The Nature of Long-Span

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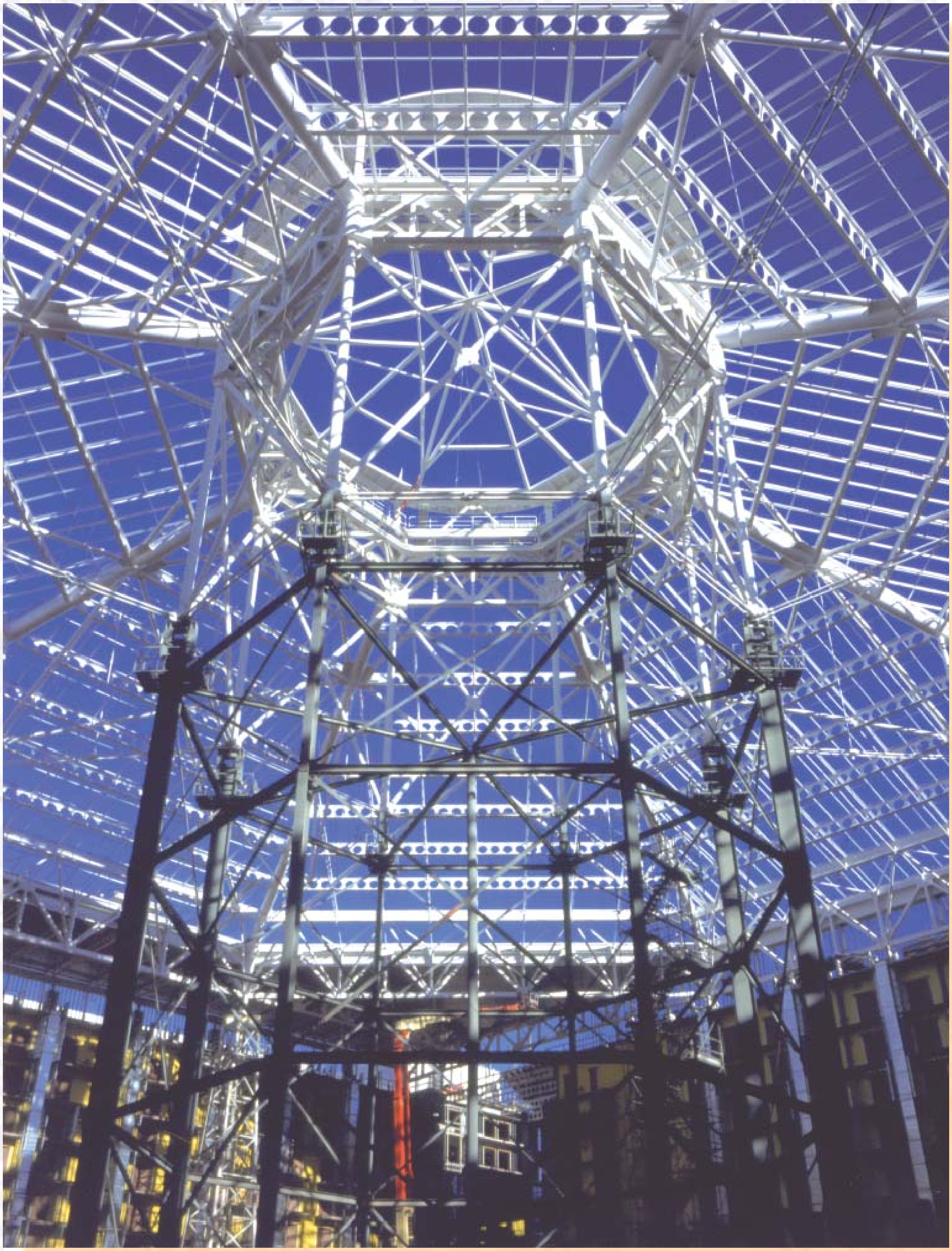

The design and construction of long-span roof structures requires a blend of skills from the structural engineer not normally required in more normal building types. Forces come into play, including material shrinkage, support settlement, temperature effects and sequence of erection, that can normally be ignored in many building types but can have a dramatic effect on long-span structures. While a firm knowledge of structural behavior is essential, there are other challenges that face the structural engineer that are equally as important. This article will explore the particular genre of buildings that are described as "long-span". It will outline some design considerations unique to this building type. It will focus attention on the necessary steps that must be taken in the design and construction of these buildings to make them live up to their high investment and lofty owner expectation.

Figure 4: Roof Erection of the Gaylord Texan, Grapevine, Texas. (photo by Dallas Visual Design)

Figure 1: Minute Maid Park, Houston, Texas. (photo by Mark Scheyer)

After the collapse of five major long-span roof facilities in the United States over a two year period in the late 1970's, the American Institute of Architects (AIA) convened a special blue-ribbon panel of industry experts to study the problem. The final report in 1981, entitled *"Towards Safer Long-Span Buildings"*, recommended some specific actions by the design-construction team that are more applicable today than ever before, as projects get more complex, construction budgets get tighter and schedules ever faster. Clearly the message from this report was "Designers and Builders Beware." Fortunately, there are certain strategies that the designer of long-span structures can implement to avoid the design and construction problems that can occur with this building type. These strategies are discussed below:

Establish the key project players, their roles and responsibilities and the proper lines of communication early in the project. In today's construction world, there are a myriad of contracting methods. Project team players can be numerous and lines of responsibility blurred. We have worked on large public projects where there were as many as five architects engaged on the project and three structural engineers. All this must be sorted out early if the project schedule is to be maintained. Every major design decision should be documented in writing, and clearly communicated to all team members. The single biggest source of project disputes, cost overruns, and delayed schedules is poor communication among the designers and builders.

Engage the fabricator/erector team as early as possible in the project. While the ability to do this is tied to the contracting approach, the benefits to the project in cost and schedule control can be significant. Decisions that need to be made early include grade of steel, connection type, bolt size and grade, welding procedures and processes, erection sequence and method, paint type and construction tolerances. Construction tolerances can be particularly important where steel members are connected to concrete. The normal tolerances for concrete may not be sufficient for steel fit-up. This includes applications where steel members are bolted to concrete embedded plates or bolts. Erection straightness in the fabricated and erected condition for compression chords of trusses is another key issue that can affect the magnitude of second order forces in the member and also bracing forces.

Use high strength steel to save on self weight of structure. The use of grade 65 steel will normally save weight and cost. This is because the cost premium (from 0 to 5%) is considerably less than the benefit from the ratio of yield strengths. (65/50 = 1.3). The key here is to maintain compression unbraced lengths that permit the higher allowable compression stress advantage to be realized.

Utilize a wind tunnel and snow study wherever possible. Code specified wind and snow loads can be very crude estimates of actual environmental loads with today's free form roof shapes often utilized in architectural designs. The potential gain in accuracy of these loads will often be more than offset by the cost of the study.

Utilize roof framing systems and materials that minimize the self weight of the structure. The designer should focus on maintaining as light a structure as possible, because the self weight of the structure is usually the heaviest design load. Besides the use of high strength steel as discussed earlier, framing systems that use tied arch or king and queen post truss systems usually yield the lightest structures. Mast and cable suspended structures, possibly with the use of a fabric roof membrane where the architectural design allows, can be particularly economical. Tie-down cables and masted roof systems should be considered where good rock foundation conditions exist. And don't necessarily rule out reinforced concrete as an alternative. With today's high strength concretes (in the range of 12 to 18 ksi), precast or site cast compression members (as in a tied arch system) can be an attractive solution where steel prices are high or delivery schedules extended.

Avoid the use of expansion joints in the roof structure. Expansion joints are very difficult to accommodate in long-span roof design and should be avoided. Our experience is that expansion joints cause more problems (in tracing them all through the structure, architecture and MEP systems and in maintenance costs) than they solve. Furthermore, temperature forces in long-span structures rarely seem to control the design of most members. None the less, a temperature change analysis should always be performed

Figure 2: Erection Towers for Minute Maid Park, Houston, Texas. (photo by Mark Scheyer)

Figure 3: Gaylord Texan Resort and Convention Center, Grapevine, Texas. (photo by Dallas Visual Design)

in a long-span roof structure, particularly to detect excessive forces in the structure from unwanted support restraints.

Consider additional design dead load for possible future re-roofing of the structure. It is impractical, disruptive and even dangerous (because of unbraced length of roof members and possible instability from unwary demolition construction workers) to remove old roof membrane and metal decking in the future.

Consider temperature, erection and foundation settlement loads in the design and construction. While temperature loads rarely seem to control the design of members, they can have a dramatic effect on erection fit-up – particularly where field welding is involved. Welding long-span steel is very problematic because of thermal shortening in the temperature variable climate of erection. Some of the most critical member stresses can occur during erection because of lifting stresses and different unbraced lengths that can exist than were assumed in the final as-built structure.

Don't be overly concerned with roof deflection and camber in long-span roofs. The exact position of the final roof structure in space is rarely critical, as long as adequate roof slope exists to drain the roof and architectural form and sightlines are not compromised.

Pay close attention to diaphragm stresses, diaphragm bracing of structural members and diaphragm attachment. Diaphragms can be critical to the structural integrity of the roof because of bracing provided to roof members, and the need to transfer external wind and seismic forces to the vertical lateral load resisting system, often at great distances. Also, a designer must make a judgment decision as to whether to allow a metal deck roof diaphragm to brace a long, heavily loaded compression chord of a roof truss, or to install special horizontal bracing members for this purpose. This decision can be an important one to consider in weighing the economy of the roof system versus the greater risk in relying on the metal deck diaphragm for this purpose. This decision is particularly critical during the vulnerable erection phase of the project. Also, it is important to remember that the plane of the metal deck diaphragm is usually not located in the same horizontal plane as the roof member axis. This eccentricity must be accounted for in the design and has been a structural flaw in some roof structure failures in the past.

Use bolted field connections wherever possible. "Shop weld – field bolt" is a good motto to live by in long-span roof construction. The difficulty of welding high in the air in windy conditions and variable temperatures makes field welding difficult to implement and to inspect. Consider using only two bolt sizes on the project – one for highly loaded members and one for the more routine purlin or brace connections. Consider limiting bolt sizes to 1 1/8-inch diameter A490 bolts (the limit for normal bolt wrenches) for the larger force members and 7/8-inch diameter A325 bolts for the more typical members. Many erectors would prefer the use of slip critical bolts in oversize holes for ease in member fit-up, even though it comes at the expense of a larger number of bolts than bearing type connections would have.

Consider preassembly of long-span trusses in the shop, in whole or in part, depending on available shop space to reduce fit-up problems in the field. Fit-up problems can result in costly retrofit and delays.

The structural engineer of record should design all major long-span roof connections as opposed to delegating this responsibility to the fabricator. In the end, this practice will reduce design and shop drawing review time and will ensure that the connection design meets the intent of the overall long-span roof design. Long-span roof design can often contain as many as 150 or more loads combinations, and to accurately communicate this information to the fabricator can be a real challenge at best. If the fabricator is on board early, connection designs can be tailored to the shop practices of the fabricator for an economical design. In all cases, the engineer should draw connections to scale to ensure that gusset plates are of reasonable size when compared to connection weights assumed in design (we have seen projects where gusset plates in truss members actually overlap!) and member conflicts are avoided. In today's world of advanced design and detailing

Figure 5: Reliant Stadium, Houston, Texas. (photo by Russ Andorka)

software, the design/shop drawing process can be streamlined to reduce the overall schedule. The structural engineer should attempt to combine the structural analysis model with the detailing model wherever possible to reduce project cost and time. Appropriate disclaimers can be transmitted to the contractor to address the liability concerns.

Group member sizes and make members as repetitive as possible (even at the cost of some extra weight in the structure) to simplify mill ordering of steel and to reduce detailing and fabrication costs. The structure should be framed to reduce the number of pieces to be fabricated and erected. Remember that "least weight is not necessarily least cost." The price of in-place structural steel in today's marketplace is much more about man hours of fabrication and erection per ton of steel than in pounds per square foot of steel. Labor costs are more dominant than the material cost of steel.

Figure 6: Erection of the Supertruss, Reliant Stadium, Houston, Texas.

Analyze the structure you design, and design the structure you build. Many past problems with long-span steel have stemmed from a discrepancy in the structural model from the actual as-built condition. Oftentimes, eccentricity of member forces has not been properly considered and has compromised the structural behavior.

Require a detailed written erection procedure. This written procedure should be reviewed and approved by the general contractor, fabricator, erector and engineer of record. This document is important to ensure that all parties are in agreement on the method, sequence and timing of the critical erection process. A thorough study and documentation of the erection procedure will force all parties to plan the erection procedure early, and help flush out problems before they occur in the field. Also, it is an excellent planning and site utilization tool for the general contractor. *Figure 1* shows Minute Maid Park, home of the Houston Astros in Houston, Texas, nearing completion of roof erection. *Figure 2* shows the shoring towers used to erect the roof trusses on Minute Maid Park. The erection process, including the placement of shoring towers, was part of the written erection procedure for the project. *Figures 3* and *4* show the roof and the erection tower placement used for the Gaylord Texan Resort and Convention Center in Grapevine, Texas. The center-raised roof for this hotel was shaped like a Texas Lone Star, and the erection procedure was documented in a construction submittal required by the project specifications.

The structural engineer should be actively involved in field observation of the construction process. We prefer to have an engineer who was part of the structural design team on site, full-time, observing the construction and endeavoring to ensure that the work is proceeding according to the intent of the construction documents. In most instances, the general contractor is very supportive of this effort in reducing the overall project risk. Our philosophy has always been to actively participate in the construction activity to be sure the project is being built according to the plans and the documented erection procedure. While a case can be made that this practice is crossing the line between design and "means and methods of construction," we believe the benefit outweighs the risk of sitting on the sidelines and watching a construction problem be blamed as a "design flaw". *Figure 5* shows Reliant Stadium, home of the Houston Texans NFL football team and site of the 2004 Superbowl. *Figure 6* shows the shoring towers used for the erection of the supertrusses at Reliant Stadium. The number and location of shoring towers was discussed and agreed upon with the general contractor, fabricator/erector team and the structural engineer. We had an engineering technician on site full time for this project, as well as regular visits by engineers who worked on the project.

We can all learn from past project failures, not just those that are structural in nature, but from those involving cost, schedule and communication failures as well. All successful projects are a result of close collaboration and teamwork among the owner, designer and builder. Following some or all of the recommendations contained here can help ensure that your project will be successful as well. After all, it's the nature of long span.▪

All photos are courtesy of Walter P. Moore.

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