Industrial Buildings—Guidelines and Criteria

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The purpose of this paper is to provide the designer of industrial buildings with guidelines and design criteria for the design of buildings without cranes, or buildings with light-to-medium cranes. It would seem a simple task to design a good industrial building. The basic elements of the structure do not present a formidable design task. However, combining the elements: roof deck, purlins, girders, columns and girts into the most functional and cost-efficient system, is a complex task.

Experience has shown the futility of strict rules where judgement still applies, i.e., intuition can still reasonably solve multi-variable problems. However, general guidelines and criteria can be stated. These guidelines and criteria do not change significantly with time. The guidelines for design can best be understood by recognizing there are interdependencies between all major components. The selection and design of the components of industrial buildings were individually discussed in an AISC publication "Light and Heavy Industrial Buildings." Roofing, walls, metal deck, purlins, main members, columns, girts, bracing, anchor bolts, floor slabs, crane girders and crane columns were discussed in detail. Listed in the bibliography are references which address the design of each of these components.

GUIDELINES AND CRITERIA FOR THE "OPTIMUM" INDUSTRIAL BUILDING

The question "What is the 'optimum' industrial building?" is answered differently, depending on whom is asked the question. To the owner, the optimum building is one that meets its intended function, one that does not leak, one with no cracks in the floor slab and one whose construction cost came in under budget.

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The engineer thinks of the "optimum" building in several ways. For example, to the young designer it is usually thought of as the building of least weight or cost that will carry intended loads, i.e. well-engineered. The senior project engineer thinks of the optimum building as one which satisfies the owner, and one for which his construction documents caused little or no confusion during construction. The owner of the firm often thinks of the optimum building as one with which the client is pleased, thus paying for it promptly, and one on which his firm makes a profit on the design.

Here are guidelines that should lead to an optimal building design for *all* parties:

1. Identification of Client Requirements

The first step is to determine who is your client—building owner, general contractor, fabricator, construction manager, etc. Next, who are the other parties, and what are your relationships with them (they are all indirect and their input must be channeled through your client). The next step is to determine the user's requirements, beginning with the initial project meeting. At this initial meeting, it is important to spend a considerable amount of time going over a design checklist. Such a list has been developed by our firm for industrial buildings. It contains questions which must be answered to get a good start on the project. Questions are asked about the following items:

Site information
Soil conditions
Plant layout and work flow
Preferred bay sizes
Future expansion plans
Loading docks
Door locations
Crane types and capacity
Floor slabs
Wall material preferences
Roofing preferences
HVAC equipment loads

Process loads
Preferred fabricators/contractors
Design responsibilities
Schedule
Payment of fees
Budget

The building budget and the engineering budget must be discussed at this initial meeting. With respect to the owner's budget, it is important to discuss how realistic it is. How was the budget established? With what degree of sophistication was it established? Can the building be built within the budget? Has the owner included fees and engineering? It is important to determine to what extent the client wants to participate in the design process; i.e., how often does the client intent to meet to discuss the project. Meetings are very expensive, and unanticipated meetings can and will destroy the engineer's budget.

2. Identification of Structural Requirements

At this point, the engineer should list and examine applicable building codes, specifications, tolerances, special loadings and stiffness requirements that have been specified or should be specified for the project. A review of the owner's criteria to determine how they correspond with the required codes, specifications and stiffness requirements is necessary. For example, standard mill tolerances for beam sweep (ASTM A6) are greater than sweep tolerances allowed by many crane manufacturers for installation of crane rails. A major conflict between suppliers can be avoided if this difference is recognized early in the design stage.

Office standards the design firm generally follows for specific design types should also be reviewed at this time. Special loading criteria must be examined, e.g., lateral guiding forces for cranes with lateral guide wheels and bumper forces (bumper forces are real and usually exceed longitudinal tractive forces) should be discussed with the crane manufacturer, and these criteria incorporated into the design.

A discussion of stiffness requirements is in order at this point. For most projects, it is not difficult to determine strength requirements. However, stiffness requirements are generally undefined, are not given in codes, and frequently are not specified. Stiffness can determine the success or failure of a structure. This not only applies to industrial buildings, but also to residential and commercial structures. In the case of the industrial building, and in particular the crane building, the live loads, as opposed to fictitious apparent floor loads, are process loads. Consequently, the structure will be loaded to its full design load early in its life and stiffness deficiencies will be immediately obvious.

Unfortunately, the designer is likely to be on his own in selecting the stiffness required for individual components and that required for the structure in general. The author's guidelines for stiffness for industrial buildings are:

Lateral Stiffness for Industrial Buildings without Cranes

Lateral stiffness requirements are generally dependent upon the wall material selected for the structure. Buildings with sheet metal wall systems have performed adequately with predicted wind drifts (based on the bare steel frame) as large as Height/100. Undoubtedly, the actual drift of the structure is considerably less due to the diaphragm action of walls and roof. The Canadian Institute of Steel Construction recommends lateral drift controls between $H/400$ and $H/200$ for industrial buildings. This same criteria cannot be used for buildings with masonry walls. For masonry wall structures, the designer should calculate the mortar stress which would occur for a proposed building deflection. The mortar stress should be kept to NCMA* allowable values. Allowable deflections for buildings with precast or tilt-up wall type construction are dependent upon the type of connections of the concrete to the foundation as well as the connection at the eave. If rotationally flexible connections are used at the base and eave, these structures can be allowed larger deflections without a great deal of distress.

Lateral Stiffness for Industrial Buildings with Cranes

Drift criteria for buildings with cranes are not only dependent upon the choice of wall system, but also upon crane movements. For pendent-operated type crane systems, buildings with calculated wind drift ratios of $H/100$ have performed. However, crane movement can generally be observed. A structure which is this flexible should be described to the owner beforehand so he is not surprised to see his structure move and rattle when the crane is in use. It is suggested, for cab-operated cranes, that building lateral drift be limited to $H/240$ for both crane loads and wind loads. In addition, the lateral sway at the elevation of the crane runway should be limited to roughly one inch. Structures supporting computer-controlled cranes will probably require more restrictive tolerances.

Although not a drift criteria, it should be mentioned here that it is not recommended to tie masonry walls into crane column steel because of the frequent movement of the columns due to crane action.

*National Concrete Masonry Association, Specification for the Design and Construction of Load-Bearing Concrete Masonry, P.O. Box 9185, Rosslyn Station, Arlington, Va. 22209.

Stiffness of Crane Runway Beams

Vertical deflections are generally calculated without vertical impact. For top running cranes typical criteria are:

Span/600 for CMAA* Classes A, B and C
Span/800 for CMAA Class D
Span/1000 for CMAA Classes E and F

For underhung and monorail crane runway beams:

Span/450 for CMAA Classes A, B and C
Underhung cranes with more severe duty cycles must be designed with extreme caution.

Lateral deflections for runway beams should be limited to Span/400 to avoid objectionable visual lateral movements.

Because stiffness criteria can have a major impact on the cost of a crane building it should be discussed with the client so he understands a proper design considering stiffness usually involves more material than a strength design alone.

3. Selection of Roofing and Wall Material

Choices for roofing and wall materials are many times not made by the designer, since the owner may often dictate what is to be used. Most industrial buildings will have either built-up roof systems, EPDM systems, sheet metal or standing-seam roofs. The choice of any one of these roof systems affects many other decisions in the design process. The roof weight affects the gravity load design of the roof system and also, in the case of seismic calculations, the lateral load design. The roofing choice affects the type of roof deck, the type of purlin used, purlin spacing, deflections of the secondary structurals, roof pitch and drainage requirements.

For example, if a standing-seam roof system is selected, the direction of secondary framing is established automatically because of the drainage requirements for this type of roof. Standing-seam roofs exhibit little or no diaphragm capacity. The structure cannot be designed using normal roof diaphragm considerations. X-bracing and/or rigid frames are required. Special considerations are also required for the gravity load design of the roof members, since the roof covering cannot be used to laterally support roof members. Uplift requirements are also more critical, because there is little dead load to offset the uplift.

Similar considerations are made when the wall system is selected. In general, the types of walls chosen will be either metal field-assembled, or metal factory-assembled, precast or masonry. In selecting the wall system, the designer should consider the following items:

Cost
Interior surface requirements
Appearance
Acoustical control
Dust control
Maintenance considerations
Ease and speed of erection
Future expansion
Fire considerations
Insulating properties

Again, once the wall system is selected, it has a major impact upon the design of the structure. Eave members, girts, foundations and wall bracings are all dependent on the type of wall. Recognizing the interaction of roof, wall and framing can eliminate rechecking the design by recognizing system decisions must be made simultaneously. Once the roof system and wall system are selected, major decisions relating to the design of the building are fairly in hand, except for bay size.

4. Selection of Bay Size

Owner requirements may dictate bay size. Depending upon the functional requirements, a certain bay size(s) may be necessary. If this is not the situation, the building plan, which may be dictated by the site, will indicate a bay size.

In general, for buildings without cranes, bays from 30 ft × 30 ft to 40 ft × 40 ft have proven to be economical sizes. Gravity loads generally control the bay size. The lighter the roof loads, the more open the bay can be made without cost penalty. As discussed earlier, the choice of wall system dictates whether or not girts are required for the structure. If girts are required, and a light structure is the criteria, then the engineer should select gage material C or Z girts. Based on both strength and stiffness ($L/180$) requirements, the maximum economical span of light-gage girts is approximately 30 ft. If larger bays are used, wind columns are required.

From the above, it may seem that a 30 ft × 30 ft bay is the most economical choice. This is especially true if the proportion of the perimeter of the enclosed area is "high" relative to the enclosed area, e.g., a long narrow building will have a high perimeter-to-area ratio. For buildings with high perimeter-to-area ratios, girt steel is a larger percentage of cost than for buildings with lower ratios. For buildings with low perimeter-to-area ratios, such as square buildings of significant size (200 ft × 200 ft) the percentage of steel that would be contained in wall framing is less of a cost factor. Thus, the 40-ft × 40-ft bay can prove economical for large square buildings. The designer is reminded here that, when wind

*Crane Manufacturers of America, Specification #70, 1983, Materials Handling Institute, 1326 Freeport Road, Pittsburgh, Pa. 15238 columns are used, a positive system must be provided to transfer the top reaction of the column into the structure. Do not rely on "trickle theory" (i.e., "a force will find a way to trickle out of the structure").

In general, soil conditions will not have a major impact on the selection of a 30-ft to 40-ft bay dimension when shallow foundations are used. When there are very poor soils, and deep foundation systems are required, larger bays will generally be more economical because they limit the number of foundations. This assumes the floor slab can be put on-grade. The reader is referred to Refs. 1 and 5 in the bibliography for more detailed discussions on bay sizes.

For crane buildings, similar judgments are required. However, in general for the light and medium crane buildings, bays in the neighborhood of 25 ft to 30 ft will be the most economical because of the cost of the crane runway steel. Designs with spans requiring plate girders rather than rolled shapes increase the structure cost considerably. Also, large bay designs that require tension flange bracing for the crane runway beams have added significant costs. This applies for spans greater than 36 ft in accordance with the AISE Technical Report #13.[2] The proposed AISC *Load Resistance Factor Design Specification* provides equations relative to tension flange bracing.

5. Selection of Framing System

As one aspect of the structural system, it is necessary to select a method for resisting lateral loads—specifically, the stability mechanism used to resist wind, seismic and crane lateral loads. Three basic options are reasonable: (1) Using a roof diaphragm system with wall bracing (not recommended for most crane buildings); (2) Using an X-braced roof system with wall bracing; and (3) Designing the structure as a rigid-frame structure. It can be seen again the choice depends very much on the choice of the roof system. Built-up roofs and/or EPDM roofs will have a roof deck with diaphragm capability, whereas the standing-seam roof does not. And the diaphragm-braced system must be ruled out for buildings with such roofs. In general, a diaphragm-braced roof with wall bracing will yield a minimum cost structure. However, one needs to consider the owner's requirements for future expansion, because the necessary braces may be in the way. The engineer also needs to consider where building expansion joints are to be located, since the diaphragm or X-bracing may be interrupted by an expansion joint or joints.

A rigid-frame scheme may be the best choice when buildings have span-to-width ratios greater than three or four to one. When the span-to-width ratio of a building is of this magnitude, roof diaphragms will not have the required strength to carry lateral loads. X-bracing in the roof will also become relatively large when these ratios exist.

The engineer can now decide upon the type and orientation of both exterior and interior columns.

For buildings without cranes, the choice of column type and orientation depends primarily on building height, the wall system and the lateral load carrying system. In general, wide-flange columns provide the most economical choice for exterior columns in a building. This is particularly true in metal wall systems where the girts can be used to brace the weak axis of these columns. Also, since wide-flange columns are ideal for bending about one axis, their use is optimum for structures in which rigid-frame action is required in one direction. The long, narrow building for which rigid-frame action is selected can be braced in the long direction by either X-bracing or by weak-axis bending of the columns. X-bracing will provide the most economical solution. The best choice for interior columns is also dependent on the lateral load system and on the building's clear height. For clear heights over 24 ft, tube columns will generally yield the most economical selection because of their high radius of gyration about both axes.

For buildings with cranes, the question of type of crane column is one of constant debate with engineers and fabricators. Several types exist: (1) straight-shafted columns with brackets; (2) a separate crane shaft; (3) a separate crane shaft laced or connected by diaphragms to the building column to create a composite section; (4) a stepped-crane column. The choice of the most appropriate column type is discussed at length in Ref. 1.

6. Design of Connections and Components

This process will be expedited if the designer first thinks through the type of connections required. Connection requirements will dictate the type of analysis and also the type of members that can be used conveniently. For example, if an X-braced roof system (horizontal roof truss) is selected as the optimum lateral load carrying system, and if joist construction is to be used in the roof, the designer must think through all the connection details to properly specify the joist. Forces in the horizontal roof truss may be of such magnitude that joists cannot be used for strut or chord members. Perimeter members must be selected so connection forces can be dealt with without undue expense. For example, special members and connections may be required at locations where roof diaphragm forces are transferred into the wall bracing.

7. Preparation of Plans and Specifications

For the majority of projects, the major expense to the design firm is in preparation of plans and specifications. It is in the preparation of these documents the firm is tempted to "cut corners" to save money. Corners are cut by not showing a sufficient number of details and sections, by not providing accurate forces for connections to be designed by the fabricator, by forcing the fabricator to design connections that should be designed by the engineer, by eliminating the in-house project review and by using old, outdated specifications.

It has been our experience these "cost-saving tactics" do not save in the long run. The result is confusion of the bidders and in the field during construction. The time lost in solving problems in the field or on the show drawings is generally greater than the time it takes to do the job right the first time. By preparing good sets of office standard details, and by constant updating your specifications, dollars can be saved the correct way.

SUMMARY AND CONCLUSIONS

General guidelines have been presented here to guide the designer of industrial buildings through the design process. Detailed procedures can be found in the bibliography relative to the design of components in these structures. It is hoped the material presented here will be helpful to the designer in his quest for the creation of the optimum structure.

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