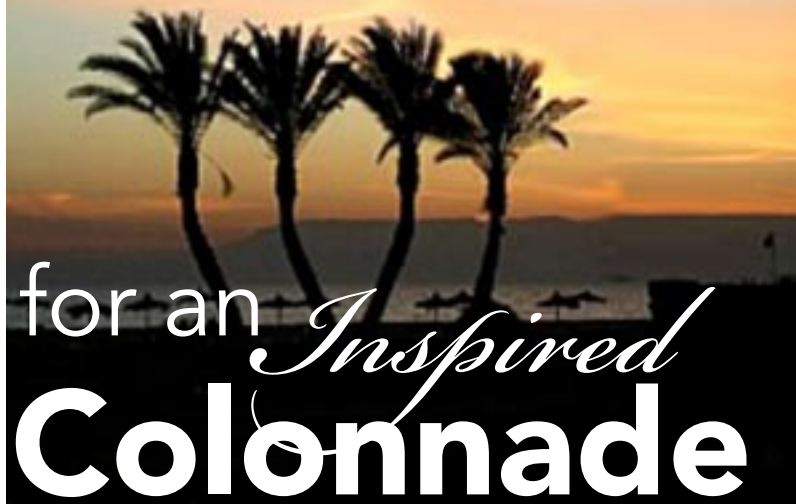


**Below:** Curved, built-up tee sections, inspired by images of the desert life, form the *liwan* (or colonnade) of the new Sahari Mall in Kuwait.



**Inset and below:** Inspiration for the design of the Sahari Mall in Jahra, Kuwait, came from the drawn swords pointing to the sky during the traditional Al Arda dance, as well as the curved elegance of palm trees and Islamic arches.



# Curved Steel

BY DANIEL BARTMINN, DIPL.-ING. CENG MICE

## for an Inspired Colonnade

Interesting solutions were found to both the design and construction challenges for the curved steelwork *liwan*, or colonnade, for Sahari Mall in Jahra, Kuwait.

**WHEN OPTION ONE INTERNATIONAL** set out to design a new shopping mall in Jahra, Kuwait, they wanted something different from the traditional concrete Islamic-type arches found on most of its neighbors. Instead, the in-house architectural team drew inspiration for the Sahari Mall from the look of swords pointing to the sky during the traditional Al Arda dance as well as from the curved elegance of palm trees.

Further differentiating the mall is a projected roof canopy, punched by the sword-like columns, and waved to resemble rolling sand dunes. And continuing the theme from the front canopy, the designers mimicked the look of striped shaping provided by palm leaves by using slender 33-mm-by-3.2-mm pipe sections to brace the main curved columns.

The colonnade, or *liwan*, consists of two sets of primary “sword” columns and one set of curved spine columns, orthogonal to the building frontage, rising from the building and piercing the canopy at 2,750 mm distance further to the front. These elements are

fabricated tee-sections (212 mm deep with a 290 mm width and 12-mm-thick flange). Every alternate column spine, however, rises from the front to back, creating the impression of a series of arches when viewed along the *liwan*. The other set of columns uses built-up angles 200 mm by 120 mm, 15 mm thick, and runs parallel to the building frontage. The columns are bent with changing curvature in a “lazy S” manner and mirrored, creating arches on the front elevation. At base points and at the roof, both sets of columns meet, in a junction comprising of one tee framed by two angles. This results in a three-pronged cross section at the base while at the roof the angle webs marry the tee web forming a single tee.

### Design Challenges

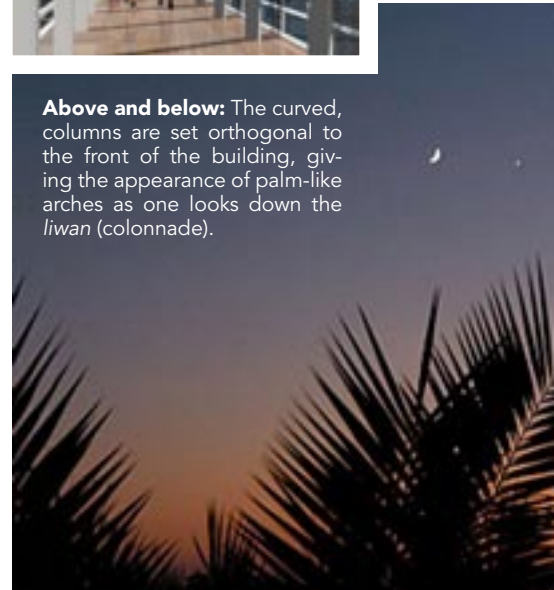
The structural scheme and stability system is essentially a series of three pin frames braced against each other both on plan and elevation. At the upper section, the spine columns are braced on plan by the louvre members, with the rigid support provided by



The contractors bidding on the project were required to construct mock-ups like this to show they could produce warp-free columns.

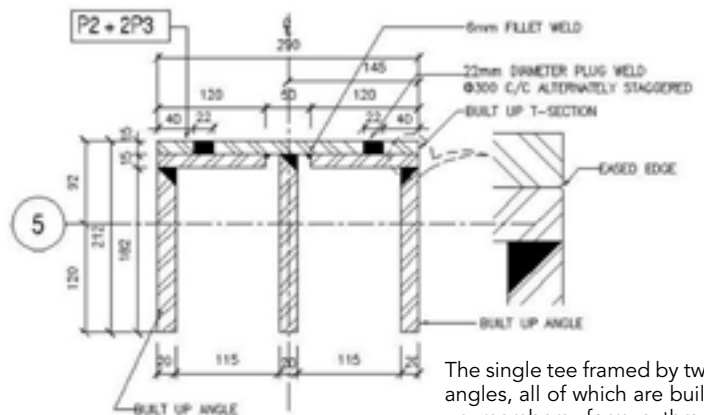


**Above and below:** The curved, columns are set orthogonal to the front of the building, giving the appearance of palm-like arches as one looks down the liwan (colonnade).



a positive connection to the main building frame. Further restraint is provided by the roof canopy, which is trussed on plan and supported vertically by the *liwan*. Further toward the ground, the lateral restraint to the spine columns is assumed to be provided by the curving members running parallel to the colonnade, which form three pin arches on the elevation.

Design and analyses of curved steel must take due consideration for residual stresses induced during the bending process. The fabrication process requires only the web of the angle and the flanges of the tees to be bent before being welded to the other element, which are cut from flat plate. Nevertheless stresses were accounted for using guidelines published in the Steel Construction Institute's (SCI) P281, *Design of Curved Steel*. Following those guidelines, reduced design stresses were calculated derived from the ratio of the elastic and plastic section moduli.



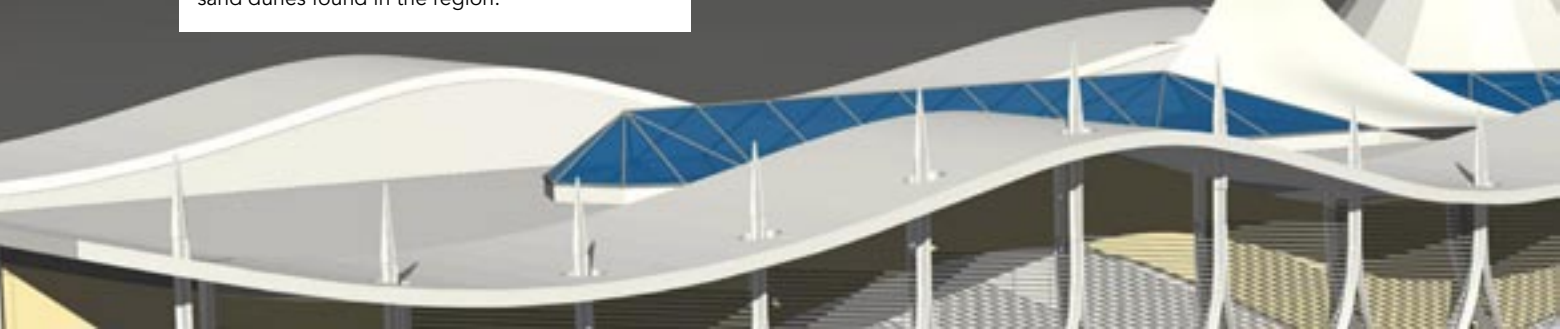
The single tee framed by two angles, all of which are built-up members, form a three-pronged cross-section at the base of each column.

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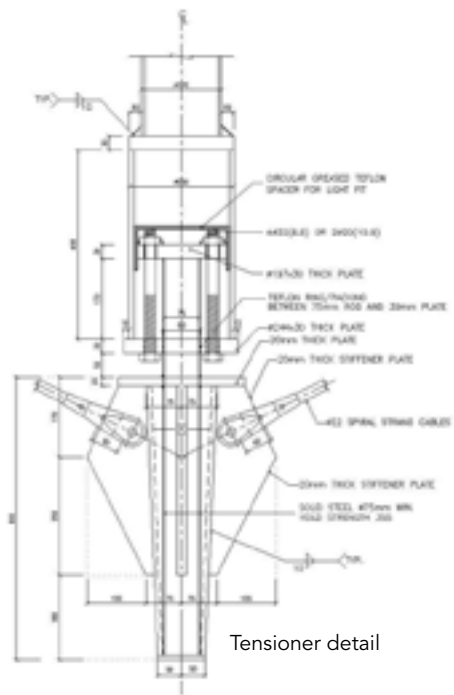
The projected roof canopy, with the sword-like columns punching through, resembles the rolling sand dunes found in the region.



### Desert Inspiration for Other Features

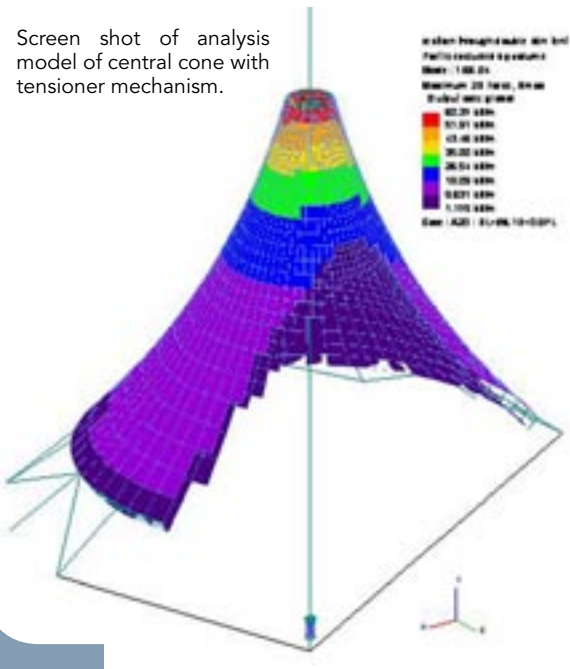
The Sahari Mall project also features glass steel bridges supporting the escalators, curved steel railing, and tent structures inspired by the desert life.

The tent structures' double-skin central cone is supported by a circular ring truss and a flying steel mast. The tensioner mechanism originally proposed by the contractor was modified by the engineer to comply with the architectural design intent. Instead of having the mechanism below the cable support point, with external bolts, the modified tensioner, has tensioner bolts inside the column above the cable support point. Since this theoretical creates a mechanism balanced by internal prestress forces similar to a "knee," detailed checks were carried out on the sensitivity to out-of-tolerance eccentricities and accidental lateral loads. The internal tension stiffness of the mechanism was verified by non-linear analysis. All analysis was carried out using GSA from Oasys.



Tensioner detail

Screen shot of analysis model of central cone with tensioner mechanism.



Flying mast and central cone before closing of double skin.

### More About Bending Steel

Much good information is freely available about how to design curved steel members as well as how to obtain the desired results. The U.K.-based Steel Construction Institute's P281, *Design of Curved Steel*, is available for online viewing at [www.steelbiz.org](http://www.steelbiz.org). (Enter your email address to log in as a guest.)

AISC also offers numerous resources on its website in the Bender-Roller channel, [www.aisc.org/benders](http://www.aisc.org/benders). In addition to links to reference materials, such as "Curved Steel—A Reference for Architects & Engineers," and published articles, it also includes a list of AISC bender-roller members and several case studies.

Further design moments needed to be amplified to account for the segmentation of the analysis model. This process was facilitated using spreadsheets and the design was carried out using BS 5950-1:2,000, the British standard for steel design. It is worth noting that this can reduce the design stress by as much as 60%, depending on the section. However in our case this effect was relatively minor due to a very refined model, as dictated by the louvre members. This stress was then used as the input yield stress for "normal" LRFD design. As a result, we decided to use high-strength steel with a yield strength of 345N/mm<sup>2</sup>.

### Fabrication and Erection

Because of the unusual geometry, the competing steelwork contractors were required to produce scaled mock-ups during the bidding period. The successful steel subcontractor went on to produce full-size mock-ups of various parts, during the pre-fabrication period, in order to assure the design architect that the design geometry could be achieved in warp-free fashion. For this purpose the contractor modified the weld design on several occasions, always seeking feedback from the consultant, until the desired end result could be proven in the full-size mock-up. The successful final weld design of the tee-angle connection, for example, comprised of 22-mm-diameter plug welds alternately staggered at 300 mm centers.

All members were fabricated in Kuwait City and transported to Jahra for assembly on site. Site welding required only little further adjustment between the design team and the steel subcontractor. It is worth mentioning that the final product is completely warp free and delivered without any variation claims. MSC

### Owner/Developer

Action Real Estate Company, Kuwait

### Architect and Structural Engineer

Option One International, Kuwait