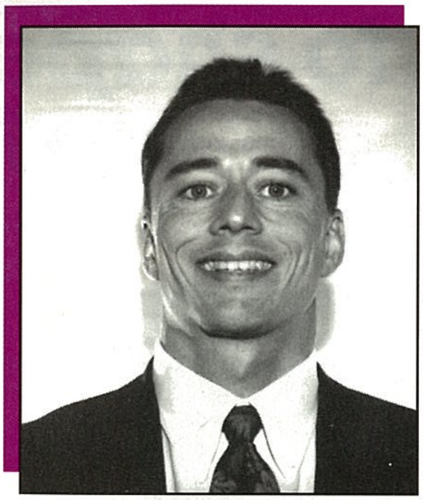
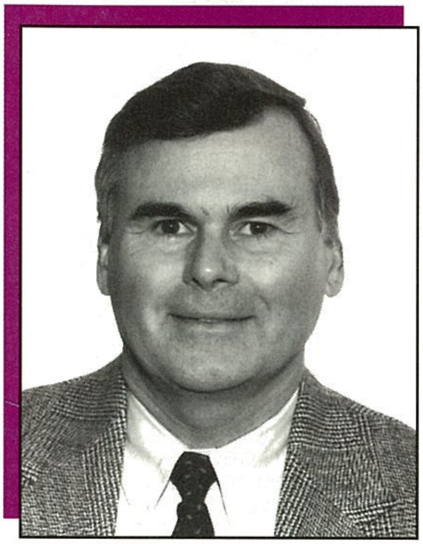
CRANE GIRDER DESIGN

An examination of design and fatigue considerations





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PROPER FUNCTIONING OF OVERHEAD BRIDGE CRANES IS DEPENDENT upon proper crane runway girder design and detailing. The runway design must account for the fatigue effects caused by the repeated passing of the crane, and the details must not create restraints that limit the girders ability to deflect under the applied crane loads. The runway girders should be thought of as a part of a system comprised of the crane rails, rail attachments, electrification support, crane stop, crane column attachment, tie back and the girder itself. All of these items should be incorporated into the design and detailing of the crane runway girder system.

Stiffer elements of a structural assembly tend to attract load. This holds true for crane girders. In a statically loaded member, the tendency for an attachment to "draw" load can often be neglected. However, with the repeated application of loads this condition can lead to fatigue damage. Relative deflections between adjacent members may often be neglected in statically loaded structures. In dynamically loaded structures these relative movements can result in some form of fatigue damage. It has been estimated that 90% of crane girder problems are associated with fatigue cracking. To address these conditions, this paper will briefly discuss the phenomena of fatigue damage, then the nature of crane loads will be discussed followed with a discussion of typical connections and details, lastly a design example will be provided.

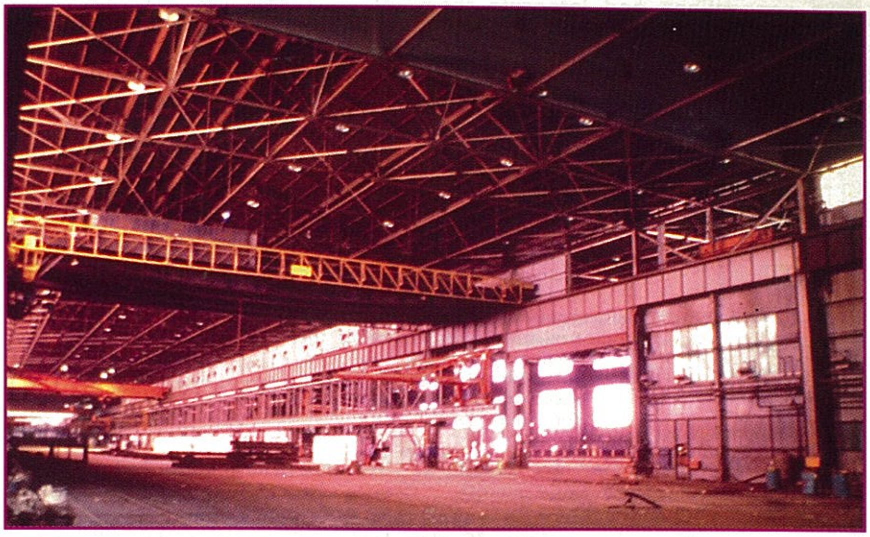
The basic phenomena of fatigue damage has been understood for may years. Engineers have designed crane runway girders that have performed with minimal problems while being subjected to millions of cycles of loading. The girders that are performing successfully have been properly designed and detailed to:

- limit the applied stress range to acceptable levels.
- avoid unexpected restraints at the attachments and supports
- avoid stress concentrations at critical locations
- avoid eccentricities due to rail misalignment or crane travel
- minimize residual stresses

Runway systems that have performed well have been properly maintained by keeping the rails and girders aligned and level.

FATIGUE DAMAGE

Fatigue damage can be characterized as progressive crack growth due to fluctuating stress on the member. Fatigue cracks initiate at small defects or imperfections in the base material or weld metal. The imperfections act as stress risers that magnify the applied elastic stresses into small regions of plastic stress. As load cycles are applied, the plastic strain in the small plastic region advances until the material separates and the crack advances. At that point, the plastic stress region moves to the new tip of the crack and the process repeats itself. Eventually, the crack size becomes large enough that the combined effect of the crack size and the applied stress exceed the toughness of the material and a final fracture occurs. Common grades of structural steel and common sizes of members used in interior applications are not prone to brittle fracture. The typical situation occurs when cracks reach a noticeable size and are repaired before catastrophic failure occurs. A damaged girder can be evaluated for fitness for purpose using various fatigue life prediction techniques and fracture mechanics. These methods are outside the scope of this discussion.



The phenomena of fatigue damage or crack growth is considered to occur in three stages: initiation; propagation; and final fracture. The ***crack initiation*** is affected by the initial flaw size, the amount of residual stress, the presence of corrosion and the applied stress range. Most of the fatigue life of an unwelded or unnotched member is taken up in the initiation of the crack. Fabricated members typically will have small defects from the welding process that can be considered as initiated cracks. In this case, the entire useful life of the section is taken up in crack propagation. The useful life of the element is usually met when the crack reaches an objectionable size.

Crack propagation occurs when the applied loads fluctuate in tension or in reversal from tension to compression. Fluctuating compressive stress will not cause cracks to propagate. However, fluctuating compressive stresses in a region of residual tensile stress will cause cracks to propagate. In this case, the cracks will stop growing after the residual stress is released or the crack extends out of the tensile region.

The general design solutions to ensure adequate service life of members subject to repeated loads are to limit the buildup of residual stress, limit the size of initial imperfections, and to limit the magnitude of the applied stress range. The AISC Specification limits the allowable stress range for a given service life based on the anticipated severity of the stress riser for a given fabricated condition. In addition, it requires conformance with Chapter 9 of the AWS D1.1 *Structural Welding Code* (“Dynamically Loaded Structures”), which provides criteria for limiting the severity of stress risers found in weld metal and the adjacent base metal.

It should be noted that higher strength steel does not have a longer fatigue service life than A36 steel. That is, *the rate of crack growth is independent of the yield strength of the material.* Similarly, the rate of crack growth is not effected by the toughness of the material. A given cross section of higher toughness will be able to resist the effect of a larger crack with out fracture. However, at this stage of the service life of the member, only a few additional cycles would be gained by having a material of greater toughness. Thus, the AISC Specification provisions regarding fatigue conditions are independent of material strength and toughness. The material design requirements for strength and toughness are the same for crane runway girders as for statically loaded girders.

Crane Loads

Each runway is designed to support a specific crane or group of cranes. The weight of the crane bridge and trolley and the wheel spacing for the specific crane should be obtained from the crane manufacturer. The crane weight can vary significantly depending on the manufacturer and the classification of the crane. Based on the manufacturer’s data, forces are: determined to account for impact, lateral loads, and longitudinal loads. The AISC Specification, and most model building codes address crane loads and set minimum standards for these loads. The AISE Technical Report No. 13 *Guide for the Design and Construction of Mill Buildings* also sets minimum requirements for impact, lateral and longitudinal crane loads. The AISE requirements are used when the engineer and owner determine that the level of quality set by the AISE Guide is appropriate for a given project. It should be noted that the latest edition of the BOCA *National Building Code* has adopted the AISE Guide for the purpose of determining crane loads.

Vertical crane loads are termed as wheel loads. The magnitude of the wheel load is at its maximum when the crane is lifting its rated capacity load, and the trolley is located at the end of the bridge directly adjacent to the girder. In addition to shear and bending stresses in the girder cross section, the wheel loads result in localized stresses under the wheel. AISE Technical Report No. 13 provides an equation for calculating this localized stress. The method is based on considering the top flange and rail as beams on an idealized elastic foundation. The axial stiffness of the web determines the stiffness of the elastic foundation. The compressive stress is oriented parallel to the axis of the member and can be added to the flexural compressive stress. Localized bending stresses at the top flange to web juncture can also occur when the rail is not aligned directly over the girder web. To minimize fatigue cracking at the junction of the web to the top flange the AISE Technical Report No. 13 requires a full penetration weld plus contoured fillet welds between the web and top flange. It should be noted that the localized wheel loads will occur with each passage of the wheel. A girder supporting a four wheel end truck will experience four stress fluctuations for each passage of the crane.

The vertical wheel loads are typically factored using the same impact factor. It accounts for the effect of acceleration in hoisting the loads and impact caused by the wheels jumping over irregularities in the rail. Bolted rail splices tend to cause greater impact than welded splices. In the U.S., most codes require a 25% increase in loads for cab and radio operated cranes and a 10% increase for pendant operated cranes.

Lateral crane loads are oriented perpendicular to the crane runway and are applied at the top of the rails. Lateral loads are caused by:

- acceleration and deceleration of the trolley and loads
- non vertical lifting
- unbalanced drive mechanisms
- oblique or skewed travel of the bridge

Except for the case of the trolley running into the end stops, the magnitude of lateral load due to trolley movement and nonvertical lifting is limited by the coefficient of friction between the end truck wheels and rails. Drive mechanisms are either equal on each side of the crane or they are balanced to align the center of the tractive force with the center of gravity of the crane

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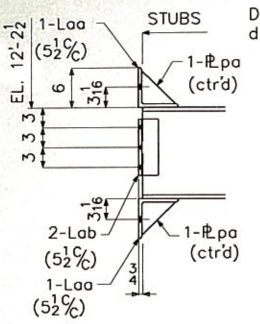

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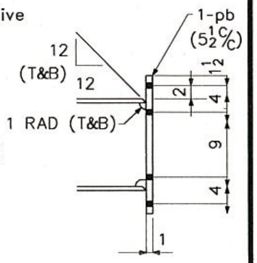

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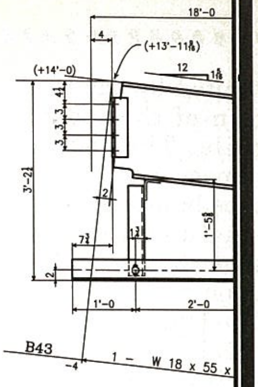
and lifted load. If the drive mechanism is not balanced, acceleration and deceleration of the bridge crane results in skewing of the bridge relative to the runways. The skewing imparts lateral loads onto the crane girder. Oblique travel refers to the fact that bridge cranes can not travel in a perfectly straight line down the center of runway. It may be thought of as similar to the motion of an automobile with one tire under inflated. The tendency of the crane to wander can be minimized by properly maintaining the end trucks and the rails. The wheels should be parallel and the should be in similar condition. The rails should be kept aligned and the surfaces should be smooth and level. A poorly aligned and maintained runway can result in larger lateral loads. The larger lateral loads will in turn reduce the service life of the crane girder.

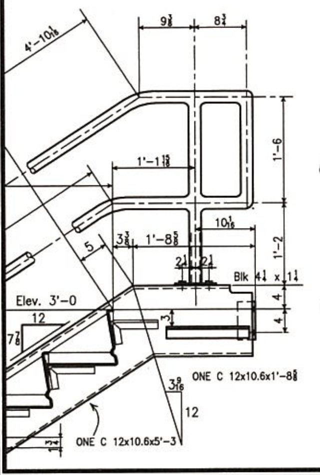
The AISC Specification and most model building codes set the magnitude of lateral loads at 20% of the sum of the weights of the trolley and the lifted load. The AISE Technical Report varies the magnitude of the lateral load based on the function of the crane (see Table 1).

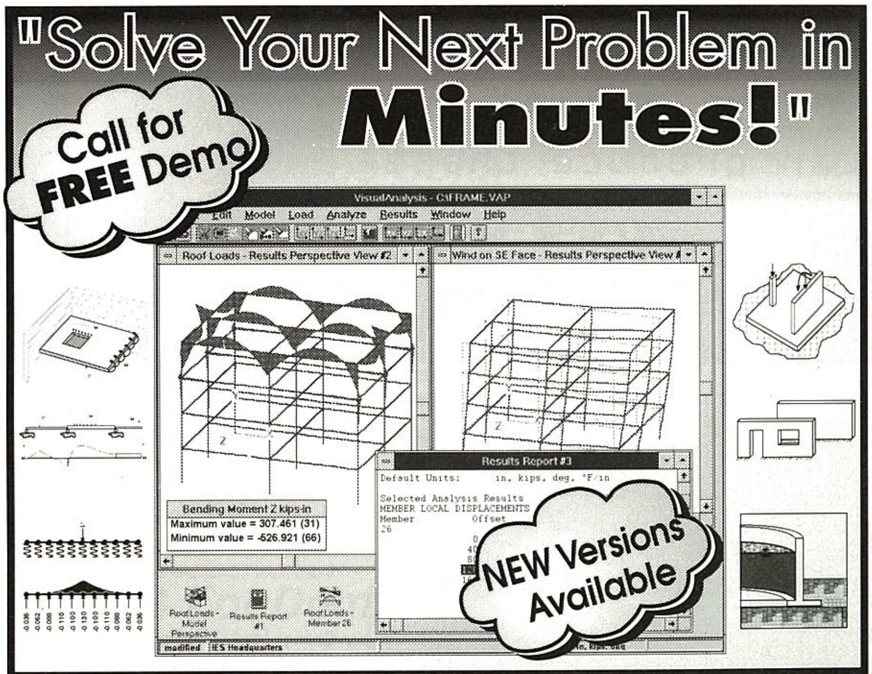
Longitudinal crane forces are due to either acceleration and deceleration of the bridge crane or the crane impacting the bumper. The tractive forces are

Table 1: AISE Crane Side Thrusts

Crane Type	Total Side thrust % of lifted load
Mill crane	40
Ladle cranes	40
Clamshell bucket & magnet cranes (including slab & billet yard cranes)	100
Soaking pit cranes	100
Stripping cranes	100
Motor room maintenance cranes, ect.	30
Stacker cranes (cab-operated)	200







limited by the coefficient of friction of the steel wheel on the rails. The force imparted by impact with hydraulic or spring type bumpers is a function of the length of stroke of the bumper and the velocity of the crane upon impact with the crane stop. The longitudinal forces should be obtained from the crane manufacturer. If this information is not available, the AISE Technical Report provides equations that can be used for determining the bumper force.

Consideration of fatigue requires that the designer determine the anticipated number of load cycles. It is a common practice for the crane girder to be designed for a service life that is consistent with the crane classification. The correlation between the CMAA crane designations and the AISC loading conditions can be seen in Table 2. The MBMA *Low-Rise Building Systems Manual* provides a design method for reducing the AISC loading condition for the girder. This method accounts for the fact that for many cranes the loading that is applied on a regular basis is less than the maximum wheel load.

Table 2: Crane Loading Conditions

CMAA Crane Classification	AISC Loading Condition
A, B	1
C,D	2
E	3
F	4

For cranes with scheduled production tasks, the number of cycles can be directly calculated based on anticipated use.

DETAILING & FABRICATION CONSIDERATIONS

Welding

The vast majority of stress risers that lead to crack propagation are weld defects. Common weld defects are: lack of fusion or penetration, slag inclusions, undercut, and porosity. Lack of fusion and penetration or cracks are severe stress risers. Slag inclusions and undercut are significant defects in areas of relatively high stress. It should be noted that surface defects are far more harmful than buried defects. Also, the orientation of the defects is important. Planer defects normal to the line of applied stress are more critical than defects parallel to the line of stress.

Visual inspection during fabrication is the most useful method of ensuring adequate quality control of the fabricated elements. It should be noted that visual inspection is mandatory (per AWS, for the contractor) for both statically and dynamically loaded structures.

The fabrication sequence should be controlled to limit restraint during welding so as to reduce the residual stresses created by the welding process. For example, when fabricating a plate girder, the splices of the flange and web plates should be made before the flanges and web plates are welded together.

Tiebacks

Tiebacks are provided at the end of the crane runway girders to transfer lateral forces from the girder top flange into the crane column and to laterally restrain the top flange of the crane girder against buckling. The tiebacks must have adequate strength to transfer the lateral crane loads. However, the tiebacks must also be flexible enough to allow for longitudinal movement of the top of the girder caused by girder end rotation. The amount of longitudinal movement due to the end rotation of the girder can be significant. The end rotation of a 40 foot girder that has undergone a deflection of span over 600 is about .005 radians. For a 36 inch deep girder this results in .2" of horizontal movement at the top flange. The tieback must also allow for vertical movement due to axial shortening of the crane column. This vertical movement can be in the range of $^1/_4$ in. In general, the tie back should be attached directly to the top flange of the girder. Attachment to the web of the girder with a diaphragm plate should be avoided. The lateral load path for this detail causes bending stresses in the girder web perpendicular to the girder cross section. The diaphragm plate also tends to resist movement due to the axial shortening of the crane column.

Bearing Stiffeners

Bearing stiffeners should be provided at the ends of the girders as required by the AISC Specification paragraphs K1.3 and K1.4. The AISE Guide requires that full penetration welds be used to connect the top of the bearing stiffeners to the top flange of the girder. Fillet welds are considered to be inadequate to transfer the concentrated wheel load stresses into the bearing stiffener. The bottom of the bearing stiffeners may be fitted (preferred) or fillet welded to the bottom flange. All stiffener to girder welds should be continuous. Horizontal cracks have been observed in the webs of crane girders with partial height bearing stiffeners. The cracks start between the bearing stiffener and the top flange and run longitudinally along the web of the girder. There are many possible causes for the propagation of these cracks. One possible explanation is that eccentricity in the placement of the rail on the girder causes distortion of the girder cross section and rotation of the girder cross section. At the support, the girder can not rotate, and the cross sectional distortion is concentrated into web bending above the stiffener. Cracking might also occur if the tie back detail holds up one edge of the crane girder restricting the movement caused by axial shortening of the crane column.

Intermediate Stiffeners

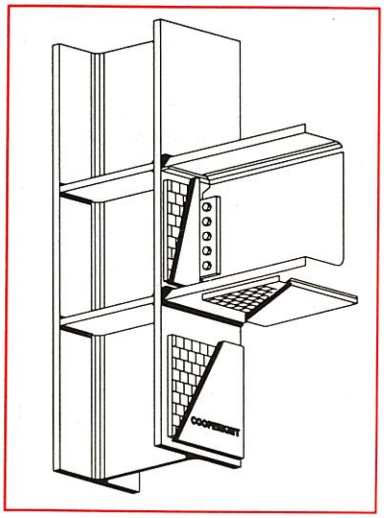
If intermediate stiffeners are used, the AISE Guide also requires that the intermediate stiffeners be welded to the top flange with full penetration welds, the stiffeners should be stopped short of the tension flange in accordance with the AISC Specification provisions contained in Chapter G. The AISE Guide also requires continuous stiffener to web welds for intermediate stiffeners.

Cap Channels

Channel caps or cap plates are frequently used to provide adequate top flange capacity to transfer lateral loads to the crane columns. The common heuristic is that a wide flange reinforced with a cap channel will be economical if it is 20 pounds a foot lighter than a unreinforced wide flange member. It should be noted that the cap channel or plate does not fit perfectly with 100% bearing on the top of the wide flange. The tolerances given in ASTM A6 allow the wide flange member to have some flange tilt along its length, or the plate may be cupped or slightly warped, or the channel may have some twist along its length. These conditions will leave small gaps between the top flange of the girder and the top plate or charmed The passage of the crane wheel over these gaps will tend to distress the channel or plate to top flange welds. Because of this phenomena, cap plates or channels should not be used with class E or F cranes. The Channel or plate welds to the top flange can be continuous or intermittent. However, the AISC Allowable stress for the base metal is reduced from Category B for continuous welds to Category E for intermittent welds.

Column Cap Plate

The crane column cap plate should be detailed so as to not restrain the end rotation of the girder. If the cap plate girder bolts are placed between the column flanges, the girder end rotation is resisted by a force couple between the column flange and the bolts. This detail has been known to cause bolt failures. Preferably, the girder should be bolted to the cap plate outside of the column flanges. The column cap plate should be extended outside of the column flange with the bolts to the girder placed outside of the column flanges. The



column cap plate should not be made overly thick as this detail requires the cap plate to distort to allow for the end rotation of the girder. The girder to cap plate bolts should be adequate to transfer the tractive or bumper forces to the longitudinal crane bracing. The engineer should consider using slotted holes perpendicular to the runway or oversize holes to allow tolerance for aligning the girders atop the crane columns.

Lacing

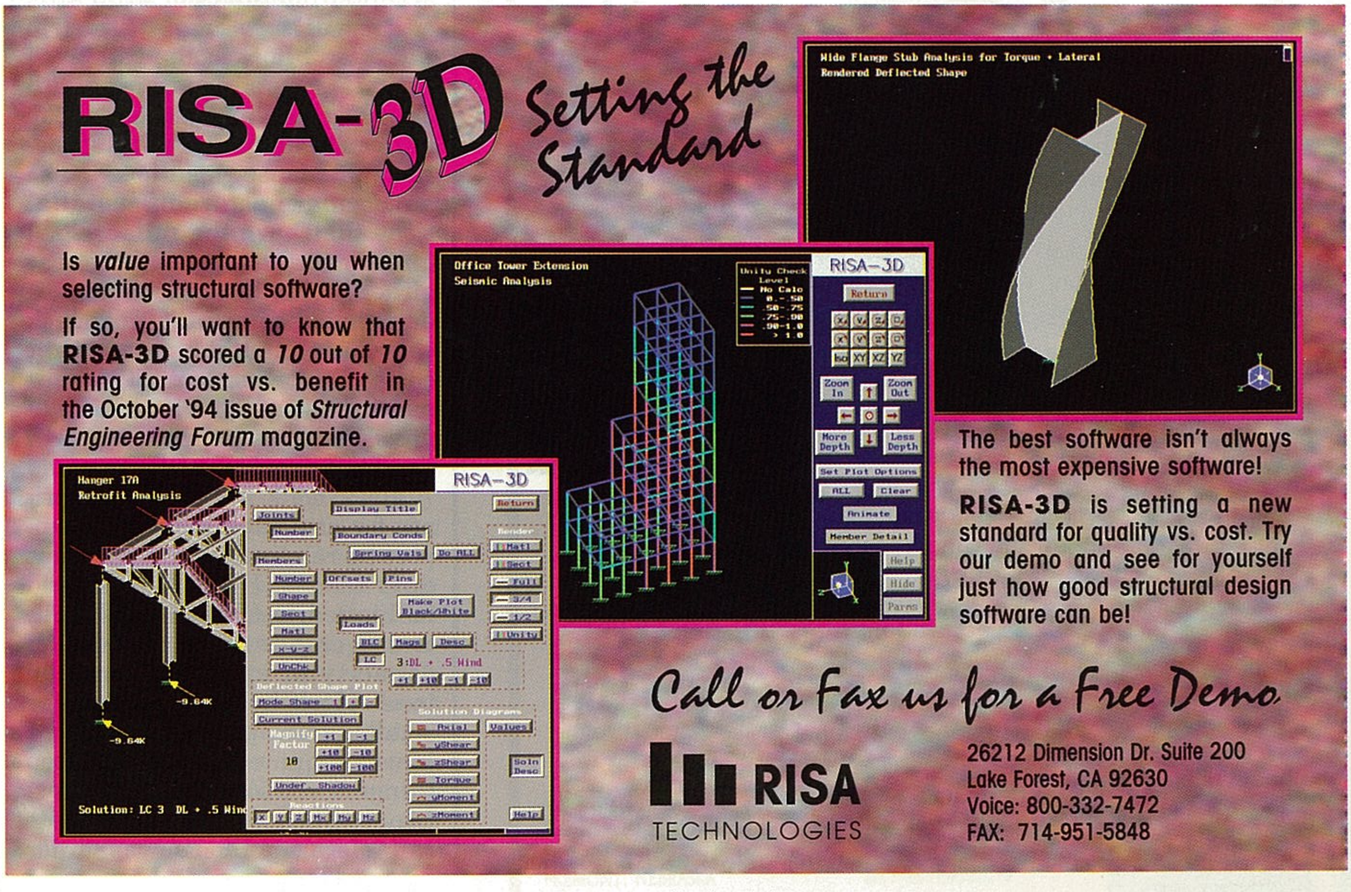
A horizontal truss can be used to resist the crane lateral forces, The truss is designed to span between the crane columns. Typically, the top flange of the girder acts as one chord of the truss while a back up beam acts as the other chord. The diagonal members are typically angles. Preferably, the angles should be bolted rather than welded. The crane girder will deflect downward when the crane passes, the back up beam will not. The design of the diagonal members should account for the fixed end moments that will be generated by this relative movement.

Walkways can be designed and detailed as a beam to transfer lateral loads to the crane columns. The lacing design may need to be incorporated into the walkway design. Similar to the crane lacing, the walkway connection to the crane girder needs to account for the vertical deflection of the crane girder. If the walkway is not intended to act a beam, then the designer must isolate the walkway from the crane girder.

The AISE Guide requires that crane runway girders with spans of 36 feet and over for building classifications A, B, and C or runway girder spans 40 feet and over in class D buildings shall have bottom flange bracing. This lacing is to be designed for $2\frac{1}{2}$% of the maximum bottom flange force, and is not to be welded to the bottom flange. Cross braces or diaphragms should not be added to this bracing so as to allow for the deflection of the crane beam relative to the back-up beam.

Sidesway Web Buckling

Crane runway girders should be checked to ensure adequate capacity to resist sidesway web buckling. Equation K1-7 contained in the AISC Specification should be used to perform this check. This criteria is likely to control the member size for crane runway girders with cap plates, welded girders with larger top flanges and girders with braced compression flanges. It seems likely that the foregoing AISE limitations on the length of unbraced tension flanges were created to address the sidesway web buckling phenomena. The sidesway web buckling criteria



was introduced into the AISC Specification in the Ninth Edition. Runway girders designed prior to this time would not have been checked for this criteria.

At present, the AISC method does not address the condition of multiple wheel loads on a single span.

Knee Braces or K Braces

The longitudinal crane forces are typically resisted by vertical X-bracing in the plane of the crane girder. The use of knee braces to create a rigid frame to resist longitudinal crane forces should be avoided. The knee brace picks up the vertical wheel load each time the wheel passes over the brace. K braces are subject to the same behavior. If a lacing system is used to resist lateral loads, this same system could be used to transfer longitudinal forces to the plane of the building columns. Then the crane vertical bracing could be incorporated into the building bracing at the building column.

Rail Attachments

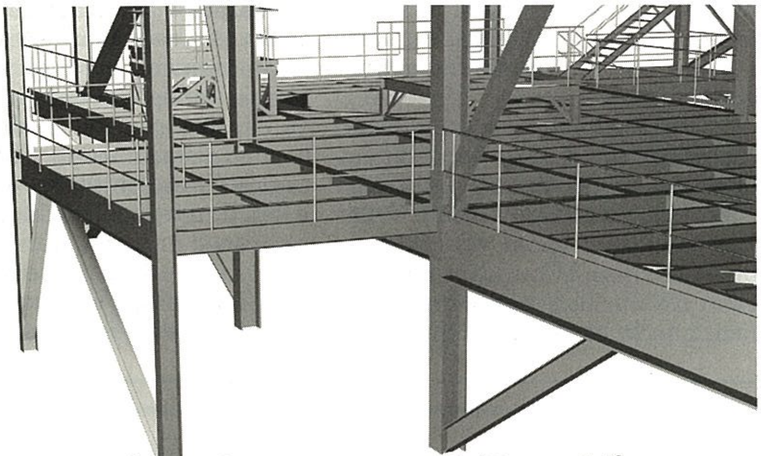
The rail to girder attachments must perform the following functions:

- transfer the lateral loads from the top of the rail to the top of the girder.
- allow the rail to float longitudinally relative to the top flange of the girder
- hold the rail in place laterally.
- allow for lateral adjustment or alignment of the rail.

The relative longitudinal movement of the crane rail to the top flange of crane girder is caused by longitudinal expansion and contraction of the rail in response to changes in temperature and shortening of the girder compression flange due to the applied vertical load of the crane.

There are four commonly accepted methods of attaching crane rails to crane girders. These are: hook bolts, rail clips, rail clamps, and patented rail clips. To varying degrees these four methods perform the functions previously mentioned. The authors are aware of installations that have the rails welded directly to the top flanges of the girders. This method is not recommended. The rails may lack the controlled chemistry that would ensure good quality welds, and there is no provision for longitudinal movement or lateral adjustment of the crane rails.

Hook bolts are only appropriate for attaching light rails supporting relatively small and light duty cranes. Hook bolts should be limited to CMAA Class A, B. and C cranes with a maximum capacity of approximately 20 tons. Hook bolts work well for smaller crane girders that do not have adequate space on the top flange for rail clips or clamps. Longitudinal motion of the crane rail relative to the runway girder



may cause the hook bolts to loosen or elongate Therefore, crane runways with hook bolts should be regularly inspected and maintained. AISC recommends that hook bolts be installed in pairs at a maximum spacing of 24 in. on center. The use of hook bolts eliminates the need to drill the top flange of the girder. However, these savings are offset by the need to drill the rails.

Rail clips are one piece castings or forgings that are usually bolted to the top of the girder flange. Many clips are held in place with a single bolt. The single bolt type of clip is susceptible to twisting due to longitudinal movement of the rail. This twisting of the clip causes a camming action that will tend to push the rail out of alignment.

There are two types of rail clamps, tight and floating. Rail clamps are two part forgings or pressed steel assemblies that are bolted to the top flange of the girder. The AISE Technical Report No. 13 requires that rail clips allow for longitudinal float of the rail and that the clips restrict the lateral movement to 0.25 in. inward or outward. When crane rails are installed with resilient pads between the rail and the girder, the amount of lateral movement should be restricted to $^1/_{32}$-in. to reduce the tendency of the pad to work out from under the rail.

Patented rail clips are typically two part castings or forgings that are bolted or welded to the top flange of the crane girder. The patented rail clips have been engineered to address the complex requirements of successfully attaching the crane rail to the crane girder. Compared to traditional clips, the patented clips provide greater ease in installation and adjustment and provide the needed performance with regard to allowing longitudinal movement and restraining lateral movement The appropriate size and spacing of the patented clips can be determined from the manufacturer's literature.