THROUGH A LENS

The new bridge is 200m long in total, and connects the train station to a new business park *(Amit Geron Photography)*

A lenticular truss was chosen as the appropriate solution for a new footbridge in the Israeli town of Beer Sheva. **Yitzhak Rokach** and **Devan Levin** report

Although the Gav-Yam technology business park was built right next to Beer Sheva's northern railway station, train commuters have only recently been able to walk to their desks within minutes, after construction of a new footbridge connecting the two. The business park was deliberately built right next to the transport hub, but the design of the railway station, which is on the south side of the railway tracks, meant until the new bridge was built, commuters had to catch a bus to reach their offices.

The Beer Sheva municipality issued an invitation to architectural firms to design a landmark bridge to link the train station to the new business park as part of a design competition. The winning proposal was that of Bar Orian Architects and Rokach Ashkenazi Engineers & Consultants.

Topographical conditions at the site, along with the structural requirements for the bridge itself, were the main criteria driving the choice of bridge type, alongside the architectural and aesthetic aspects.

The bridge was required to span the operational railway tracks, the sidings, and also an area which is planned to be used for future railway expansion. Crossing all three of these brought the total length of the bridge up to 200m, and the arrangement of the tracks meant that the only options were a single span or two-span bridge; while the former may have been possible, it was not considered practical nor cost-effective. Hence the winning design consists of two spans; the longer of the two on the north end of the bridge, measuring 100m, with a shorter 70m span at the south end. These, together with the two end supports, combine to create the 200m-long structure.

Each of the two main spans takes the form of a steel truss, and the depth of each truss varies across the span. The depth varies from approximately 600mm at the pier top positions, to a maximum of 11m at the mid-point of the northern span and 7.5m at the mid-point of the southern span. Each span is a system of planar trusses at variable angles, which enclose the bridge walkway and create a structurally-stable space truss providing adequate stiffness despite their delicate appearance.

In addition to the variable-depth truss, and in a similar way, the inclined angles of the wall trusses add a dimension of variable width to the structural system, enhancing its aesthetics. At the middle of the northern span, the width reaches a mammoth 15m at mid-span. The dynamic nature of the bridge is echoed by the bridge deck which widens and narrows across the length of the truss system that supports it.

Historically a structure of this type is known as a lenticular truss, because of its lens-like appearance. These trusses begin at single points of minimal proportions, and grow symmetrically towards a mid-span apex, visually similar to a biconvex optical lens. Bridges have been built using this static scheme since the 19th century, the most famous being Brunel's Royal Albert Bridge over the Tamar River in the UK, which was completed in 1859. This form makes sense structurally when used correctly, and is well suited to simply-supported pinned beam structures - since the truss height reaches its maximum at mid-span where the bending moment is generally highest. This static scheme and structural concept are efficient and practical for the Beer Sheva project and bridges of similar dimensions, and enable the structure to easily withstand the applied forces, respond with allowable stress and deformations, yet retain a visually pleasing height-to-span proportion without any structural compromise.

The main spans were assembled before being lifted into place

The Beer Sheva Bridge has three simple static schemes in its three primary directions. Vertically, the predominant forces are the gravitational forces, such as the dead load of the structure and the live load of the pedestrians. In this direction the bridge is designed to behave as two independent, simply-supported beams with pinned supports at each end. Each span is supported by its end pier at the bridge's extremity and by the central pier where they meet. Despite the material's physical continuity above the central column, and at the end piers, each span works and behaves as a single span with pinned end restraints which do not bear bending moments. This approximation is made possible because of the high bending flexibility of the cross-section at the point of connection compared to the high rigidity of the span resulting from the truss height, in addition to a sliding detail connecting the deck to the central column but not allowing any coupling forces to develop between the deck and the truss itself.

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The bridge is 15m wide at its mid-span *(Amit Geron Photography)*

Because of the contrasting rigidities, the rotational deformation at the truss-column interface is relatively small, and this, together with the high flexibility, means the bending moments above the central column are of very low magnitude compared to the moment of a fixed-pinned beam. Hence the approximation of two simply-supported beams may be used.

In the axial direction, the most substantial influences are generated during thermal loading due to the length and material properties of the bridge, and the temperature range at the site. If the engineer chose a static system of higher restraint (hyperstatic) in the axial direction, these internal stresses will be higher. Theoretically, a bridge which is completely restrained at both ends will not expand, but will develop high stresses, while a minimally-restrained (isostatic) system will allow deformations without any additional stress. These hyperstatic forces are proportional to the bridge's strength, so adding material or enlarging cross sections would result in higher forces and would not have significant effects on the high stresses of systems of higher redundancy.

The Beer Sheva Bridge's axial static scheme is that of a cantilever; the bridge's full rigidity stems from the central column and its resistance to bending as a cantilever, the column is fully fixed to the foundation at its base. The flexibility of the truss ends, the slenderness of the end piers, and a steel hinge detail at the pier-foundation interface, allow the piers to function approximately as a compression strut would. They do not resist loads in the bridge's axial direction, creating an approximately isostatic system. Axial forces are resisted solely by the central column as a cantilever.

The transverse system resists forces perpendicular to the bridge axis such as wind, seismic loading, horizontal live load effects etc. The three-dimensional truss system acts as a continuous beam across the entire bridge length; the varying width of the truss system affects the bridge's stiffness but not to the extent that the more flexible points act as hinges. In this direction the bridge acts as a continuous beam supported by three restraints. The end piers are able to restrain transverse movement due to their geometry and act as truss structures resisting these forces. The central column works as a cantilever, bending in its strongest direction, and fixed at its base.

While the bridge possesses a sound structural system which can withstand forces in all directions, large-span steel bridges are notoriously characterised by low natural frequencies. These frequencies are susceptible to activation by pedestrian traffic on the bridge, and can cause amplified displacements and accelerations.

During the design stage, the dynamic characteristics of the bridge were analysed. Due to the flexible static scheme in the axial direction, where the only stiffening element is the central column bending around its weaker primary axis, the theoretical axial frequency was calculated as 1.22Hz with a participating mass equal to 75% of the total mass. This frequency is within the range of frequencies vulnerable to pedestrian-induced vibrations and user discomfort.

This mode was extensively examined by the design team in collaboration with Professor Izhak Sheinman of the Haifa Technion. Without substantial changes to the bridge's static scheme, it would have to be damped artificially using a heavy, expensive tuned mass damper system. A stiffer scheme would enable the frequency to be raised above the critical range, but in order to stiffen the scheme without substantially increasing the column's cross-sectional dimensions, the bridge deck would have to be axially restrained. This restraint would increase stresses from thermal loading and would have required changes to the bridge architecture, for example the addition of tension members connecting the end supports to the foundations to limit rotation.

The final decision was to fix the escalator support beams at the north side, raising the frequency to 1.72Hz and lowering the mass to 24%, which improved the characteristics and reduced the cost of the damping system.

In order to solve the vibrations without adding thermal stresses, the damping solution had to restrain the axial direction under pedestrian loading but allow for thermal expansion. The initial proposal was to use viscous dampers, which are well suited to the axial restraint problem as they can be calibrated to lock up under rapid human induced vibrations and move freely under slow changes in temperature. The eventual solution was a friction-based detail designed to resist the relatively low axial forces caused by vibrations yet slide with the large thermal forces. According to the theoretical model, in addition to the axial mode the bridge has slightly problematic vertical and transverse frequencies, albeit with low participating masses. The final design addressed the possibility of incorporating TMD systems for all three directions.

Complex design requires complex detailing and the intricate space truss was no exception. The drastically-varying geometry does not allow for standardisation of any kind; the truss chord cross-sections change along the length of each span, as do the spacings of the bridge's cross-sectional axes, and the cross-beam spans, angles, and end details depend on the truss orientation and distance from the supports.

No two-dimensional drawings were prepared for the steel structure since the entire bridge was modelled in-house using Tekla Structures and sent directly to the steel fabricators. This saved a lot of time, eliminated the need to examine endless ambiguous cross-sections and respond to endless requests for information, and led to a seamless interface between design and fabrication. Three-dimensional modelling complemented the design process throughout; among the countless advantages the model was used for form finding, detail geometry, calculations, and identifying problematic situations which would otherwise have become apparent at a later stage when solutions would have been more expensive and much less desirable than those implemented.

After winning the tender for the construction, civils contractor Shura began work on the foundations while steel fabricator Addi 2000 Steel Industries began factory production of the steel elements. The presence of numerous train tracks and platforms below the bridge site made it impossible to build the bridge on site. The entire structure was fabricated in pieces at the factory, and delivered to a site adjacent to the final location. Eighteen months later, the bridge had been assembled into five separate elements; the two spans side-by-side on the ground, with the three piers in place waiting for installation. The central pier was bolted into the massive pile cap, while the end piers were connected to their bases through a pinned steel detail, providing a fixed and hinged connection respectively and allowing the static schemes described above. In addition to allowing thermal expansion, these hinges enabled easy installation while accommodating any slight deviations in bridge dimensions. While the central pier would remain rigid, the movements required could easily be achieved through rotation of the end supports. Two operations were carried out to lift the two spans into place, with rail traffic halted for less than 24 hours in total.

The 230t southern span was lifted into place first and welded to its supports and the 430t northern span was lifted in a separate operation.

The lifting subcontractor Taavura Holdings used a Terex CC-2800-1 crawler crane to lift the southern span – measuring 70m long, 7m high and 11m wide – in a single pick.

The crane held the load above the centre of gravity, where the cables split at an angle and connected to the structure at deck level at each end. In order to reduce horizontal forces on the deck beams, additional detailing enabled the cables to be vertical at the deck ends and only be angled above the top arch level, to allow for the fact that the deck beams have a strong vertical resistance but low horizontal resistance. The crane picked the span and carried it to its final position, driving over compacted soil that had been placed on the railway tracks to protect them.

The northern span, measuring 100m long, 12m high, and 15m wide was lifted at one end by the Terex CC-2800-1 crawler crane and at the other end by two cranes, one LTM1400 and one LTM1500. This span was moved into place on trailers, but did not need any large movements once hoisted; the final placement was achieved using the cranes' radii.

The client was the Beer Sheva Municipality, and the construction cost of the bridge was approximately US$7.3 million

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