Knee braced crane girders—Problems and solutions

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Knee braced connections between columns and beams have been an important part of many different structures throughout the centuries. Portal-type knee braced structures, in different variations, can be found in old bridges, churches and castles. In old industrial buildings, knee braced connections were widely used in the roof trusses to connect columns in the lateral plane, between columns and struts in the longitudinal direction, and between columns and floor beams. In all of these cases, especially timber construction, knee braced connections provided a perfect engineering solution that increased stability of the structure, created rigid connections between elements and reduced the bending span for beams. Therefore, it is understood why the designers of early crane runway girders for overhead traveling cranes adopted this approach which had worked well in portal-type structures before.

Crane girders with knee braces are a typical feature in many mill buildings. The majority have survived in service for many years without any problems. However, some of them have experienced fatigue related damage.

The original intended function of the knee brace in crane runway design was to provide longitudinal stability of the crane runway against crane longitudinal forces and to help the columns deliver a horizontal shear to the foundations (Fig. 1).

The secondary effect of the knee brace, acting as an intermediate spring support for the girder, had not been considered. Girders were analyzed without considering this effect while knee braces were only analyzed for runway horizontal loads. In addition to the spring support function, knee braces provide a partial restraint to the crane girder support rotation resulting in a stress reversal in the girder and its supports. This stress reversal could lead to fatigue failure of the girder and/or girder to column connection details. It has been analytically proved that the magnitude of this stress reversal depends, to a great extent, on the relationship between stiffnesses of the girder, knee brace and column. Occasionally, this stiffness relationship was established by the design in such a way that it resulted in a minor stress reversal which was successfully resisted by the structure, thereby, causing no fatigue failure.

A computerized design approach is proposed in this article for the analysis of knee braced crane runway girders as a longitudinal frame with special modeling of the knee brace and crane girder supports. The proposed approach helps the design engineer determine the magnitude of the force reversal in the girder/knee brace system, check the fatigue stress range in these members and more accurately account for knee brace effects in crane runway modification projects.

Study case review

Knee braced crane girders can be found in steel mill buildings designed up to the late 1960’s. In many steel mill buildings, knee braced crane girders are combined with X-bracing (Fig. 2). The introduction of X-bracing between crane columns has eliminated the original intended function of knee braces. Nevertheless, design engineers continued to design the runways with knee braced girders and X-bracing. The designers of this belt and suspenders system probably considered that extra tools for longitudinal stability would never decrease overall effectiveness, but it did. Numerous cases have been documented in which knee braced crane girders have developed cracks in the web of the girder in the support region, sheared web splice bolts and ruptured girder seat bolts.

In 1965, Mueller described knee braced crane girder problems as well as the failure modes of these girders. An
exaggerated model presented by Mueller (Fig. 3), illustrated the possibility of knee brace buckling, in addition to web cracking, web splice plate distortion and uplift of the girder seat. However, Mueller indicated that he had not actually observed knee brace failure other than occasional loose rivets.

For the last 10 years, the authors of this article have observed many knee braced crane runway girders, from light 10-ton shipping cranes up to 180-ton metal shop cranes. Buckled knee braces were never observed. The majority of failure cases included sheared and ruptured bolts, broken web splice plates and girder to column diaphragms. Girder web failure has been rarely observed. At the same time, large numbers of knee braced crane girders without any sign of failure have been observed. The reason why some knee braced crane girders fail and others perform without problems is the relationship between the independent stiffnesses of the girder, knee brace and column. This relationship governs the magnitude of the knee brace axial load, reversible girder support reactions and vertical bending moment envelope for the crane girder. These forces define fatigue type stresses in the girder which could cause the observed failures of knee braced girder components.

Based on the reported number of knee braced crane girder failures, the AISE Technical Report No. 13, Guide for Design and Construction of Mill Buildings does not recommend the knee braced crane girder design. Although the authors agree with that recommendation, there are large numbers of existing knee braced crane girders already installed which raise the question whether they should be removed or kept. This question demands attention especially when a crane runway upgrade is being considered. It can be answered by analyzing the crane runway as a longitudinal frame consisting of crane girders with knee braces, columns and any existing X-bracing, prior to modifying the runway girders. Computerized programs equipped with moving load design features (STAAD-III, STRUDL, etc.) can be used to create force envelopes for the girder and knee braces under investigation. An increase of reversal stresses, which could cause a fatigue failure of the knee braced girder components arising from an increase in crane loads, can be evaluated from the proposed framing analyses.

In most cases, especially in girders with a design span up to 30 ft, analyses of knee braced crane girders as a longitudinal crane runway framing show a substantial reduction in the maximum positive bending moment for the girder in comparison with simple span girder analyses. A negative bending moment in the critical mid-span area of the girder could appear when the adjacent girder is loaded but the magnitude of the total moment fatigue range would still be less than the maximum positive moment for the simple span girder. In such cases, special attention should be paid to detailed analyses of knees and their connections to the column and girder. In all analyses, the designer should recognize the reversible character of stresses and check the members for compliance with fatigue design criteria.

An analysis of an existing crane runway without accounting for the knee brace effect provides an inaccurate solution. Reinforcement of an existing knee braced crane girder based on simple span girder analyses without subsequent knee brace removal could create conditions for a low-cycle fatigue failure of elements, such as the girder web, seat bolts and web splice details, arising from cyclic stresses which will increase after the upgraded crane loads are applied. Removal of knee braces without girder support modifications could create an even more favorable condition for the fatigue failure of the girder web in a widely spread type of girder support with web splice plates.

In the case of a proposed crane load increase, there is a possibility that accounting for the knee brace effect could eliminate reinforcement of the crane runway girders. Reinforcement or replacement of knee braces is less expensive than reinforcement or replacement of crane girders.

Computer modelling of crane girder/knee brace column framing system

Longitudinal crane runway framing consists of knee braced crane girders supported on columns. This framework is a statically indeterminate system, in which simple span girders are transformed by knee braces into a type of continuous crane girder with partial rotational restraints at girder supports. The intersection detail between the crane girder, the knee brace and the column is the most important detail of this frame model.

Two major types of knee braced crane girder supports are shown on Fig. 4 and 5. Crane girders supported independently on the column are illustrated in Fig. 4. The girders are free to rotate at their supports. Crane girders with a bolted or riveted web splice over the column, which provides restraint to the girder support rotation, are shown in Fig. 5. This type of girder has been utilized more often in the steel mill crane runways.

Fig. 3 — Mueller knee brace crane girder failure model. 3

Fig. 4 — Knee braced crane girders without web splice at support.
In this computer frame model, the crane girder is represented by members located at the girder's neutral line level. The points of the girder supports on the column and the knee braces are located below the girder neutral line at the bottom flange level. This feature should be included in the computer model. An example of the knee braced girder support computer model is shown in Fig. 6. Members 1 through 4 and 11 through 14 are crane girder, column and knee brace members, respectively. Members 5 through 10 are false rigid members with large flexural stiffness, representing the girder to column and knee brace connection offsets. The column member properties in this frame are represented by the properties of the crane shaft only.

The model of the crane girder support with end girder rotational restraints is similar to Fig. 6 with the exception of an additional member between the girder ends, which represents the web splice.

Crane moving loads should include two cases, recommended by the AISE Technical Report No. 13:

- Case 1—Vertical wheel loads from one crane with impact.
- Case 2—As many cranes as can be positioned (from total number of cranes operating on the crane run- way) to produce the most severe loadings without impact.

The following examples illustrate how use of the proposed computerized analyses assist in evaluating the knee braced runway condition under existing or upgraded crane loadings, while investigating the most economical method of crane runway modification.

**Design example No. 1**

An existing runway with knee braced crane girders was designed for a 10-ton crane with maximum wheel loads of 34 kips (4-wheel crane, wheel spacing 13 ft-0 in.). It is proposed to upgrade the existing crane to 20-ton lifting capacity with a maximum wheel load of 50 kips. The existing 21-ft span crane girder is made from W27x85 with double angle knee braces of L5x5x3/8.

Two analyses are made to determine the appropriate modifications to the runway:

- Simple span crane girder analysis.
- Knee braced crane girder frame analysis.

The solutions are based on the following criteria: girder material, steel ASTM A7, FY = 33 ksi; and formula F1-6 (AISC 89), allowable top flange bending stress, 15 ksi (compression).

**Simple span crane girder analysis** — Analysis of the existing and proposed crane wheel loads indicate:

- Existing crane wheel loads with impact factor, 1.25.
- \( M_{max} = 223 \text{ ft-kip} \), maximum bending stress = 12.4 ksi < 15 ksi allowable.
- Proposed crane wheel load increase from 34 to 50 kips.
- \( M_{max} = 328 \text{ ft-kip} \), maximum bending stress = 18.2 ksi > 15 ksi allowable.

These data show that the existing girder should be replaced with a new girder, W27x102 (ASTM A36) or the bottom flange of the existing girder to be reinforced with W27x37.

**Knee braced crane girder framing analyses** — Because crane loadings in adjacent spans affect the analyzed girder forces, a model of four bays of framing is employed with the moving crane load through all bays. A computer model for vertical load analysis is shown in Fig. 7. The typical girder to be investigated is located in the second bay. Deflection and moment diagrams for the girder are illustrated in Fig. 8. An analysis shows:

- \( M_{max} = 245.2 \text{ ft-kip} \) with impact.
- Maximum bending stress = 15.9 ksi < 15 ksi allowable.
- Bending moment fatigue range (no vertical impact included) = \((+245.2 - (-37.5))/1.25 = 226.2 \text{ ft-kip} \).
- Bending stress fatigue range = 12.4 ksi < 16.0 ksi allowable for category B fatigue.

It is, thus, concluded that the girder does not need reinforcement.

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*Fig. 7 — Example No. 1 — Crane runway framing computer model.*
• $M_{\text{max}} = -742 \text{ ft-kip}$ to $M_{\text{min}} = -120 \text{ ft-kip}$ (vertical impact included).
• Maximum bending stress = 20.3 ksi < 22 ksi allowable.
• Bending moment fatigue range (no vertical impact included) = $\frac{-742 - (-120)}{1.25} = 550 \text{ ft-kip}$.
• Bending stress fatigue range = 18.9 ksi vs 18 ksi for category B fatigue leading 3.

The 18.9-ksi bending stress fatigue range represents an acceptable 4.7% theoretical over-stress. For the knee braces:
• Knee brace maximum compression 79.6 kips, tension 2.1 kips.
• Unbraced length, 6.1 ft.
• Allowable compression force for two 4 x 3 x 3/8\-in. bolts = 87.6 kips.

The data indicates that the knee braces are satisfactory but the connection between the knee brace, column and girder with three double shear 1/4\-in. dia. A325 bolts would fail since the allowable shear, 61.2 kips, is less than 79.6 kips. The recommendation is to replace existing bolts with 1/4\-in. dia. A325 bolts.

Analyzing conditions for the 4\-in. dia. A325 crane girder seat bolts:
• Maximum cyclic uplift, 43 kips or 10.6 kips/bolt, in cyclic tension is acceptable (see Example No. 1).
• Maximum cyclic horizontal shear is 59.2 kips or 14.8 kips/bolt.

The maximum cyclic horizontal shear/bolt exceeds the allowable 10.6 kips/bolt for slip-critical joints. Changing from a slip-critical to a bearing type of connection in the joints subjected to force reversal is not recommended (see example No. 1 for explanation). Therefore, the seat bolts should be replaced with 1/4\-in. dia. A325 bolts.

In summary, the 30% crane wheel load increase will not require crane girder reinforcement if the knee brace girder is analyzed as a part of the crane runway framing. Bolts in fatigue sensitive connections should be replaced with stronger bolts to satisfy fatigue design requirements.

Summary
Knee braced crane girders are fatigue sensitive structures. Most of the observed cases of failure include shear of girder seat bolts, cracking of girder web splice plates over supports or shearing of bolts at splice plates and cracking of girder to column diaphragms. Less frequent modes of failure include girder web cracking in the support area and bolt or rivet shear at the knee brace to girder or column connections.

The new AISE Subcommittee on Lubrication and Fluid Power Technology

A new Applied Engineering Subcommittee on Lubrication and Fluid Power Technology has been approved. An organizational meeting will be held at 9:00 a.m. on May 7, 1993, at AISE headquarters in Pittsburgh.

Employees of steel companies involved in lubrication and fluid power may apply to attend the meeting and can apply for subcommittee membership. Consultants and vendors may also apply. All attendees must have supervisory or other responsible direct role in lubrication and fluid power. Sales personnel are not eligible. A membership balance between steel company employees and others will be maintained.

Persons who are regularly active in the areas described above and wish to attend the organizational meeting may obtain more information by contacting: Association of Iron and Steel Engineers, Three Gateway Center, Suite 2500, Pittsburgh, PA 15222, Phone: (412) 281-6023 or Fax: (412) 281-4857.