New Fatigue Provisions for the Design of Crane Runway Girders

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Proper functioning of 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. Runway girders should be thought of as a part of a system comprised of the crane rails, rail attachments, electrification support, crane stops, 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.

Based on the authors experience it is estimated that 90 percent of crane runway girder problems are associated with fatigue cracking. To address these conditions, this paper will discuss the AISC LRFD Specification (AISC, 1999) fatigue provisions, crane loads, typical connections and typical details. A design example is provided.

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 and other out-of plane distortions
- Minimize residual stresses

Even when all state of the art design provisions are followed, building owners can expect to perform periodic maintenance on runway systems. Runway systems that have performed well have been properly maintained by keeping the rails and girders aligned and level.

Some fatigue damage should be anticipated eventually even in perfectly designed structures since fabrication and erection cannot be perfect. Fabricating, erecting, and maintaining the tolerances required in the AISC *Code of Standard Practice for Steel Buildings and Bridges* (AISC, 2000), and the AISE Technical Report 13, Guide for the Design and Construction of Mill Buildings (AISC, 1996) should be followed in order to provide predicted fatigue behavior. Fatigue provisions have a 95 percent reliability factor (two standard deviations below the mean curve of test data) for a given stress range, and expected life condition. Thus, it is reasonable to expect that 5 percent of similar details can experience fatigue failure before the expected fatigue life is expired. However, if the designer chooses a design life of the structure to be shorter than the expected fatigue life per AISC criteria, the reliability of a critical detail should be higher than 95 percent.

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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 the 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. Fatigue failures result from repeated application of service loads, which cause crack initiation and propagation to final fracture. The dominant variable is the tensile stress range imposed by the repeated application of the live load not the maximum stress that is imposed by live plus dead load. Fatigue damage develops in three stages: crack initiation, stable crack growth and unstable crack growth to fracture. Of these the crack initiation phase takes up about eighty percent of the total fatigue life; thus when cracks are of detectible size the fatigue life of a member or detail is virtually exhausted and prompt remedial action should be taken. Abrupt changes in cross section, geometrical discontinuities such as toes of welds, unintentional discontinuities from lack of perfection in fabrication, effects of corrosion and residual stresses all have a bearing on the localized range of tensile stress at details that lead to crack initiation. These facts make it convenient and desirable to structure fatigue design provisions on the basis of categories, which reflect the increase in tensile stress range due to the severity of the discontinuities introduced by typical details. Application of stress concentration factors to stresses determined by usual analysis is not appropriate. However, fluctuating compressive stresses in a region of tensile residual stress may cause a net fluctuating tensile stress or reversal of stress, which may cause cracks to initiate.

An excellent reference on fatigue for the designer of crane runway systems is *A Fatigue Primer for Structural Engineers* (NSBA, 1998).

THE 1999 AISC FATIGUE PROVISIONS

The AISC ASD Specification (AISC, 1963) was the first to contain fatigue design provisions based upon S-N curves that define allowable stress range values for given typical structural details, categories and loading conditions. The step-wise format for presentation of criteria was adopted for convenience of users to avoid necessity of solving exponential expressions using hand calculation methods, which were prevalent at that time. The relationships were established based upon an extensive database developed in the United States and abroad. The database for the provisions was based upon testing of actual joints, thus the effects of stress concentrations were directly accounted for in each of the details and the category appropriate for each of the details was determined. Over the years the database has been expanded through testing of additional details and electronic calculation has replaced hand calculation methods.

The 1993 AISC LRFD fatigue provisions (AISC, 1993) defined Loading Conditions based on the number of cycles expected in the life of the structure. The loading conditions are defined as 20,000 to 100,000 cycles, 100,000 to 500,000 cycles, 500,000 to 2,000,000 cycles or more than 2,000,000 cycles (Table A-K3.1). Stress Category Classifications are defined based on the configuration of the given conditions and the associated stress concentrations (Table A-K3.2). The Design Stress Range is determined based on the Loading Condition and the Stress Category Classification.

In the 1999 AISC LRFD Specification (AISC, 1999), the format has been changed to provide continuous functions in terms of cycles of life and stress range in lieu of the previous criteria for fatigue life that accurately reflected the database only at the break points in the step-wise format. The 1999 AISC provisions use a single table that is divided into sections, which describe various conditions. The sections are:

1. Plain material away from any welding.
2. Connected material in mechanically fastened joints.
3. Welded joints joining components of built-up members.
4. Longitudinal fillet welded end conditions.
5. Welded joints transverse to direction of stress.
6. Base metal at welded transverse member connections.
7. Base metal at short attachments.
8. Miscellaneous.

The 1999 AISC provisions use equations to calculate the Design Stress Range for a chosen design life, N, for various conditions and stress categories. For the first time, the point of potential crack initiation is identified by description, and shown in the table figures. The tables contain the threshold design stress, F_{TH}, for each stress category, and also provide the detail constant, C_f, applicable to the stress category that is required for calculating the Design Stress Range F_{SR}. For example, for the majority of stress categories:

$$F_{SR} = \left[\frac{C_f}{N}\right]^{0.333} \geq F_{TH}$$

where

C_f = Constant from Table A-K3.1

N = Number of stress range fluctuations in design life
= Number of stress range fluctuations per day × 365 × years of design life

F_{TH} = Threshold fatigue stress range, maximum stress range for indefinite design life

The standard fatigue design equation applies:

$$f_{sr} \leq F_{sr}$$

where

f_{sr} = the service fatigue stress range based on the cyclic load range, an analytical model, and the section properties of the particular member at the fatigue sensitive detail location

F_{sr} = the Design Stress Range for a defined load condition (number of cycles) and a stress category of the fatigue sensitive detail

The 1999 AISC LRFD Specifications as well as previous AISC Specifications limit the allowable stress range for a given service life based on an anticipated severity of the stress riser for a given fabricated condition.

CRANE RUNWAY 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. ASCE 7-98 (ASCE, 1998) addresses crane loads and sets minimum standards for these loads. AISE (1996) 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.

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.

The vertical wheel loads are typically factored by the use of an impact factor. The impact factor accounts for the effect of acceleration in hoisting the loads, the sudden braking of a falling load, and impact caused by the wheels rolling over irregularities in the rail. Bolted rail splices will tend to cause greater impact than welded rail splices. In the US, most codes require a twenty-five percent increase in loads for cab and radio operated cranes, and a ten percent 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:

1. Acceleration and deceleration of the trolley and loads
2. Non-vertical lifting
3. Unbalanced drive mechanisms
4. Oblique or skewed travel of the bridge

The AISC (ASD) Specification (AISC, 1989) and most model building codes set the magnitude of lateral loads at 20 percent of the sum of the weights of the trolley and lifted load. The AISE Guide (AISE, 1996) varies the magnitude of the lateral load based on the function of the crane. For crane runways stress checks, the AISE equations are based on the 1989 AISC (ASD) provisions.

Longitudinal crane forces are due to either acceleration or deceleration of the bridge crane or the crane impacting the bumper. The tractive forces are 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, the velocity of the crane upon impact with the crane stop, and the supported weight of the end truck. The longitudinal forces should be obtained from the crane manufacturer. If this information is not available, the AISE Guide (1996) provides equations that can be used for determining the bumper force.

Consideration of fatigue requires that the designer determine the anticipated number of full uniform amplitude load cycles. To properly apply the AISC Specification (1999) fatigue equations to crane runway girder fatigue analyses, one must understand the difference between the AISC fatigue provisions determined using data from cyclic constant amplitude loading tests and crane runway variable amplitude cyclic loadings. It is a common practice for the crane runway girder to be designed for a service life that is consistent with the crane classification. The Crane Manufacturers Association of America (CMAA) Specifications for Electric Overhead Traveling Cranes (CMAA, 1996) includes crane designations that define the anticipated number of full uniform amplitude load cycles for the life of the crane. Correlating the CMAA crane designations for a given crane to the required fatigue life for the structure cannot be directly determined. The crane does not lift its maximum load, or travel at the same speed, every day or every hour. Shown in Table 1 are estimates of the number of cycles of full uniform amplitude for CMAA crane classifications A through F over a 40-year period. It must be emphasized that these are only guidelines and actual duty cycles can only be established from the building owner and the crane manufacturer.

Table 1.

CMAA Crane Classification	Design Life
A	20,000
B	50,000
C	100,000
D	500,000
E	1,500,000
F	>2,000,000

The AISE Guide provides specific load combinations to be used for fatigue calculations. The most common method of designing for fatigue considerations is to consider the maximum wheel loads as creating the full uniform amplitude load cycles. This is in agreement with Section 3.10 of the AISE Guide. The AISE Guide allows the use of more sophisticated analysis methods. Two methods commonly used to estimate an accurate application of constant amplitude cyclic loading fatigue design criteria for a runway subjected to variable amplitude loadings are Miner s damage accumulation principle, and the equivalent mean constant amplitude stress range method. AISE Technical Report No. 6, Specification for Electric Overhead Traveling Cranes for Steel Mill Service (AISE, 1996) uses the equivalent constant amplitude method in an expected fatigue life analysis of crane bridge girders. The AISE Guide suggests an application of the damage accumulation principle as a solution. The use of these methods is particularly useful when evaluating the expected life of existing runway systems.

For lightly loaded cranes, the MBMA Low Rise Building Systems Manual (MBMA, 1996) provides a method for accounting for the difference between the maximum applied load and the uniform amplitude load. This publication provides a method for adjusting the service classification of a crane based on a relationship that compares the total weight of the crane and the rated capacity of the crane.

CRANE RUNWAY FATIGUE DESIGN

General Comment

Cyclic dynamic loading within the elastic range of stresses leading to fatigue failure is very different from impact or impulsive dynamic loading which is dependent upon the strain rate of loading leading to inelastic distortions or sudden brittle fracture. Fatigue design can be rationally provided for on the response side of the design and analysis process using working loads.

Design for impact loading is traditionally covered on the loading side by application of impact factors, which probably are based more upon judgment than upon direct consideration of strain rate of loading which is at the heart of the matter. On the response side, resistance to high strain rate (impact) loading is enhanced by the use of notch-tough material, avoidance of biaxial and triaxial stress conditions, geometric discontinuities and is exacerbated by low temperatures. To date, incorporation of these issues in the design procedure has not been formalized.

Application of maximum loads (except as provided by Miner s rule) or overloads such as bumper loads, do not occur with sufficient frequency to constitute a fatigue problem. A thorough and rational design for fatigue, in no way, will cover impact problems, likewise, the use of factored loads to cover impact is inappropriate for determining the cyclic stress range for fatigue design.

Tension Flange Stress

When runway girders are fabricated from plate material, fatigue requirements are more severe than for rolled shape girders. In the 1999 AISC Specification Appendix K3, Table A-K3.1, Section 3.1 applies to the design of the plate material and Section 1.1 applies to plain material. Stress Category B is required for plate girders as compared to stress Category A for rolled shapes.

Web-to-Flange Welds

Section 8.2 of Table A-K3.1 in the 1999 AISC LRFD Specification controls the shear in fillet welds, which connect the web to the tension and compression flanges and fall in Stress Category F. Cracks have been observed in plate girders at the junction of the web to the compression flange of runway girders when fillet welds are used to connect the web to the compression flange. Such cracking has been traced to localized tension bending stresses in the bottom side of the compression flange plate with each wheel load passage, which may occur two or four or more times with each passage of the crane; thus, the life cycles for this consideration is generally several times greater than the life cycles to be considered in the girder live load stress ranges due to passage of the loaded crane. The calculation of such highly localized tensile bending stresses is so complex and unreliable that the problem is buried in conservative detail requirements. To reduce the likelihood of such cracks the AISE Guide recommends that the top flange-to-web joint be a complete-joint-penetration groove weld with fillet reinforcement.

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-ft girder that has undergone a deflection equal to span over 600 (L/600) is about 0.005 radians. For a 36-in. deep girder this results in 0.2 in. 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 … in. In general, the tieback 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. Various AISC fatigue provisions are applicable to the loads depending on the exact tieback configurations. A typical tieback is shown in Figure 1.

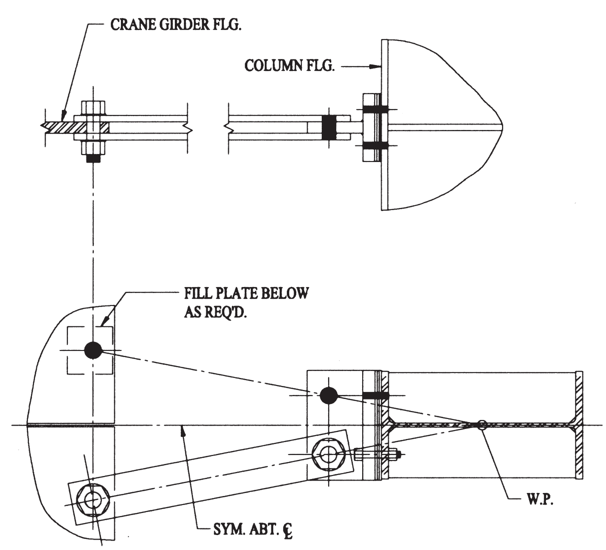


Fig. 1. Tieback Detail.

Bearing Stiffeners

Bearing stiffeners should be provided at the ends of the girders as required by the AISC Specification (1999) Paragraphs K1.3 and K1.4. Fatigue cracks have occurred at the connection between the bearing stiffener and the girder top flange. The cracks occurred in details where the bearing stiffener was fillet welded to the underside of the top flange. Passage of each crane wheel produces shear stress in the fillet welds. The AISC (1999) fatigue provisions contain fatigue criteria for fillet welds in shear; however, the determination of the actual stress state in the welds is extremely complex, thus the AISE Guide recommends that complete-joint-penetration groove welds be used to connect the top of the bearing stiffeners to the top flange of the girder. The bottom of the bearing stiffeners may be fitted (preferred) or fillet welded to the bottom flange. All stiffeners to girder webs 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 stiffeners 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.

Intermediate Stiffeners

If intermediate stiffeners are used, the AISE Guide also recommends that the intermediate stiffeners be welded to the top flange with complete-joint-penetration groove welds for the same reasons as with bearing stiffeners. Stiffeners should be stopped short of the tension flange in accordance with the 1999 AISC LRFD Specification (AISC, 1999) provisions contained in Appendix F2.3. The AISE Guide also recommends continuous stiffener to web welds for intermediate stiffeners.

Fatigue must be checked where the stiffener terminates adjacent to the tension flange. This condition is addressed in Section 5.7, Table A-K3.1, of the 1999 AISC LRFD Specification.

Channel Caps and Cap Plates

Channel caps or cap plates are frequently used to provide adequate top flange capacity to transfer lateral loads to the crane columns and to provide adequate lateral torsional stability of the runway girder cross section. A rule of thumb used by designers is that a wide flange reinforced with a cap channel will be economical if it is 20 pounds per foot lighter than an unreinforced wide flange member. It should be noted that the cap channel or plate does not fit perfectly with 100 percent 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 channel. The passage of the crane wheel over these gaps will tend to distress the channel or plate to top flange welds. Calculation of the stress condition for these welds is not practical. Because of this phenomena, cap plates or channels should not be used with Class E or F cranes. For less severe duty cycle cranes, shear flow stress in the welds can be calculated and limited according to the AISC (1999) fatigue provisions in Section 8.2. The channel or plate welds to the top flange can be continuous or intermittent. However, the AISC Design Stress Range for the base metal is reduced from Category B (Section 3.1) for continuous welds to Category E (Section 3.4) for intermittent welds.

Crane Column Cap Plates

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. Traction plates between girder webs may be required for large tractive forces or bumper forces. 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.

Laced Crane Girders

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 horizontal truss 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 as a beam, then the designer must isolate the walkway from the crane girder.

The AISE Guide recommends that crane runway girders with spans of 36 feet and over for AISE Building Classifications A, B and C or runway girder spans 40 feet and over in AISE Class D buildings shall have bottom flange bracing. This lacing is to be designed for 2‰ percent 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 backup beam.

Various AISC fatigue provisions are applicable to lacing systems depending on the detail used to connect the lacing to the runway girders and the back up girder.

Rail Attachments

The rail-to-girder attachments must perform the following functions:

1. Transfer the lateral loads from the top of the rail to the top of the girder.
2. Allow the rail to float longitudinally relative to the top flange of the girder.
3. Hold the rail in place laterally.
4. Allow for lateral adjustment or alignment of the rail.

The relative longitudinal movement of the crane rail to the top flange of the 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 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 attachment, 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 Guide recommends that rail clips allow for longitudinal float of the rail and that the clips restrict the lateral movement to … 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.

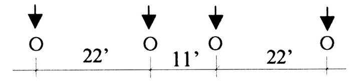
Patented rail clips are typically two part castings or forgings that are bolted or welded to the top flange of the crane girder. The patented rail clips have been engineered to address the complex requirements of successfully attaching the crane rail to the crane girder. Compared to traditional clips, 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. When rail clips are attached to the runway girder by welding, the runway girder top flange stress must be checked using the requirement of Section 7.1, Table A-K3.1 of the 1999 AISC LRFD fatigue provisions.

Miscellaneous Attachments

Attachments to crane runway girders should be avoided. The AISE Guide specifically prohibits welding attachments to the tension flange of runway girders. Brackets to support the runway electrification are often necessary. If the brackets are bolted to the web of the girder, fatigue consequences are relatively minor, i.e. stress category B, Section 1.3 of the 1999 AISC LRFD fatigue provisions. However, if the attachment is made with fillet welds to the web, Section 7.2 of the fatigue provisions applies. This provision places the detail into stress category D or E depending on the detail. If transverse stiffeners are present, the brackets should be attached to the stiffeners.

EXAMPLE

Design a welded plate girder to support the following pair of cranes. The runway beams are to be designed for 2,000,000 cycles, and the owner has required conformance with the AISE (1996). Use the 1999 AISC LRFD fatigue provisions and the prescriptive requirements of AISE. Check stresses using the 1989 AISC ASD Specification.



Crane Capacity: (2) 30-ton magnet cranes
Wheel Spacing: 22 ft, two wheels per end truck

Crane Spacing: 11 ft between wheels
Bridge Length: 100 ft
Bridge Weight: 270 kips
Trolley Weight: 30 kips
Maximum Wheel Load: 108 kips
Rail Size: 135# / rail with welded clamps
Runway Girder Span: 40 ft

Girder loaded with both cranes:
Maximum Crane Shears and Moments:
Position the cranes with the center of the girder midway between one wheel and the centroid of the crane loads. Allow 500 plf for the girder and attachments.

M_{dead} = 0.5(40)^2/8 = 100 ft-kips
V_{max} = 10 kips
M_{live} = (108/40)(40 − 17.25 + 11.75) 17.25
= 1,607 ft-kips (no impact)
M_{total} = 1,707 ft-kips

Determine the maximum lateral load per wheel:
Per AISE 3.4.2 (Assuming equal runway stiffnesses):
V =100 percent of the lifted load
V =1.0(60)/4 = 15 kips/wheel (controls)
Or 20 percent of the lifted load plus trolley
V = 0.2(60 + 30)/4 = 4.5 kips/wheel
Or 10 percent of the lifted load plus the crane weight plus the trolley weight
V = 0.10(60 + 270 + 30)/4 = 9.0 kips/wheel

Determine the maximum lateral moment:
Per AISE 3.10.2 use 100 percent of the lateral load for only one crane when multiple cranes exist. Position the wheels at the same location as for the maximum vertical load.
M_y = (15)(17.25)22.75/40 = 147 ft-kips

Determine the maximum shear:
V_{max} = 108(7 + 29 + 40)/40 = 205 kips
V_{total} = 215 kips

Girder loaded with one crane:
Include 25 percent impact per AISE 3.4.
M_{live} =1.25 (108)(40 14.5 + 3.5) 14.5/40 = 1,419 ft-kips
M_{total} =1519 ft-kips

Determine the maximum lateral moment for one crane:
M_y = 15(40 14.5 + 3.5) 14.5/40 = 158 ft-kips

Determine the maximum shear:
V_{max} = 1.25(108)(18 + 40)/40 = 196 kips
V_{total} = 206 kips

Determine the required moment of inertia to limit the maximum vertical deflection to L/1,000.

The critical location occurs when the wheel loads are centered on the girder.

$$\Delta = \frac{P_a}{24EI_x}\left(3L^2 - 4a^2\right) = \frac{L}{1{,}000}$$

$$I_{x\ required} = \frac{1{,}000P_a\left(3L^2 - 4a^2\right)}{24EL}$$

$$I_{x\ required} = \frac{(1{,}000)(108)(9)\left(3\times 40^2 - 4\times 9^2\right)144}{24\times 29{,}000\times 40} = 22{,}500 \text{ in.}^4$$

Trial Section:
Try a plate girder with a 28 in. × 1.5 in. top flange, 22 in. × 1 in. bottom flange and a 42 in. × 0.75 in. web. The girder has the following cross section properties. Use F_y = 36 ksi.

I_x	= 32,647 in.^{4}	A	= 95.5 in.^{2}
S_{xtop}	= 1,825 in.^{3}	y_{bar} (from top)	= 17.9 in.
$S_{xbottom}$	= 1,227 in.^{3}	d/A_f	= 1.0 in.$^{-1}$
S_{ytop}	= 196 in.^{3}	r_T	= 7.72 in.

Check bending stresses for two cranes with 100 percent of the maximum lateral load acting for one crane:
Note the lateral loads are increased to account for the rail height of 5.75 in.

Per AISC ASD F1-6 F_{bx} = 20.7 ksi
Per AISC ASD F1-8 F_{bx} = 22.0 ksi
Per AISC ASD F2-1 F_{by} = 27 ksi
f_{bxc} = (1,707)(12)/1,825 = 11.2 ksi < 22.0 ksi o.k.
f_{bxt} = (1,707)(12)/1,227 = 16.7 ksi < 22 ksi o.k.

$$f_{by} = (147)(12)\frac{50.25}{44.5}\times\frac{1}{196} = 10.2 \text{ ksi} < 27 \text{ ksi o.k.}$$

Check combined stresses per AISC ASD H1-3:

$$\frac{11.2}{22.0} + \frac{10.2}{27} = 0.89 < 1 \text{ o.k.}$$

Check bending stresses for one crane:
f_{bxc} = (1,519)(12)/1,825 = 10.0 ksi < 22.0 ksi o.k.
f_{bxt} = (1,519)(12)/1,227 = 14.9 ksi < 27 ksi o.k.

$$f_{by} = (158)(12)\frac{50.25}{44.5}\times\frac{1}{196} = 10.9 \text{ ksi} < 27 \text{ ksi o.k.}$$

$$\frac{10.0}{22.0} + \frac{10.9}{27} = 0.86 < 1 \text{ o.k.}$$

Check shear on the girder web:
h/t_w = 42/0.75 = 56 < 380 /$\sqrt{36}$

Per AISC ASD F4.2: F_v = 14.4 ksi
f_v = 215/(42)(0.75) = 6.8 ksi < 14.4 o.k.

Check sidesway web buckling per AISC ASD K1-7:
$(d_c/t_w)/(l/b_f)$ = (41.375/0.75)/(480/28) = 3.2 > 1.7
No sidesway web buckling.

Fatigue Design
The allowable stresses for fatigue design are based on the 1999 AISC Specification Appendix K. In accordance with AISE Section 3.10 fatigue loading is based on the vertical load from one crane including impact and 50 percent of the maximum lateral load. The following fatigue conditions will be evaluated:

1. The tension flange flexural stress.
2. The web to tension flange shear flow stress.
3. The top flange at the rail clips for lateral load flexural stress.
4. The weld at the base of the intermediate stiffeners.

1. Tension Flange
Check the tension flange at the flange to web junction. Only the live load moment is used to determine the bending stress.
f_{sr} = (1,419)(12)(43.5 − 17.9)/32,647 = 13.4 ksi

From the 1999 AISC LRFD Specifications Table A-K3.1, Stress Category B, Section 3.1, $C_f = 120 \times 10^8$

$$F_{SR} = \left[\frac{C_f}{N}\right]^{0.333} = \left[\frac{120\times10^8}{2\times10^6}\right]^{0.333} = 18.12 \text{ ksi}$$

18.12 ksi > 13.4 o.k.

2. Web-to-Flange Welds
Determine the fillet weld size for the bottom flange attachment to the web. This fillet weld is designed to provide adequate shear flow capacity. The shear is based on the maximum live load shear on the girder.

$$\frac{VQ}{I} = \frac{(196)(44.5-17.9-0.5)(22)}{32,647} = 3.45 \text{ kips/in.}$$

From the 1999 AISC LRFD Specifications Table A-K3.1, Section 8.2, Stress Category F, $C_f = 150 \times 10^{10}$

$$F_{SR} = \left[\frac{C_f}{N}\right]^{0.167} = \left[\frac{150\times10^{10}}{2\times10^6}\right]^{0.167} = 9.57 \text{ ksi}$$

$$\text{Weld size} = \frac{3.45}{(2)(9.57)(0.707)} = 0.255 \text{ in.}$$

Use 5/16 in. fillet welds NS/FS.

At the top flange use a complete-joint-penetration groove weld with contoured fillets per AISE Guide.

3. Intermediate Stiffener Welds
Assume that intermediate stiffeners are provided at equal spaces along the length of the girder (although not required by this design). The flexural stress level at the bottom weld termination of the stiffeners needs to be checked. It should be emphasized that the flexural stress at this location is not a stress in the stiffener weld. Rather, it is the flexural stress that occurs at the location of this stress riser. Per 1999 AISC LRFD Table A-K3.1, Section 5.7, the Stress Category C is appropriate, and $C_f = 44 \times 10^8$.

$$F_{SR} = \left[\frac{C_f}{N}\right]^{0.333} = \left[\frac{44\times10^8}{2\times10^6}\right]^{0.333} = 13.00 \text{ ksi}$$

Per 1999 AISC LRFD Appendix F2.3, terminate the intermediate stiffener between 4 and 6 times the web thickness from the near toe of the flange to web weld.

Determine the distance from the end of the stiffener to the neutral axis.
C = 44.5 − 17.9 − 1.0 0.3125 − (6)(0.75) = 20.79 in.

Determine the stress range at the end of the stiffener.
M_{live} = 1,419 ft-kips
F_{bx} = Mc/I = (1,419)(12)(20.79)/32,647 = 10.84 ksi
13.00 > 10.84 o.k.

4. Top Flange Rail Clips
The fatigue concern at the top flange of the girder is created by the stress due to the lateral loads. The vertical wheel loads always cause compressive stress in the top flange. Since fatigue cracks do not propagate in regions of compressive stress, a check will be made of the various combinations of minimum vertical load with maximum lateral load to determine if any of the loading conditions results in a net tension.

For the condition at the top flange, the critical location occurs at the weld of the clip to the top flange. Depending on the configuration of the attachment, the appropriate Stress Category from Table A-K3.1, Section 7.1, is C, D, E or E′.

The distance from the center of the top flange to the back of the clip is 5.25 in.

The minimum wheel load is 72 kips.

Check for the one crane condition:
Include impact and 50 percent lateral load for the minimum wheel load of 72 kips.
M_x = 946 ft-kips
f_{bx} = 6.22 ksi

$M_y/2 \quad = 79$ ft-kips
$f_{by} \quad = (79)(12)(5.25)/2{,}744 = 1.8$ ksi
$f_{by} \quad < f_{bx}$

No net tension occurs for the single crane loading condition.

No further fatigue investigation is required for the top flange.

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