Twisting Steel and Bending the Imagination

By Kevin Legenza

Dynamic…Fluid…Organic! Like the spiraling building blocks of DNA within each living cell, the new Marina Bay Pedestrian Bridge in Singapore is expected to energize and give life to a host of new developments along the city's showcase bay. Inspired in design by the twisting form of DNA strands, the 280-meter (920-foot) long, world's-first double helix pedestrian bridge challenged designers, engineers, and drafting technicians to the limits of available technology and tools.

Resort Plaza Perspective. Courtesy of Cox-Rayner.

Competition

In 2005, the Urban Redevelopment Authority of Singapore opened an international design competition for a new pedestrian and vehicular connection across Marina Bay in Singapore. The new connection will link the city's cultural, recreational and entertainment facilities to the new highly-anticipated Marina Bay Sands Integrated Resort, a Venetian Sands Casino, and Leisure Center. In March 2006, the global consortium of Cox Architects (Australia), Architects 61 (Singapore), and global consulting engineers, Arup, was announced as the competition winner. Shortly after the competition drew to a close, the design team proposed a plan to separate the project into two bridges, a pedestrian link and a vehicular bridge. By building a simple, economical vehicular bridge, a much larger budget could be made available for a captivating pedestrian bridge. The proposal, with its creative potential, excited the client and the artistic design process for the pedestrian bridge began.

The Bridge

The spiraling steel tube superstructure of the pedestrian bridge is curved in plan, wrapping around Marina Bay and the city. Mimicking the existing Benjamin Sheers Bridge, the pedestrian bridge has 4 supporting piers in the bay. Atop each of the piers, a pair of inverted tripod supports, fabricated from large diameter tapered circular hollow sections, split the structure into 5 spans. Three 66-meter (217-foot) internal spans and two 41-meter (134-foot) end spans make up the superstructure. Bookcasing the bridge, two concrete approach ramps launch 12 meters (39 feet) from concrete plaza-styled abutments to meet the steel bridge. The bridge deck is 6 meters (20 feet) wide. It is suspended in the center of the tubular structure and spans 2.7 meters (9 feet) between deck beams. The deck beams span 9 meters (30 feet) from one side of double helix 'tube' to the other. Over the piers in the bay, large elliptical viewing platforms cantilever out 9.5 meters (31 feet) through the helix toward the bay and central business district (*Figure 1*). These generous platforms, 13.8 meters (45 feet) wide, are supported from below by a slender cantilevering arm.

Figure 1: Viewing Pod and Singapore CBD. Courtesy of ARUP.

The Mechanics

The main load carrying system is comprised of two sets of circular hollow tubes – an outer and inner group. The tubes are 273 millimeters (10¾ inches) in diameter and primarily carry axial loads. The outer helix group includes 6 tubes. They are set equidistant from one another in cross-section (*Figure 2, page 48*) on a 10.8-meter (35-foot) diameter circle. The tubes travel longitudinally along the bridge, twisting clockwise around the centroid of the group at a pitch of 5.5 degrees of rotation per meter length. The inner helix set consists of 5 tubes. Similar to the outer tubes, they are set equidistantly but on a 9.4-meter (31-foot)) diameter circle. Balancing the outer tubes, the inner tubes twist counter-clockwise around the centroid of the group at a pitch of 6.5 degrees per meter. The two group center points coincide laterally, but the inner group is vertically lower by 2.7 meters (9 feet). This offset enables the two helices to interconnect at deck level.

Independently, the helices are incapable of such a span. To develop capacity, the two groups are linked together forming a tube-in-tube structure. The link is provided by cross frames which stabilize, engage and load the tubes. The cross frames are set at 2.7-meter spacing along the length of the bridge. Each frame consists of a deck beam, struts, and ties. The deck beam spans the circular cross-section, connecting at the points where the inner and outer helices overlap. Both the inner and outer helix tubes have a ring of strut elements linking adjacent helix tubes. The helix ties link the inner helix tubes with adjacent outer helix tubes above the deck level. The deck beams serve to support the

Perspective through the Helix. Courtesy of Fox-Rayner.

deck and transfer its load to the ring tubes. The ring tubes distribute the load from the deck beams to all of the helix tubes. The ring tubes and ties work further to stabilize the helix members by directing their unraveling forces to act as restraint against one another. The load path and behavior is similar for both vertical and lateral loads.

Materials, Durability, and Maintenance

Due to the marine environment, durability and maintenance were important design considerations. The bridge has many complex joints with curved members intersecting at tight angles. This complexity, coupled with the large exposed steel surface area, challenged the feasibility of maintaining a painted carbon steel structure. The design team investigated the use of non-typical metals which would circumvent the maintenance issues associated with carbon steel structures. Due to its resistance to surface staining, engineers considered duplex stainless steel. In addition to its corrosion resistance, duplex stainless steel has a strong alloy composition with significantly higher yield strength than carbon steel.

In parallel, the weldability of duplex grade stainless steel was investigated. Drawing on their experience on other projects, such as the Stonecutters Bridge in Hong Kong, Arup engineers demonstrated there were no additional difficulties associated with duplex stainless welding. In fact, it is simpler to weld than carbon steel because it is not susceptible to hydrogen embrittlement. Although significantly more expensive, the reduction in material quantity, robust chemical composition, and ease of welding made duplex stainless steel the ideal material and was accepted by the client.

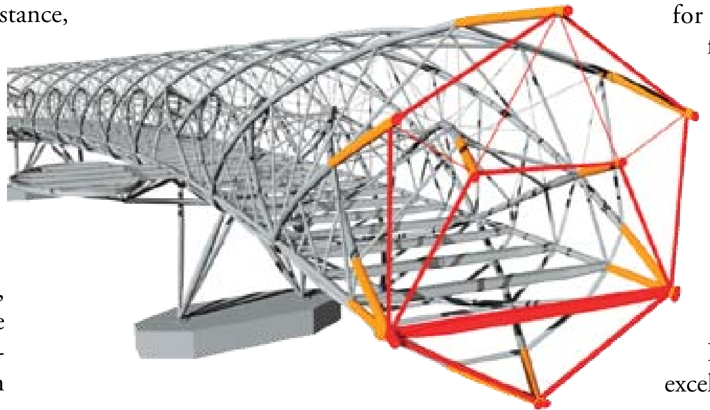

Figure 2: 3D Double Helix Cross-Section. Courtesy of ARUP.

Drafting and Design Integration

The bridge geometry is very complex, incorporating global plan and vertical curves. To understand its impact on design and construction, three-dimensional modeling and analysis was imperative. From conception, designers scrutinized the abilities of current software packages to coordinate between engineering analysis and documentation software. From this study, a workflow process was formed with commercially available products and in-house software yet to be created.

The central workflow used a streamline of information between various packages used for design and documentation. Bentley Generative Components, a parametric and associative modeling module, allowed the design team to begin modeling the complex helix exoskeleton before finalizing the bridge centerline. With the ability to dynamically update the structural models, the critical path timeframe was compressed, enabling simultaneous work on separate tasks. With changes in bridge geometry, new models could be generated quickly and distributed to members of the design team.

Upon generation, an unaltered model was imported into Bentley Structural to form the base 3D model for documentation. The exportation for structural analysis began with the selection of the programs themselves. The finite element package Strand7 and OASYS GSA (General Structural Analysis), Arup's in-house structural analysis program, were used for structural design and optimization. The analysis packages were selected due to their sophisticated Application Programming Interfaces (API) and excellent solution engines. API allows users to drive software externally through proprietary software. This functionality allowed engineers and technicians to develop special pre- and post-processors. These API programs/processors were used to modify 3D documentation models and for member design and optimization.

The fusion of software allowed technicians and engineers to merge results of the structural analysis and drafting models. Any updates to structural members could be translated to the 3D documentation model. In combination with 'drawing extraction' technology, the process allowed engineers to create flexible 3D working drawings very early to help describe the complex structure and facilitate design.

Structural Design Optimization

Since duplex stainless steel was selected, existing structural analysis programs with steel code checkers could not be utilized due to substantial differences in material composition and buckling behavior from standard carbon steel. Designers modified a piece of existing in-house software, the Arup Steel Optimizer, for use with stainless steel. The program was originally written for design and optimization of the Beijing National Aquatics Centre, also known as the "Water Cube." The Optimizer was written to iteratively interact with Strand7 and GSA, and optimize structural members.

The Steel Optimizer runs a Strand7 analysis, checks the member capacities based on analysis results and design criteria, substitutes in new member sizes with a lower or higher capacity, and repeats the procedure. This process is continued until all design criteria are satisfied. After solving successfully, a new model with utilization ratio plots is created in a GSA compatible format.

The utilization output for an optimization run of the Marina Bay Pedestrian Bridge is shown in *Figure 3*. After sufficiently testing the software, minimal checks were required for the process, saving many hours of design time. Using this out-of-the-box approach to design, a more cost-effective solution was realized by reducing a significant amount of material from the structure.

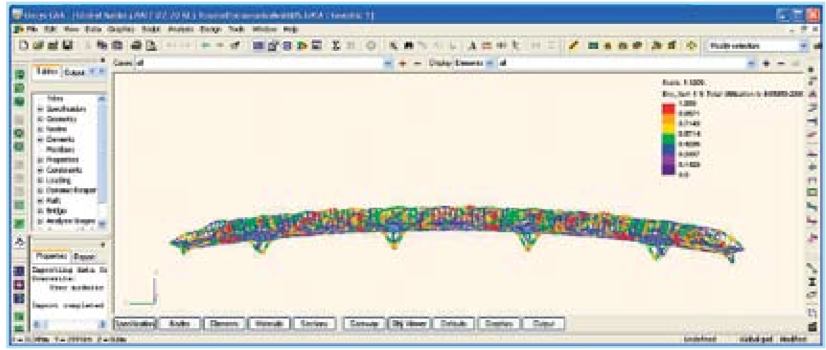

Figure 3: Oasys GSA Optimization Output. Courtesy of ARUP.

Conclusion: A Beginning

The innovative, double-helix structure of the Marina Bay Pedestrian Bridge is truly a world-first in architecture and engineering design. This was made possible by the synergy of design disciplines sparked by the creative collaboration of Arup engineers and Cox Architects from the early stages of conception. The design process for the project was entirely forward-looking, breaking from historical approaches. This vision, spurred by creativity and imagination, was carried from concept to delivery and provided an efficient solution for the complex, landmark structure. The Marina Bay Pedestrian Bridge is due for completion in 2009.▪

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