Structural Design

design issues for
structural engineers

Survival of a Crane Truss in a Waterfront Project

Part 2

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Site conditions often dictate the engineering of long-span trusses for container cranes. Part 1 of this article (August 2012, STRUCTURE) included discussions on stress and fatigue, corrosion, dynamic impact allowance and the effect of dynamic impact on fatigue. Part 2 provides additional insight into torsional resistance, fracture critical connections and buckling analysis of built-up box elements. Other important issues discussed include methods of corrosion protection within ice fluctuation zones, and proposed deflection and camber criteria for long-span crane ways.

Truss Bearing and Torsional Resistance

The rotational restraint imposed on the bearing ends of a truss creates large negative moment, which can crack the deck and impose high tension cyclic loads in the deck over the support detail. The best solution is to allow the truss support unimpeded rotation (*Figure 6*).

Deck beams supported by the crane truss must provide a restraint for top chord rotation around its longitudinal axis (*Figure 7*). The deck beam connection to the crane girder has to resolve the torsional moment imposed by the deck beam support reaction into the flexural moment action at the beam support. Fatigue longevity of such a connection is controlled by the magnitude of the built up plastic deformation. Plastic deformations occur only in the presence of shear stress. In a biaxial state of stress, the maximum shear stress,

$\tau = (f_1 – f_2) / 2 \rightarrow 0$ (Equation 5)

as the principal stresses f_1 and f_2 approach the same value. Biaxial tensile stresses tend to cause brittle failure, rather than plastic shear deformations. The state of biaxial stress can be aggravated by notches or other geometric discontinuities. Therefore, it is important to select weld designs and weld locations properly. The connection detail shown in *Figure 7* falls under "Von Mises" criteria, described for plate design by:

$f_y^2 = f_1^2 + f_2^2 – f_1 * f_2 + 3f^2_v \leq F_y$ (*Equation 6*)

where f_1 and f_2 are principal axial stresses, and f_v is a shear stress. Obviously, the maximum shear stress (τ) approaches zero only when both axial principal stresses have the same sign and magnitude.

Both principal stresses at the top plate of the connection are compression stresses, while those at the bottom plate have opposite signs. The connection detail described in *Figure 7* prevents angular twist of the top chord of the truss. However, the ability of the torsional supports to prevent angular twist comes at a price. Any restraint imposed on cyclic movement is prone to fatigue distress. Such connections should be carefully designed, in order to keep the stress range in the connection below the fatigue threshold limit. It is also good practice to keep intersecting welds away from geometric discontinuities, where forces normal to each other frequently reverse signs.

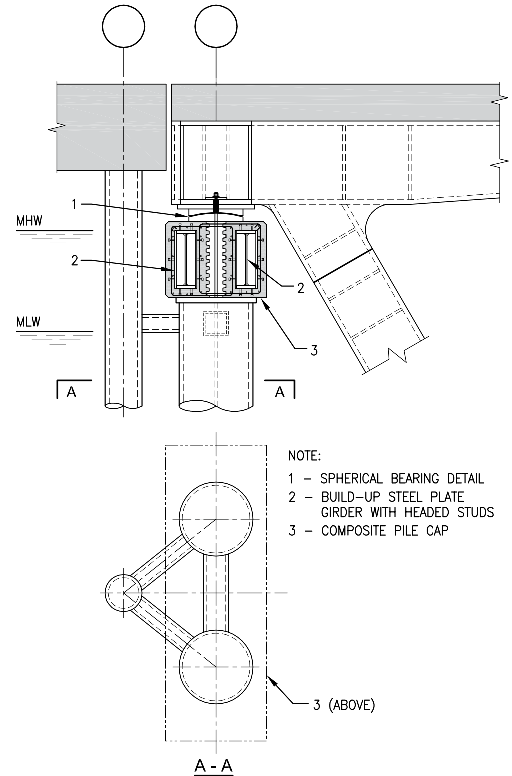

Figure 6: Truss bearing detail.

Buckling of Compression Elements and Fatigue

Some truss elements are subjected to large compression forces. Buckling of any of these elements leads to accelerated fatigue. That phenomenon was observed in the continuous span crane girders of steel mills, where tension field action (or truss action) led to accelerated fatigue of welds connecting the web to the flanges. Similarly, buckling of truss compression elements increases forces on elements in the tension stress range. It is extremely important to check all compression elements for local "lobe type" buckling. The present state-of-the-art is outlined in section E7.2 of the AISC 13th Edition. However, formulas in that section are based on a reduced effective width of the plate, which is based on the assumption that the total load is carried by strips adjacent to the supported edges (the box corners) of the buckled plate. Section E7.2 discusses post-buckling behavior of square and rectangular slender plates of uniform thickness. Such behavior is characterized

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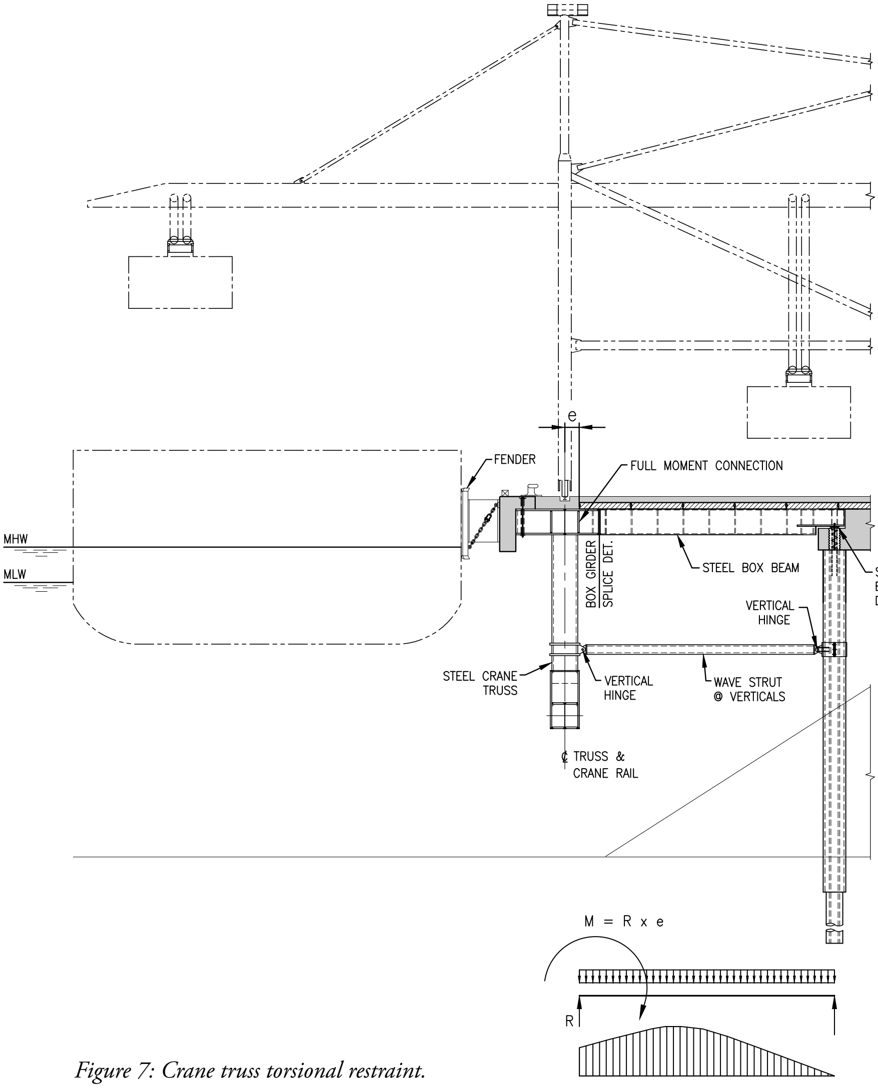

Figure 7: Crane truss torsional restraint.

by the number of lobes, or half waves, developing in the plate after buckling. As the load is increased, the edge stresses increase, but mid-width stresses decrease. Analytically, that behavior is approximated by selecting the total width of the strips, known as the effective width, such that the product of this width and the maximum stress in the plate is equal to the integrated product of the actual stress over the entire plate width. The plate's ability to resist shear strain contributes to its post-buckling strength. Unfortunately, the AISC 13th Edition does not fully explain this concept; such behavior creates a useful resistance mechanism, but the designer must understand the limitations of such an approach. In particular, while post-buckling behavior can be used for the analysis of redundant systems, it should not be used for the analysis of non-redundant structures subject to cyclic loading.

Original formulas for the strength analysis of circular tubes were based on test results restricted to elastic local buckling cited by Brockenbrouh and Johnston (*USS Steel Design Manual*). A circular tube section with a thick wall usually fails in multi-lobe buckling, and is a preferable section for compression elements. The buckled form of the circular tube is unstable and cannot be used in the post-buckling mode. According to experimental test data, the local buckling stress for a circular tube is:

$f_{cr} = 0.75f_y + 0.016\ Et / R$ (*Equation 7*)

where R is the inside radius and t is the wall thickness. Test results confirmed that tubes with a slenderness ratio of $f_yR/(Et) \leq 0.064$ could be stressed to the yield point without local buckling.

In circumstances where a circular tube section cannot be used as a compression element due to truss geometry, a rectangular box section is the next preferable section for a compression member. However, the rectangular box section tends to fail in a four-lobe buckling mode. The section with a larger number of lobes, or half-waves, is more stable and can resist a larger buckling force. One way to deal with that particular problem is to install properly spaced internal diaphragms, and check the plate between diaphragms for buckling from uniform compression loads. The rectangular box section buckles after the plate with the smallest stiffness begins buckling. The stiffness of the two adjacent plates, and the stiffening effect of the internal angle, delay the buckling of the whole box assembly. Plate theory provides a generic expression for rectangular plate local buckling in the elastic range:

$f_{cr} = f_y = k_c\ \pi^2 D / (b^2 t)$ (*Equation 8*)

where
$D = Et^3 / 12(1 - \nu^2)$ = plate flexural stiffness;
$\nu = 0.30$ = Poisson ratio in the elastic range;
$\nu = 0.50$ = Poisson ratio in the plastic range;
t = plate thickness;
b = plate width; and
k_c = buckling coefficient based on relative flexural stiffness of both plates.

Brockenbrouh and Johnston provide modified local buckling coefficients, k_w, based on the interaction of two adjacent long plates of a rectangular tube.

Rectangular tube buckling in the plastic range ($f_{cr} \geq 0.5f_y$) can be determined from:

$f'_{cr} = f_y - 0.25f_y^2/f_{cr}$ (*Equation 9*)

The original formulas from the theory of plates cited in the *USS Steel Design Manual* have better defined boundaries and are more user-friendly. In that sense, the "old forgotten art" should be given due respect.

Both *Equations 8* and *9* represent nominal buckling strength. Appropriate resistance or safety factors should be applied to both formulas.

$\phi_c = 0.9$ (LRFD) $\Omega_c = 1.67$ (ASD)

Plate design for post-buckling behavior of built-up compression elements of the truss should not be allowed.

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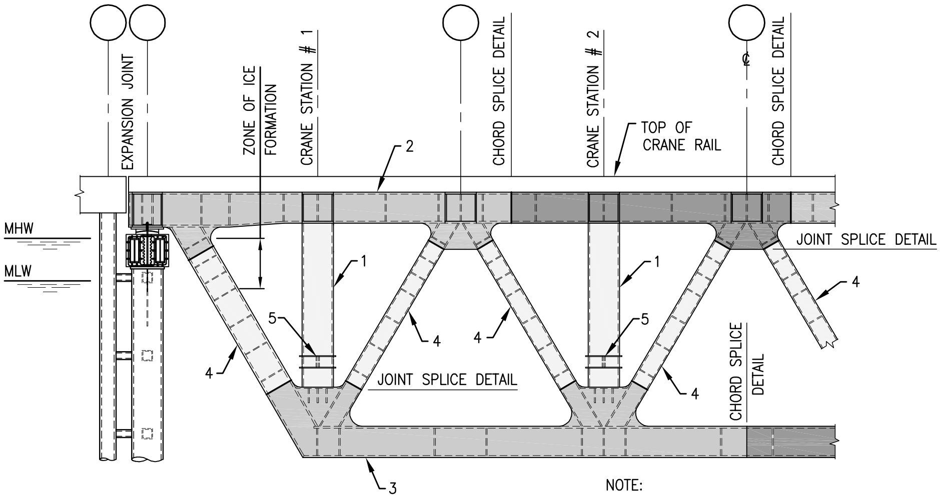

Figure 4 (from part 1): Crane truss elevation.

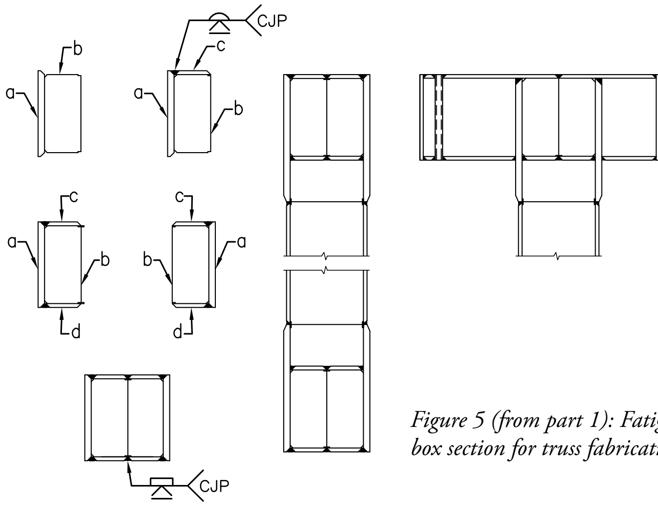

Figure 5 (from part 1): Fatigue resistant box section for truss fabrication.

Additional Factors Affecting Fatigue Life

Residual Stresses and Lamellar Tear

Welding, cutting, preheating, and any processes involving heat or deformation can produce high levels of tensile residual stress. Residual tensile stress decreases fatigue strength. Sometimes, the likelihood of brittle failure in the structure can be minimized by post-weld heat treatment, but the mechanical properties of the welded joints may be adversely affected. A suggested fabrication sequence for a box section with efficient fatigue resistance is shown in *Figure 5*.

One of the most critical issues requiring the designer's attention is related to welding details. Weldments prone to lamellar tear must be avoided. While it is impossible to avoid such potential behavior completely, the designer is urged to use prequalified, full-penetration welds as shown in the AISC 13th Edition.

Grain Size

Smaller metal grain size allows for longer fatigue life. Extensive heating increases the size of the metal crystals, reducing fatigue strength.

Internal Defects

Weld porosity, non-metallic inclusions and internal shrinkage can significantly reduce fatigue strength. Therefore, all welds subjected to cyclic loading should be checked for porosity and internal cracks using advanced quality control methods.

Weldments

The designer of the truss is urged to develop a welding procedure that minimizes the number of assembly welds. The ideal assembly is shown in *Figure 4* and *Figure 5*.

The designer should realize that any additional welds will increase stresses caused by weld shrinkage. Intersecting or even parallel welds increase the likelihood of the so-called "banana effect" in built-up plate assemblies. The best way to control this phenomenon is to minimize the number of welds and avoid intersecting welds. It should be noted that sectional distortions have serious detrimental effect on fatigue life of the structure that cannot be analytically factored into the assembly design.

Another highly important issue, frequently neglected by design professionals, is the selection of weld material. The weld materials should be neutral or cathodic against the base metal. A similar approach should be used for selection of bolts in bolted connections. The consequences of mistakes in selecting the right weld and fastener material can be extremely costly, and sometimes catastrophic.

Fracture Critical Elements

The crane truss is a non-redundant structure. Failure of any truss element has catastrophic consequences. All members of the truss having a stress ratio $-1 \le R < 1$ should be designed as fracture critical elements. Both, the AISC 13th Edition and the AASHTO LRFD manuals prescribe certain Charpy V-notch toughness requirements for weld and base metal materials in such members. However, it is prudent to use even more stringent toughness requirements than those currently prescribed by both codes. The Charpy V-notch impact test evaluates notch toughness, or the resistance of a specimen to fracture in the presence of V-shaped notches. The amount of energy required to fracture the specimen is used for plotting two curves:

- Energy vs. Temperature
- Percentage of Shear Fracture vs. Temperature

The temperature at which the percentage of shear fracture decreases to 50% is called the fracture transition temperature. The temperature at which the selected value of energy is absorbed (usually 20 ft-lb) is called the ductility transition temperature. The lower the transition temperature, the better the resistance to brittle fracture. Selected steel components must absorb a specified energy (E = 20 ft-lb) at the lowest expected operation temperature. The best material for structures subjected to high cyclic loads in an aggressive marine environment is ASTM A852 steel with F_y = 70 ksi, formerly known as COR-TEN B-QT (high strength, low alloy quenched and tempered steel).

Environment and Corrosion Protection

Corrosion fatigue is a problem encountered by many marine structures. The best way to protect a submerged waterfront structure is to prevent contact with the aggressive medium. Protection is especially important within the boundaries subjected to high abrasion and ice movement. A newly developed, highly alkaline modified cementitious epoxy coating, Cemprotec E942, provides superior resistance to impact and water ingress. However, even the best paint will eventually peel off the steel due to ice abrasion and ice adhesion during high tide/low tide fluctuation. The fact is, treatment of steel with a protective coating is always too little, too late and too expensive. What is the solution? The best way to deal with corrosion protection of steel within a zone of high abrasion is to prevent the coating from peeling off. Creation of a low friction zone around the steel within high tide/low tide depth solves that problem. Such treatment prevents direct ice contact with the painted surface and allows ice to slide up and down during the tide fluctuation. The abrasion protection detail shown in *Figure 8* efficiently protects the paint on struts and diagonals from peeling off. UHMW-PE panels bolted to box and tube sections within the affected depth will prevent ice from adhering to steel elements. A final line of defense for fully submerged steel can be provided by passive cathodic protection.

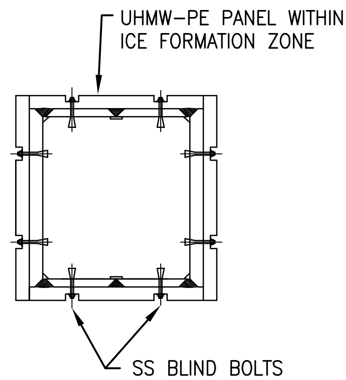

Figure 8: Abrasion protection detail within ice formation zone.

Open sections of diagonal joints at the truss top chord are highly susceptible to accelerated low water corrosion (ALWC). The best solution is to fill the annular space between the side plates of the open sections with expandable closed-cell foam, which prevents moisture retention and growth of sulfate-reducing bacteria.

Truss Camber Design

A crane girder or truss that spans more than 75 feet should be cambered for deflection due to dead load (weight of the crane girder + attributed weight of the deck) plus half of the live load, including any load on the deck and the maximum load delivered to the girder from the wheels of the crane bogie. No impact factor should be included. The maximum vertical deflection for a crane girder due to dead load and 100% of the live load is limited to L/1000. Girders or trusses with spans greater than 100 feet are designed with deflections below L/1200. Larger deflection creates severe traction problems, and leads to untimely rail or bogie wheel replacement.

Summary

Fatigue analysis is not an exact science, but rather an art based on statistical formulas and solid engineering judgment. However, it is an important and valuable tool for estimating the service life of a structure. Fatigue is a plastic damage accumulation. Signs of fatigue are frequently visible. Therefore, it is highly important to identify all fracture critical connections, and schedule periodic inspections from early in the structure's lifespan. Understanding the plastic damage accumulation concept will help the engineer design a cost-effective and long-serving structure.▪

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