Old mill buildings vs current design loads—
A survival approach

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UPGRADING existing mill buildings is a high priority task. Companies are modifying their technology and facilities to increase production and reduce product cost. A significant cost benefit is realized with the modification of existing mill buildings and structures, as well as new ones.

Mill building modification usually involves upgrading capacities of existing cranes or installation of additional cranes. This means that additional loads will be applied to the existing structures which have to be checked for these new load conditions and brought into compliance with requirements of presently active design codes.

Design work associated with upgrading existing mill buildings, especially old mill buildings, presents a challenge for the design engineer. Old mill buildings are considered in this article as those designed prior to 1960, when the first edition of the Guide for the Design and Construction of Mill Buildings, AISC Technical Report No. 13 was published. (The first edition of AISC Technical Report No. 13 and the subsequent second edition, 1979, contain the current recommendations for steel mill building design loads and load combinations.)

Design codes and techniques (structure modeling, determination, application and distribution of design loads) used in the past have changed significantly. Design codes presently used (eg, AISC, AISE and others) establish various design criteria, many of which were not (or only partially) recognized in the original design of existing mill buildings.

Currently, it is common for the design engineer to encounter significantly overstressed conditions when current design criteria are applied to existing mill buildings and their original cranes. However, many of these buildings have performed satisfactorily for many years and do not show any sign of distress in the regions that have been over stressed during that time. In such cases, modification of existing mill buildings to handle additional crane loads could require a substantial reinforcement with an associated long downtime period for the mill operation and large capital expenses. Such decisions could make a modification project economically unacceptable.

The following inequality defines the theoretical over stress condition in terms of the allowable stress design (ASD) method:

$$\Sigma Q \leq \frac{R_n}{F.S.}$$

The left side of the inequality is the required strength (design forces or moments) which is a function of loads and the design model of the structure. The right side of the inequality is the allowable strength which is the nominal strength divided by a factor of safety. When the two sides of the inequality are divided by the appropriate section property (eg, area or section modulus), the inequality is converted into a relationship between design and allowable stresses. The theoretical over stress is a condition when 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 building.
- Review and revise design loads and combinations.

Choosing the safety factor is difficult for the designer unless the building can be proven that the building is generally strong enough to remain intact in the case of over stressing. The designer must be able to choose between the cost of additional reinforcement and the risk of structural failure.

Increasing the section properties of the structure is the simplest way to ensure that the building is strong enough to handle the additional loads. However, this approach is undesirable because the designer will go against a common tendency to increase the required safety factor for old structures.

Increasing the section properties of the structure means reinforcement.

Improving the design model of the building has the objective of obtaining more realistic load distributions which would be expected to lead to a design force reduction. Changing the building design model could require some modifications in the structure that are less expensive and more convenient to perform than direct reinforcement of the overstressed members.

Some design loads and combinations recommended by current design codes are unduly conservative, especially loads generated by the crane or trolley motion. Some load combinations recommended by design codes include at least two instantaneous impact type loads with a probability of coincidence close to zero. Such combinations, after approval of the mill building owner, can be excluded from consideration or used with a substantially reduced safety factor.

Optimal structural design of mill building modifications should minimize the total cost of the project. The project cost consists of a direct cost of building modifications and losses associated with downtime in the mill operation required to accomplish the modification.

An advanced structural model and critical review of crane loads and load combinations can help achieve the optimal design in existing mill building modification projects.

Historical review of mill building design models

In early days, designers did not have the benefit of the knowledge which extensive research and computerized analysis provided today and, instead, had to depend on common sense. Because designers had no practical means of dealing with indeterminate building structures, they made the structures statically determinate by assuming pinned ends and designing columns and trusses as simple elastic structures.

At the beginning of the 20th century, Ketchum proposed solutions for statically indeterminate mill building frames. Utilizing Ketchum’s formula, the designer was able to analyze the building as a statically determinate planar frame.
For many years, Ketchum's books on steel mill building design were the only textbooks for students and the handbooks for design engineers. Many mill buildings were built using his recommendations and many are still providing dependable service. However, analysis of these buildings using present design codes predicts significant overstressed conditions, mainly due to increased design load factors.

In 1966, Murray described a new approach in mill building design called the space frame concept. Murray proposed two different models for mill building frame design: Model No. 1, for crane and roof loads and Model No. 2, free to swing frame, for wind loads. In Model No. 1, the crane column was taken out of the space frame and analyzed as a free body or isolated member. The column was considered as fixed at the base and pinned at a point midway between the knee-brace and the bottom chord of the roof truss. No side sway of the pin was allowed. Utilization of the Murray approach provided more economical mill building column design in comparison with the plane frame model.

However, all buildings experience side sway. The side sway may be small for slender stiff bracings with well developed bottom chord bracing or it may be large in tall, 1 or 3-bay flexible buildings. Large side sway also occurs at building and bents and at bents located next to temperature expansion joints. The Murray single-column model neglects the side sway effect. This results in underloading of the lower part of the column and overloading of the upper part due to crane loads in comparison with a contemporary 3-D building model which includes side sway provisions.

In summary, mill buildings designed prior to the late 1950's were most likely designed as plane framed structures. Strong columns and weak bottom chord bracing are typical features of these buildings. Changing the building model from a plane into a space frame allows for crane load sharing. Such a model change would require modification of the bottom chord bracing and probably a few minor column modifications.

Mill buildings designed after the late 1950's may have been designed as a plane frame, but with much stronger bottom chord bracing. The possibility exists that a particular mill building design was based on the Murray space frame concept. In this case, the designer faces a difficult problem to bring the existing building into compliance with the current design codes without significant reinforcement and/or rationalizing design loads and combinations.

Computer modeling of mill building frame

It is now commonly accepted that mill buildings are space structures. Crane runway girders deliver crane loads directly to two or three transverse bents simultaneously (Fig. 1). These localized crane forces are then distributed from the loaded bents in the form of reactive forces to adjacent transverse bents through horizontal diaphragms (eg., bottom chord horizontal bracing, floors, etc.). In this transaction, the crane acts as a rigid link between two sides of the runway.

It is possible to develop an elastic 3-D finite element computer model of a mill building. However, such a model, even for a mid-sized mill building, could easily consist of a few thousand nodes and elements (Fig. 2). Many design companies are not equipped with computers and programs to perform such an analysis. In addition, it is inconvenient to work with a large program when many changes can be expected before the final solution is obtained.

An alternative approach, which provides a high degree of accuracy, is to resolve the 3-D mill building frame problem into 2-D problems using a series of 2-D stiffness computer analyses (Fig. 3). Each transverse bent is modeled as a planar frame. Interaction between bents is provided by a horizontal diaphragm (roof truss bottom chord bracing or floor framing) which is considered as a horizontal continuous frame on a series of elastic supports with linear elastic stiffnesses equal to the lateral stiffnesses of the transverse bent at the level of the horizontal diaphragm. Reactive forces from crane-loaded bents at the horizontal diaphragm level are distributed by the horizontal diaphragm between all bents which are used as elastic supports for the diaphragm. The solution can be formulated as a sequence of steps (Fig. 3).

- Step No. 1—Develop a planar model of each transverse bent and apply horizontal load T = 1kip at the horizontal diaphragm level (the bottom chord bracing in the example). Run the analysis and determine the frame horizontal displacement at this level. The reciprocal of this displacement is a linear elastic spring constant for the horizontal diaphragm support. Prior to Step No. 2, the design crane loads (vertical and horizontal) have to be determined for the analyzed and adjacent bents (Fig. 1).

Fig. 1 — Crane loads on mill building adjacent transverse bents.

Fig. 2 — Mill building space frame.
Prior to analyzing an existing mill building using the 3-D concept, the designer should perform the planar, free to sway, frame analysis of the original building frame and determine the need for column reinforcement. The designer should then decide whether bottom chord modification is required to change the building design model. (The author has experienced cases where the existing building columns being analyzed as part of a planar frame, satisfactorily resisted the current design load and, thus, required no modifications.)

Evaluation of crane loads

All overhead traveling cranes operate dynamically, simultaneously generating and being under the action of forces which include steady-state and time-varying components.

The steady-state part of the total crane loads is represented by the static loads such as the weight of the crane bridge, trolley, lifting mechanism, other equipment and the lifted load. At each moment of crane operation, the static crane wheel loads can be determined by applying the laws of statics. Dynamic forces are time varying in direction and/or magnitude. Crane dynamic loads are introduced by the crane work and by the inertia of the masses, which are put into motion. The crane operation generates forces due to load lifting, trolleying, crane travel and friction. The inertia forces are those that result from overcoming the inertia of the load and crane component masses in acceleration and deceleration processes for all functional motions.

Fig. 4 — Crane side thrust effect on different frame models.
For any defined condition, the crane dynamic forces can be calculated with reasonable accuracy, but it is seldom possible to define the operating condition accurately. This is especially true for the dynamic forces in a coupled system such as a mill building/crane. Interaction between the building and crane develops through the runway, crane rails and crane wheels, which makes the analytical definition of the system relatively complicated. Apparently, this is the reason why no adequate methods of describing crane dynamic forces have been developed since the first mill buildings were designed.

Current design codes define crane dynamic forces as a percentage or factors of known static loads such as lifted load, trolley and bridge weight, wheel load, etc. A similar approach was used by Ketchum at the beginning of the century in the General Specifications for Steel Frame Mill Buildings.

Dynamic forces determined by using design code recommendations do not reproduce a reasonable approximation of the actual forces because they do not include in their determination such variables as motion characteristics of the crane and its components and the stiffness of the crane way support structures. This can be demonstrated by the following example.

### TABLE I  Vertical Impact

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
<th>Total vertical impact, kips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ketchum</td>
<td>25% X wheel loads—</td>
<td>372</td>
</tr>
<tr>
<td></td>
<td>for runway girders only</td>
<td></td>
</tr>
<tr>
<td>AISC®</td>
<td>25% X wheel loads—</td>
<td>372</td>
</tr>
<tr>
<td></td>
<td>for runway girders only</td>
<td></td>
</tr>
<tr>
<td>AISE Technical Report No. 13</td>
<td>25% X wheel loads—</td>
<td>372</td>
</tr>
<tr>
<td></td>
<td>for runway girders and building frame</td>
<td></td>
</tr>
<tr>
<td>AISE Standard No. 8</td>
<td>0.2 X wheel loads</td>
<td>207</td>
</tr>
<tr>
<td>CMAA®</td>
<td>1 X wheel loads</td>
<td>223</td>
</tr>
<tr>
<td>German Standard DIN 4122</td>
<td>0.1 X wheel loads—</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>for building structure</td>
<td></td>
</tr>
<tr>
<td>USSR Standard SNP 2.01.7-85</td>
<td>0.1 X wheel loads—</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>for runway girders H2</td>
<td></td>
</tr>
<tr>
<td>Hotel operation analyses</td>
<td>Uplift with max. acceleration 0.1 g. This is 10% of lifted load or 3.5% X wheel load</td>
<td>52</td>
</tr>
<tr>
<td>Crane travel analyses</td>
<td>Max. lowering speed with full load and instantaneous stop (conservative case)</td>
<td>182</td>
</tr>
<tr>
<td></td>
<td>This is approximately 11% of wheel loads</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Crane wheel jump due to vertical rail misalignment (5 in. jump). Crane travel speed max. 6 fps</td>
<td>24</td>
</tr>
</tbody>
</table>

Example of dynamic force calculations

Dynamic forces have been determined using different design code requirements and simplified dynamic analyses based on the stiffness and motion characteristics of the crane and building. The simplified dynamic analyses included a few assumptions: all vertical and horizontal (from straight side thrust) wheel loads were equal on one crane side; and the lateral stiffnesses of the crane girders were not taken into account. Longitudinal horizontal dynamic forces were not included in the example because of the simplicity of their determination. These forces cannot exceed the sum of crane traction forces which equal the vertical loads on drive wheels times the coefficient of static friction for steel on steel, or the crane runway stop collision force.

A 250-ton ladle crane, positioned to produce the maximum column load, was used.

Vertical impact — Vertical impact forces result from crane longitudinal travel and hoisting operations. The variety of crane vertical impact forces determined for the same crane using different design sources is illustrated in Table I.

Several tests performed on mill cranes show that impact during real operating conditions did not exceed 7% of the crane static loads.

It is difficult to develop a realistic analytical model or simulate a test load condition that results in a 7% impact factor for crane loads. A drop-off load case should be excluded as unrealistic. Griggs proposed that this conservative design impact factor should be called an overload factor rather than a dynamic impact factor.

Lateral side thrust — Lateral crane straight side thrust forces (Fig. 6) are the result of trolley operations; acceleration or deceleration; friction forces due to start of trolley travel or braking; and collision with the trolley stop. The straight side thrust force for the 250-ton ladle crane based on various design sources is shown in Table II.

There is a noticeable nonconformity between two AISE documents, Technical Report No. 13 and Standard No. 6, in the determination of lateral side thrust forces (Table II). In reality, the forces applied by the crane to the runway are equal to the reactive forces from the runway to the crane.

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**Fig. 9** — Crane lateral forces (general concept).

**Table II** — Lateral side thrust forces (kips).
Skewing forces — Crane_skewing forces are the least investigated dynamic forces (Fig. 5). These forces originate from the tendency of the crane to meander as it travels in the longitudinal direction. The reason for such a movement is dynamic asymmetry which generates different traction forces on the two sides of the runway, imperfections in cranes and improper runway maintenance. Information for the evaluation of skewing forces can be found in references 13 and 16. Skewing forces determined for the 250-ton ladle crane based on various design sources are shown in Table III.

Crane skewing forces always provide a local horizontal bending for craneway girders and building columns. They only generate a horizontal twist on the overall space frame of the building. (Only space frame analyses could provide accurate distribution for the frame forces due to crane skewing.)

The lateral loads from crane skewing could be more unfavorable than the lateral loads from trolley operations for crane girders and their connections to columns. The probability of the peak magnitudes of the trolley lateral forces and the crane skewing occurring simultaneously is practically zero.

The absence of a crane skewing force provision in AISC Technical Report No. 13 and AISC specifications, and excessively high, straight side thrust forces in comparison with other design codes, suggests that the skewing force provision is built into the total side thrust force. Such an approach creates an excessively conservative design case for the building frame analysis.

During the last few years, two field tests were performed in the U.S. and Canada on steel mill plants. The magnitudes of vertical impact and lateral side thrust forces determined using test results were substantially below the same forces determined in accordance with the AISC Technical Report No. 13 and the AISC specifications. The results of these tests were successfully used in the projects of upgrading the existing steel mill plants.

At the present time, in the absence of rational methods for crane dynamic force determination recommended by the design codes, there are two basic alternatives which can be exercised by the design engineer in cooperation with the steel mill owner to determine realistic crane forces for the particular crane and building, an analytical and a field test method.

In the analytical method, crane dynamic forces should be determined by dynamic analyses using motion and stiffness characteristics of the crane and the building.

In the field test method, the most severe crane operation conditions should be simulated to produce the maximum impact and side thrust forces. The system of strain gages installed on the crane girders and the crane makes it possible to determine the stress fluctuation due to various crane actions producing dynamic forces. The recorded stresses then can be transformed into forces which caused these stresses.

The second method is more precise because it eliminates all analytical assumptions which cannot be avoided in the first method. The cost of the field test will be easily recovered later by savings received from the elimination or reduction in the building reinforcement and downtime required to perform the reinforcement.

Load combinations

Engineering judgment is required in selecting realistic load combinations, especially when the designer deals with an existing mill building. The goal is to include in each load combination only those loads that can be reasonably expected to occur simultaneously. In addition to static vertical loads, crane loads include a group of instantaneous dynamic loads: vertical impact; horizontal longitudinal forces; horizontal

### Table III: Crane Skewing Forces

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
<th>Skewing force, kips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ketchum</td>
<td>No provision for crane skewing</td>
<td>—</td>
</tr>
<tr>
<td>AISC</td>
<td>No provision for crane skewing</td>
<td>—</td>
</tr>
<tr>
<td>AISC Technical Report 13</td>
<td>No provision for crane skewing</td>
<td>—</td>
</tr>
<tr>
<td>AICE Standard N. 811</td>
<td>Two forces each</td>
<td>±148</td>
</tr>
<tr>
<td>CMAA</td>
<td>Sum of skewing forces</td>
<td>±20</td>
</tr>
<tr>
<td>German Standard DIN 1501312</td>
<td>Sum of skewing forces</td>
<td>±121</td>
</tr>
<tr>
<td>USSR Standard SNIP 2.01.7-85'</td>
<td>Sum of skewing forces</td>
<td>±77</td>
</tr>
</tbody>
</table>

### Table II: Lateral Straight Side Thrust

<table>
<thead>
<tr>
<th>Source</th>
<th>Description</th>
<th>Total Side Thrust, kips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ketchum</td>
<td>0.2 X (trolley weight + 149)</td>
<td>168</td>
</tr>
<tr>
<td>AISE Technical Report No. 13</td>
<td>10% (trolley weight + 149)</td>
<td>168</td>
</tr>
<tr>
<td>AICE Standard No. 811</td>
<td>40% (trolley weight + 149)</td>
<td>200</td>
</tr>
<tr>
<td>CMAA</td>
<td>(7.4 x 0.01' trolley weight) X r</td>
<td>118</td>
</tr>
<tr>
<td>German Standard DIN 4102</td>
<td>1.5 x 0.2 X (min. trolley weight)</td>
<td>51</td>
</tr>
<tr>
<td>USSR Standard SNIP 2.01.7-85'</td>
<td>Trolley load</td>
<td>42</td>
</tr>
<tr>
<td>Trolley operation analyses</td>
<td>Max. friction forces due to the start of trolley travel or due to braking before driven wheels start slipping</td>
<td>84</td>
</tr>
<tr>
<td>Trolley operation analyses</td>
<td>Coefficient of friction for wheel on rail was taken as 0.2</td>
<td>45</td>
</tr>
<tr>
<td>Trolley operation analyses</td>
<td>Trolley collision force at 50% max. trolley speed K20</td>
<td>22.3 kips</td>
</tr>
<tr>
<td>Trolley operation analyses</td>
<td>Trolley collision force at 50% max. trolley speed (conservative case)</td>
<td>33</td>
</tr>
</tbody>
</table>

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present computer programs could provide a force envelope (maximum and minimum forces from all load combinations) for each framing member.

Exclusion of unrealistic loading cases from structural analyses of existing mill buildings does not require any sacrifices of present safety standards but creates an opportunity to develop an effective upgrading project.

Conclusions and summary

One experienced engineer wrote that the design of a mill building is 90% judgment and 10% perspiration. While the exact percentages are debatable, especially for upgrading existing mill buildings, sound engineering judgment should form an important part of the structural design for the upgrade of existing mill buildings.

Some basic questions that must be resolved by the design engineer are:

- What building design model best fits the existing structure? What minor frame modifications can be implemented to change the behavior of an existing structure to minimize or eliminate member reinforcement?
- How should crane runway girders with restrained supports and knee braces be treated? Remove, neglect or consider the knee brace effect on girders and columns? What should be done with fatigue sensitive details? Fix them or monitor them and see what happens?
- How to create load combinations that will include all possible realistic loads occurring simultaneously? How many instantaneous crane dynamic forces should be included in one load combination? How to consider the probability of simultaneous maximum loads from several cranes working in the vicinity of a particular column?

All these and many other questions (omitted from this article) have to be answered by the design engineer and approved by the steel mill owner prior to detailed analyses and design.

A mill building modification project will inevitably require the solution of many problems which were not discussed in this article. Even for the problems which were discussed, there is no direct and clear solution. In all stages of the project, the design engineer should continuously use sound engineering judgment to achieve the best results.

Two important parts of the structural design of mill buildings have been considered; building modeling and crane loads. Each of these subjects requires further development and improvement. Accurate methods of crane load determination and better understanding of soil-structure interaction should help in the future development of more rational criteria for mill building design.

Since 1980, the design approach presented has been successfully used in numerous steel mill modification projects in the U.S. and Canada. Implementation of this approach resulted in achieving a reliable building modification with minimum cost required to perform it.

REFERENCES