Crane runway upgrades - the challenging but rewarding task and how to optimise it

This fascinating presentation was put to the Association for Iron and Steel Technology (AIST) Crane Symposium on June 13 2006 by Middough’s Ray Milman and Chip Hoppel

Strong competition between steel producing companies has been the driving force behind the recent popularity in upgrading existing mill buildings. Steel producing companies in an attempt to lower their product cost have been forced to review each component of their production cost. This explains why many companies are modernising their technology and installing it into existing mill buildings which require either upgrading or modification.

The results of the existing crane runway and mill building upgrade analyses to a great extent depend on the following:
- How accurately the crane loads, especially dynamic loads, are evaluated
- How accurately the crane runway support system (crane girders, building framing and foundations) is presented in the structural model used in the analysis
- How accurately the remaining fatigue life of the crane runway fatigue sensitive components is evaluated

Excessively conservative design criteria accepted in the upgrade project analyses might show that the crane runway and building should be reinforced. This crane runway and building reinforcement usually associates with a long downtime period for mill operation and large capital expenses. This conclusion could make the mill upgrade project economically unfeasible.

The following equation defines the theoretical relationship between the required strength and the allowable strength in terms of the allowable stress design (ASD) method:

$$R_u \leq \frac{R_n}{F_S}$$

The left side of the equation is the required strength (design forces or moments) which is a function of loads and the design model of the structure. The right side is the allowable strength which is the nominal strength divided by a factor of safety. When the two sides are divided by the appropriate section property (cross section area or section modulus), the equation is converted into a relationship between design and allowable stresses.

The theoretical over stress is a condition where the design stress is greater than the allowable stress. To eliminate the theoretical over stress situation, the design engineer could use one of the following techniques separately or in combination:
- Reduce safety factor
- Increase section properties
- Improve design model of the investigated structure
- Review and revise design loads and combinations

In this paper, the major components of the crane runway and mill building upgrade project optimization will be reviewed:
- Evaluation of crane dynamic loads
- Crane runways
- Fatigue of crane runway girders
- Building framing and foundations
- Engineering cost versus final results

Evaluation of crane dynamic loads

At the 2004 AIST “Crane Maintenance and Technology Advancement II” symposium in Pittsburgh, the authors of this paper made a presentation entitled “Crane/Building Interaction Review” (Ref. 3).

This paper included the historical review and presently available methods for evaluation of crane dynamic loads:
- Evaluation of crane dynamic loads by design codes
- Analytical determination of crane dynamic loads
- Dynamic analyses
- Computer simulation

- Crane load field tests
- Application of the presently recommended crane dynamic loads to the existing mill building often results in a significant theoretical over stress of crane runway and building components. However, these structures have performed satisfactorily for many years and do not show any sign of distress in those theoretically over-stressed regions.

Dynamic forces determined by using current design specification recommendations do not reproduce a reasonable approximation to the actual forces, because they do not include in their determination such variables as motion characteristics of the crane and its components and dynamic properties of the craneway support structures.

There are a few simplified methods to analytically determine the inertial forces produced by the crane and/or
CRANE RUNWAY UPGRADES

Crane runways

In general, each row of a crane runway girder system represents a longitudinal frame. This frame includes crane girders supported at the bottom flange level on column seats, columns, and a vertical bracing system.

If each crane girder has one pin support and another support as a roller, it would work as a simple beam, similar to large span highway bridges.

However, crane girders are not designed this way. Usually, a simple span crane girder has similar support details at each end, neither of which permits free expansion of the girder bottom flange due to vertical bending.

The restraint to the bottom flange extension creates reactive shear forces at girder seats. The magnitudes of these forces depend on horizontal stiffness of the girder supports in longitudinal directions.

Computerised analyses of the crane runway as a longitudinal frame with proper modeling of girder and column connections permit determination of the above shear forces (Fig 3). In many cases, these shear forces govern over crane traction or uplift forces used previously for seat bolt design.

The horizontal longitudinal displacement of the crane girder top flange at the column area due to vertical bending, determined by the crane runway framing analysis, could reach a magnitude of 1/4 of an inch, which could lead to fatigue damage.

Crane girder reinforcement is a challenging task for a design engineer because it involves not only a girder reinforcement design to meet strength and serviceability criteria, but also problems as downtime in the crane operation to construct the reinforcement, interference with the existing structures and equipment and modifications of elements attached to the girder (walkways, hot rails, piping, electrical conduit supports, etc).

According to the conventional method of beam reinforcement, an increase of the crane lifting capacity requires an increase of the crane runway girder vertical and horizontal section properties to satisfy biaxial bending criteria under the action of the increased crane vertical and horizontal loads. In addition, if vertical web shear design stresses exceed allowable, the girder web shall be reinforced.

If a substantial increase of the crane lifted load is considered, the total cost (fabrication and field work) of a conventional method of crane girder reinforcement could exceed the cost of girder replacement.

A non-conventional approach (Ref 9) includes two alternate methods of the crane girder reinforcement, which allow a substantial increase in the crane lifted load and minimize the scope of field work required to install the girder reinforcements (Fig 4):

- Girder conversion into a truss type structure
- Crane load sharing between a crane girder and a beam installed below the crane girder

Both of these methods are based on the idea to break the girder span on two or more continuous spans supported by the elastic springs at the girder mid-span.

A more complicated case of crane runways is represented by the crane runways with knee-braced crane girders (Fig 5). Knee-braced girders can be found in steel mill buildings designed up to the late 1960s.

Today, new knee-braced crane runways are not designed. However, a significant number of the existing mill buildings with knee-braced crane girders are still in service.

Computerised analyses of the knee-braced crane runway as a longitudinal frame (Fig 6) with a special modelling of the interaction detail between the crane girder, the column, and the knee brace enabled us to determine the knee brace spring support effect on the crane girder and magnitude of the stress or force reversal at the critical elements of the system.

In many cases, analyses show that knee-braced crane girders can carry cranes with up to 30% increase in the
lifting load, if the knee brace effect is taken into account. In such cases, minor modifications of the connections can be expected, but no crane girder reinforcement or replacement is required (Ref 4).

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 longitudinal loads. In addition to the spring support function, knee braces provide a partial restraints 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.

**Fatigue of crane runway girders**

Crane runway fatigue analyses should be considered as an important part of any crane runway upgrade project. The design engineer should know how much of the existing crane girder fatigue life remains after the crane capacity is increased.

The fatigue life of a structure is defined as the number of load cycles required to initiate and propagate a fatigue crack to a critical size, which could result in failure of the structure.

By the nature of a crane operation, most runway girders are subjected to variable amplitude loadings. However, the American and Canadian structural codes do not specify this effect, making design engineers use the maximum stresses in the fatigue analyses, which is an overly conservative approach.

Many methods to predict the fatigue life of a specimen subjected to variable amplitude loadings have been proposed. The most popular and widely used method is the Miner's linear damage accumulation hypothesis. The linear damage accumulation hypothesis assumes if ni cycles of a stress range Sr are applied, where n is less than Nf (Nf is the fatigue life for stress range Sr), the fatigue damage occurring during this application is the ratio of ni / Nf.

An application of Miner's method for evaluation of the expected fatigue life of crane runway girders is proposed and examples of fatigue analyses are provided in Ref 8. The AISE Technical Report No. 13 (Ref 1) in paragraph 79.1 recommends:

"As an alternate to (par 3.10.2.1) method, especially with existing crane runway upgrade projects, the engineer may utilise in fatigue-related analyses the damage accumulation principle for structures subjected to variable amplitude loadings."

In welded crane runway girders, fatigue related failures are mostly represented in the form of cracking of fillet-welded toe flange to web, stiffener to web and flange connections. Other cases included the failure of girder to column rigid connections, which restrained the girder support from free rotation, and stich or plug welded connections of the runway components (walkway plates, girder cap channels, etc).

Another quite typical case of the fatigue failure is the girder bottom flange cracking at the welded attachment (hot rail brackets, piping and electrical conduit supports, etc) locations, from where the crack would propagate into a full bottom flange cross section and into the web.

The engineer should keep in mind that according to fracture mechanics studies, an increase of the design stress range by 25% reduces the expected remaining fatigue life by 50% (Ref 8).

**Building framing and foundations**

It is now recognised that mill buildings are space frame structures. The planar frames consisting of columns and roof trusses are combined by a roof truss bottom chord bracing into the space frame. The main function of this bracing is to stabilise the building space frame by minimizing relative horizontal movement between cross bents and distribute the localised crane loads to adjacent bents.

Mill building framing analyses performed prior to the personal computer revolution were planar frame analyses with fixed or pinned column bases. Some engineers still use this simple approach by utilising computers. The planar frame analysis does not consider crane horizontal side thrust forces to be shared between adjacent bents, and this makes building columns and foundations larger than they can be, if the above force sharing effect had been taken into account.

However, in the real world, the column upper shafts deliver to the roof trusses a portion of the crane side thrust force, the magnitude of which depends on a relative stiffness of lower and upper column shafts and a horizontal stiffness of the total building frame at the column top.

The planar frame analysis does not determine the magnitude of this force distribution, and as a result of this, the upper column shafts can be underdesigned having been analysed only for roof and wind loads.

The space frame concept in mill building framing analysis became realistic for design engineers after computer programs (GTSNtra, STAADIII, etc) were widely introduced.

It became possible to develop a full 3D computer model of a Mill Building. However, even for a mid-sized mill building, such a model could consist of a few thousand nodes and members. This formidable problem was resolved by introduction of a simplified space frame analysis approach which provides a reasonable degree of accuracy (Ref 5).

An advantage of the space frame approach, especially for mill buildings with large lifting capacity cranes (ladle cranes, heavy coil cranes, etc) versus the planar frame concept was proven in many cases.

The space frame concept combined with the soil structure interaction modelling represents the most accurate approach in mill building framing analyses. The reduction of maximum soil bearing pressures (or pile loads) and building framing force redistribution could present an opportunity for the engineer to increase loads on the existing building structures without any or only minimum reinforcement required.

**Engineering cost versus final results**

The above described computer assisted process of more accurate engineering modelling and solutions on mill building structural design does not come without associated costs.

This process requires substantially more engineering time to be spent in comparison with the time required to
simplify framing modeling and crane load approaches.

The client was not satisfied with the above study results and requested the second firm, who provided an original bid for $100,000, to perform the study.

The second study included:

Crate load dynamic analyses for the existing ladle cranes upgraded to 400 US tons. These analyses permitted to substantially reduce the crane dynamic loads in comparison with the AISE Technical Report No. 13 recommendation.

Computerized crane side thrust distribution for wide variety of framing situations. Framing analyses which accounted for the space frame effect for all different framing models in the three investigated buildings.

A full crane runway system analyses, including fatigue analyses performed by utilizing the damage accumulation principle.

During the final stage of the study, additional work on crane dynamic load determination was performed. It included the field crane load test and computerised crane/building analyses using the "ADAMS" program by MDI (additional cost of $40,000).

The analyses proved that the existing continuous casting shops and the teeming aisle crane runways and framings could carry the upgrade to 400 US ton ladle cranes without exceeding allowable design limits. Modification works were limited to repair of minor deficiencies found during structural inspections with a total cost not exceeding $300,000.

Conclusion

The personal computer revolution and creation of computerised engineering programmes equipped the design engineers with analytical tools to more accurately analyse mill building structures. As a result of that, engineers are now able to provide a cost-effective design of new mill buildings or open hidden opportunities to upgrade existing mill buildings to increased crane loads.

An advanced computerised solution of the new mill building design or upgrade projects requires additional time to produce the results in comparison with a simplified computer solution, and this means a higher engineering cost. However, higher engineering costs will be more than offset by the effective construction cost reduction and reduced downtime received as a result of a sophisticated design procedure.