UNCONVENTIONAL STEEL CONNECTIONS:
SOME NEW APPROACHES

To meet the special demands of modern bridge construction, equipment designers have developed innovative ways to connect steel

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BUILDERS AND ARCHITECTS TODAY PLACE A HIGH PREMIUM on originality, vying continually with one another to "push the envelope" of daring design. It is the structural engineer, of course, who must come up with a sound structural underpinning to support these lofty concepts. Very often, this means the engineer must go far beyond the "standard" engineering literature. This is particularly true in the area of structural connections, where the accepted standards may not be sufficient to meet the stress and strength requirements posed by non-traditional structures.

One fruitful source of new approaches and solutions is bridge construction, and more specifically, in the innovative designs of the unique steel equipment that has been developed to meet the challenges of advanced bridge construction. There is good historical precedent for this, by the way: when Bradford Lee Gilbert announced plans for the Tower Building, New York City's first skyscraper, in 1885, he declared that his intention was "to stand a steel bridge structure on end."

TRIANGULAR TRUSSES FOR CANTILEVER CONSTRUCTION

Most three-dimensional steel trusses have rectangular cross-sections, with the diagonals are in either a vertical or a horizontal plane. The state of the art for design of rectangular trusses is well established, and adequate

EXPECT THE UNEXPECTED

It is axiomatic that connections in steel structures are critical to structural strength. Indeed, several well-publicized disasters in recent years have been attributed to the failure of a single connection, which then caused the collapse of an otherwise sound structure. At the same time, the structural connections are often the most complex elements within an overall design. This is especially true with many of today's highly sophisticated and highly irregular bridge and building structures, which do not always behave in a "textbook" fashion, and which therefore do not comfortably fit into the range of standard practice.

Despite this, there is a tendency among designers to use the same theoretical tools for connection designs as for structural members. Consider a commonly used bridge truss, whose members are connected by gussets. AASHTO guidelines specify that "gusset plates shall be designed for shear, bending and an axial load by the conventional 'Method-of-Section' procedures." In other words, the elementary formulas for beams are considered applicable to gusset plate connections as well.

Yet it has been well known for decades that this is not strictly true. As one textbook warns, these formulas "are valid only for beams whose span is more than twice the depth and at cross sections not closer to concentrated loads than about half the depth. The ordinary gusset plate falls considerably short of these requirements, so that the results obtained by the application of beam formulas are of questionable value and may be misleading" (E. Gaylord, *Design of Steel Structures*; McGraw-Hill, 2nd ed., 1972).

In practice, gusset plate thicknesses are generally chosen in accordance with average values for similar structures rather than according to beam formulas. Experience thereby serves as a guide to current practice. But the designers of modern, unique steel structures, unfortunately, do not always have a reliable model to imitate. Since standard empirical equations are not available for unique designs, engineers must rely on their intuition and experience to assess unique conditions and respond with appropriate solutions.

In short, reliable connections demand a great deal of engineering skill and effort, more than is sometimes realized, and this issue becomes more critical as structures become more complex. In each of the examples in this article, the designer was faced with connection problems that had no obvious "textbook" solutions. In each, it was necessary to devise unique connection details that would assure the integrity and proper performance of the equipment. The general lesson is that, when confronting undocumented connection issues, structural designers should be alert for situations that demand an innovative design approach.

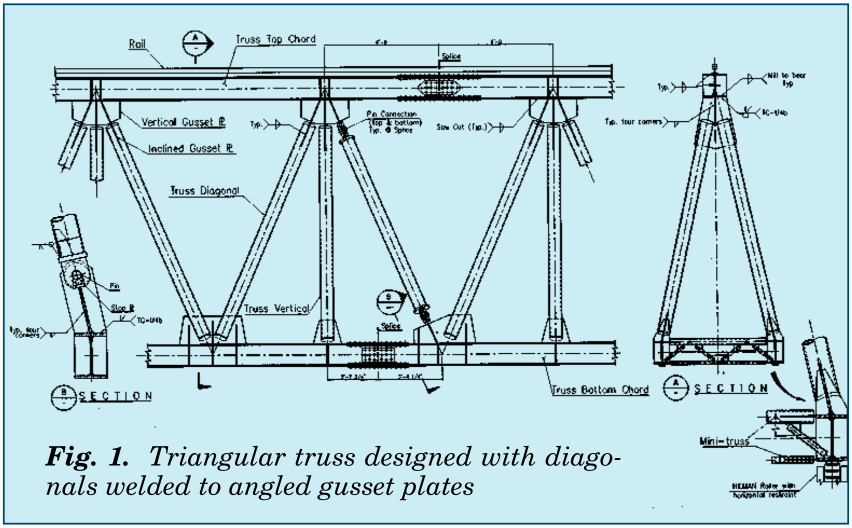

Fig. 1. Triangular truss designed with diagonals welded to angled gusset plates

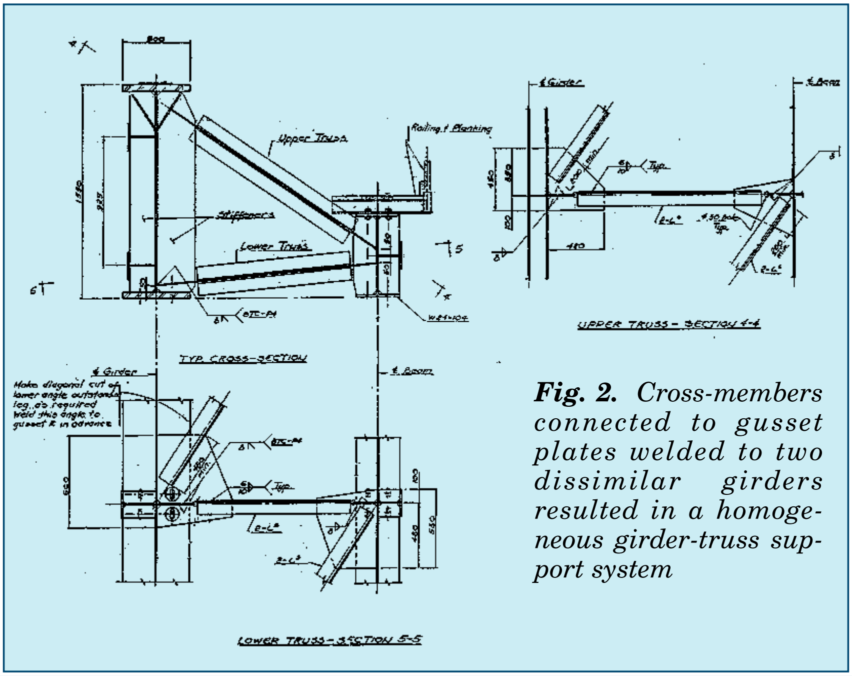

Fig. 2. Cross-members connected to gusset plates welded to two dissimilar girders resulted in a homogeneous girder-truss support system

connection details may be found in any technical manual on steel structures.

In many applications, triangular trusses can perform the same function as rectangular trusses. Moreover, with one top chord instead of two and less bracing between the chords, triangular trusses offer the considerable economic advantage of requiring less steel. But the design of triangular trusses is far more complicated, since chords connect to diagonals at oblique rather than perpendicular angles, and there is no standard textbook solution for the design of such connections.

The concept of a triangular truss for a launching gantry was recently developed for the cantilevered precast-concrete-box-girder construction of sections of Boston's Central Artery Project. In this application, two triangular trusses would be used as a runway for a gantry crane that transports and erects precast segments. As each bridge span is completed, the trusses are advanced on that span and the next span is constructed. Each truss has to carry the moving vertical load from the gantry crane as it delivers the bridge segments, the lateral force imposed by the moving crane on the top chord, and the lateral force the advancing truss transfers to the bottom chord. The critical design issue was the capacity of the top chord to withstand high moments created by horizontal forces.

The truss designer proposed a combination of vertical and inclined gusset plates welded to each other, to the top chord, and to the diagonals. As Figure 1 shows, the central vertical plate is in the plane of the top chord web; the two others are aligned in the angles of the truss diagonals. This design permits the axial force to flow from the top-chord beam web to the vertical gusset plate, which then distributes the load between the diagonal gusset plates. At the same time, the combination of the chord's stiffeners and the diagonal gussets creates a rigid beam that carries lateral forces and eccentricity moments to the diagonals and bottom chords.

A similar arrangement of gusset plates was designed for the bottom chord. In addition, mini-trusses were introduced to balance forces between the flanges of the bottom chords. The precise distribution of forces allowed the designer to employ typical bolted shear splices for the top and bottom chords and typical pin connections at the diagonal end points.

GIRDER-TRUSS FOR SPAN-BY-SPAN CONSTRUCTION

Span-by-span bridge construction with precast concrete box segments often employs either trusses or girders to support each segment under its wings prior to post-tensioning. In the design of the Panchiao Viaduct in China, the space under the wings was too shallow for a stand-alone truss, and single girders on either side would have lacked the stability to support either lateral adjustments or the whole supporting system as it advances. Thus an unusual

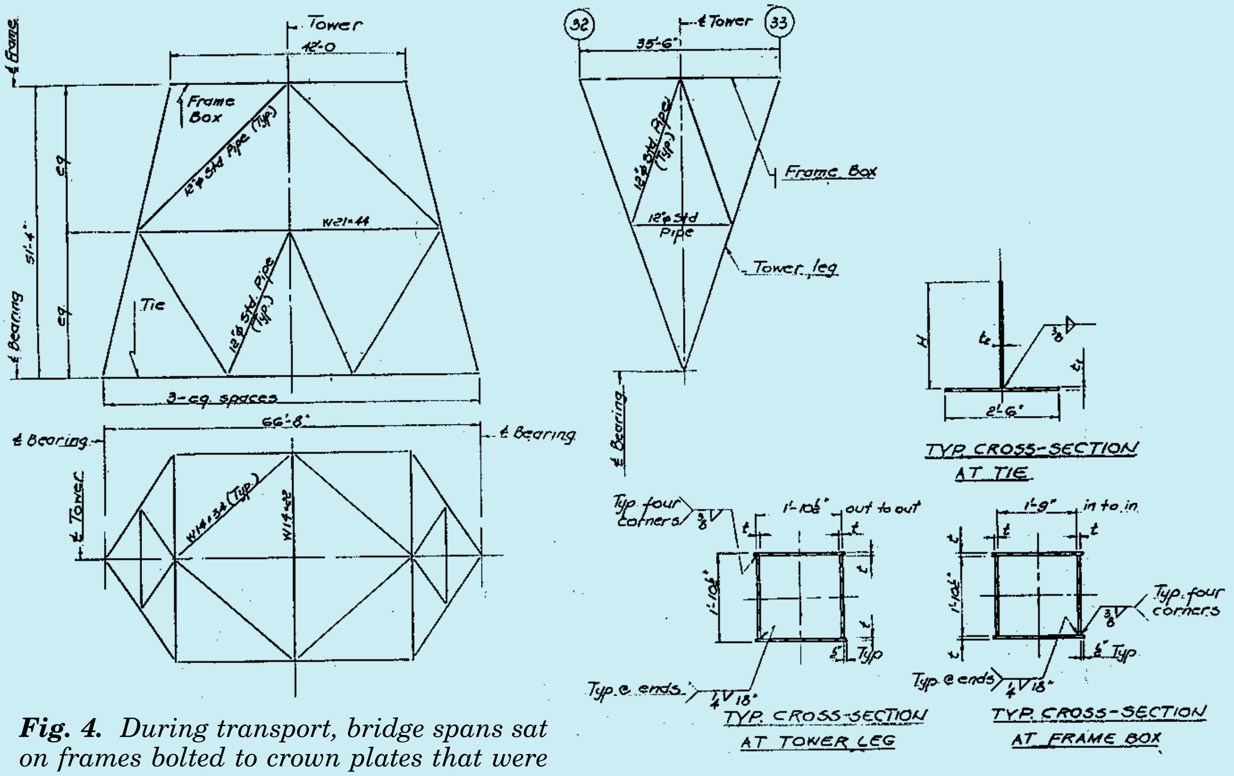

Fig. 4. *During transport, bridge spans sat on frames bolted to crown plates that were connected by full-penetration welds to the inclined tower legs.*

Fig. 3. *Span of Coleman Bridge supported by unique barge-tower transport system. Tower design required innovative steel connections described in article.*

girder-truss combination was introduced.

The segment-supporting system consisted of one tall and one short girder connected by diagonal members. The tall girder would bear the dead load of the segment and the short girder, acting as a truss chord, would bear lateral loads during adjustment of the segments. The space truss was designed with diagonals and verticals to connect the top and bottom flanges of the tall girder with the short girder, which itself became a truss chord (Figure 2).

The design challenge was to develop member connections to convert this highly asymmetrical system into a homogeneous structure. The solution was to weld gusset plates to the girder stiffeners at oblique angles that would accommodate vertical and diagonal truss members in two planes. Thus the stiffeners, in combination with the girder webs, effectively became truss members.

This unique gusset plate design offered an efficient and economical solution to a rare truss/girder application.

Bridge-Span Transport System

A project to design 51'-tall twin towers for transporting fully constructed replacement spans of the George P. Coleman Bridge on the York River in Virginia offered a variety of unprecedented opportunities for developing original steel connections (Figure 3). In order to meet a highly accelerated 12-day schedule for replacing all above-water spans of the bridge, the contractor completed fabrication of the replacements 40 miles upriver and planned to transport the structures on towers mounted on linked barges to the pre-existing piers.

In terms of connections, the tower designer had four objectives:

1. Stabilize the tower tops to accommodate the spans, which were up to 559 feet long and weighed as much as 4128 tons;
2. Brace the unusual V-shaped tower-leg system;
3. Develop a pivoting mechanism at the tower base (the point of the "V") to enable the entire system to adjust to lateral forces; and
4. Transfer the lateral forces from the loaded tower system to bulkheads below the barge deck.

At each tower top, a rectangular frame was designed to receive a four-point load; each bridge span would therefore be supported at eight points. The frame was bolted to thick crown plates that were welded to the leg tops (Figure 4). A load from a bridge span would thereby be transmitted through the frame diaphragms to the frame base, through the crown plates, and eventually to the tower legs. The key to this detail was the introduction of the crown plates,

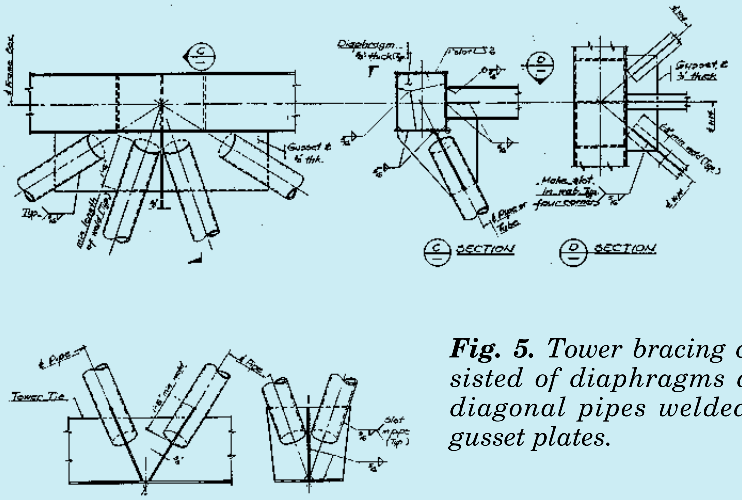

Fig. 5. *Tower bracing consisted of diaphragms and diagonal pipes welded to gusset plates.*

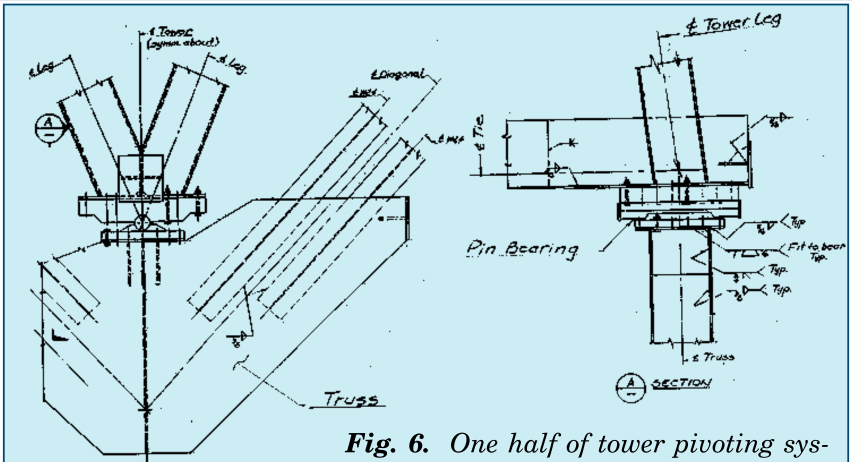

Fig. 6. *One half of tower pivoting system, showing base plate, tie, and legs, all connected by welds.*

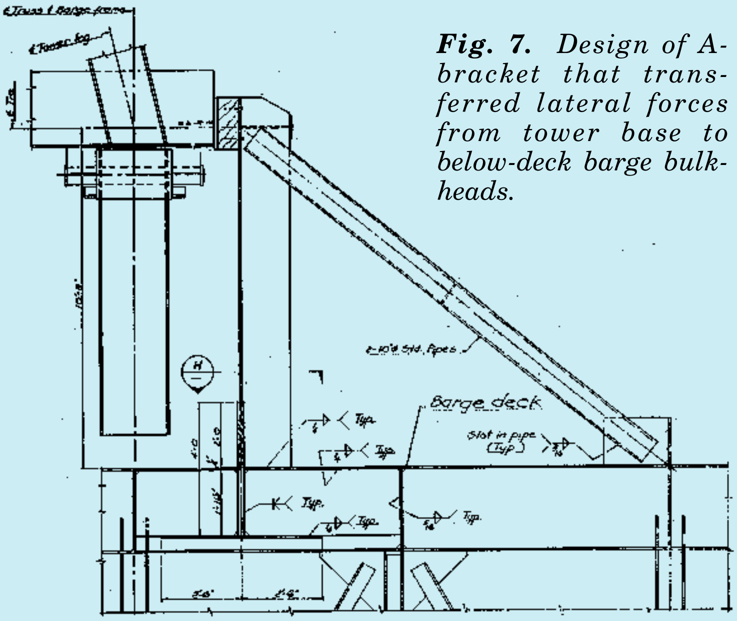

Fig. 7. *Design of A-bracket that transferred lateral forces from tower base to below-deck barge bulkheads.*

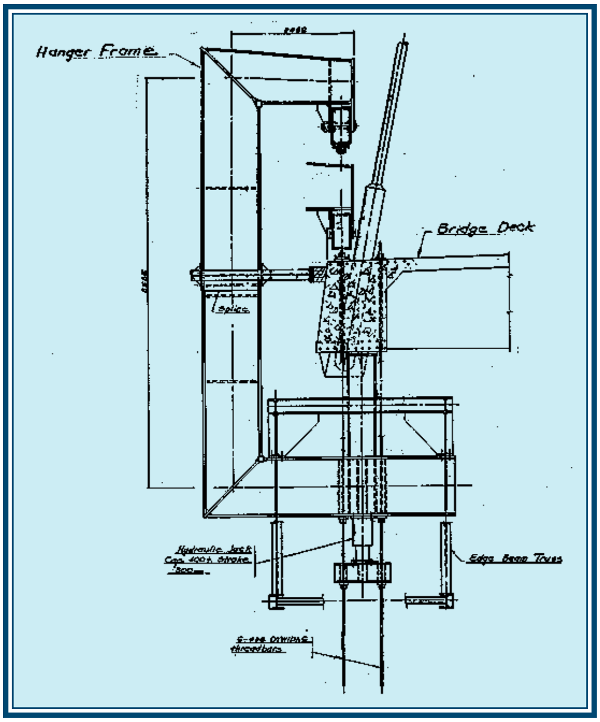

Fig. 8. *C-hanger and detail of low-sulfur steel bar welded to inner knee to resist tension forces.*

to which leg tops could be connected by full-penetration welds.

Bracing Connections. Design of the bracing connections between the legs was complicated by the leg inclinations, by the box shape configurations of the legs and the upper frame, and by the inverted T-section shape of ties. The solution was to install diaphragms and gusset plates at different angles to connect the diagonal pipes with the rectangular boxes of the main members (Figure 5).

Pivoting System. The pivoting system comprised two pin bearings, thick base plates, and a horizontal tie joining the "V" end points (Figure 6). The legs were connected by full penetration welds to the vertical and horizontal components of the tie. The welds created a smooth force transition from each leg to the tie and to the bearing plates on which the tie ends were seated. The tie spanned the space between the leg bottoms and ensured uniform movement of the two leg sets. The pin bearings, located under the base plates, were designed to slide in the direction of the elongation when a bridge span was applied to the towers.

Transverse Forces. The combination of barge and tug motions and wind and wave pressures would create the transverse component of the cargo weight, a force comprising hundreds of kips of random loading. The design strategy was to absorb these forces at the tower base and transfer them directly to the barge bulkheads. To perform this function, large "A"-shaped brackets, which would serve as horizontal restraints, were first installed near the bearing pins (Figure 7). The vertical tension component of the bracket would be a T-shaped post anchored by vertical bars that passed through the deck where they were welded to vertical plates. The other ends of the plates were in turn welded to the bulkheads. The key to this solution was to also weld the tops of these plates to the bottom of the 0.5-inch-thick barge deck. The deck and plate thereby acted together as a stiff beam to successfully carry all applied loads to the bulkheads.

KNEE CONNECTIONS

Knee or haunch connections are common in building frames. The inner corners of such frames are typically strengthened with a welded compression node, a standard and well-developed design. In contrast, methods to strengthen inner knee-frame corners subjected to tension forces are not readily available in the body of engineering standards. The basic approach of welding an inner corner where three plates intersect may result in lamellar tearing and subsequent structural failure when sequential tension forces are applied.

Potential tension failure of an inner knee connection was a major concern in the design of C-shaped hanger frames proposed for the construction of the Dame Point Bridge in Jacksonville, Florida. The frames were to be used to support and advance formtravelers for casting inverted-U bridge segments.

The equipment designer proposed that the necessary strength could be achieved by fusing a square bar of low-sulfur steel to the inner intersection of the three hanger plates. Low-sulfur steel has an improved through-thickness ductility, and thus is highly resistant to lamellar tearing. The bar was connected at the required angles to the C-frame knee with a full-penetration weld, creating a homogeneous node (Figure 8).

C-frames containing this detail performed successfully in the construction of both the Dame Point Bridge and the Glebe Island Bridge in Australia. Low-sulfur steel is manufactured by Bethlehem under the Integra brand name and by Lukens under the Fineline brand name.

ART IN DESIGN

Because of their complexity and structural importance, connections are among the most difficult and costly design and construction details. For reasons of safety and durability alone, the author believes that connections should be receiving the increased attention of design engineers.

Because they serve as a visual focal point in many steel projects, innovative and well-designed connections also have the potential to greatly enrich an overall design. Indeed, many critics who address themselves to the aesthetic aspects of buildings, bridges, and other engineering and architectural works often give considerable attention