operation. All-in-all, the mast swap was executed in 9 days.▪

The online version of this article contains additional graphics and larger versions of the drawings. Please visit **www.STRUCTUREmag.org**.



Removing the first mast (left) and inserting the top of the new mast (above).

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