Regulated Structural Peer Review

With the trend toward more complex structures and building codes, a properly conducted review of a structure's design can be of great help in avoiding disaster.

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On June 19, 1992, mandatory requirements for independent structural engineering review of the design of new structures built in the Commonwealth of Massachusetts became part of the Massachusetts State Building Code (MSBC). The process, known as *peer review*, applies to the design of all structures over certain threshold limits of size or occupancy. The purpose of the review is to enhance public safety through independent verification that a new structural design appears to be conceptually correct and free from major errors. Under the MSBC provisions, the prospective "owner" of a new building retains a reviewing structural engineer, who is independent of the design engineer of record and others on project team, to conduct an overview of the structural design by checking the building's overall design criteria and the concept of the structural system, and by checking the design of a representative fraction of the structural elements. The review is not intended to be an exhaustive check.

The Commonwealth of Massachusetts is progressive in adopting such requirements for peer review — only one other state, Connecticut, is known to have similar requirements. But the concept of structural peer review is not new. It has been developed and promoted for over ten years by industry organizations concerned with mitigating the occurrence of life-threatening structural failures. Nationally, support for the adoption of structural peer review is growing rapidly, and other countries have had similar requirements for decades.

Two years after adopting MSBC requirements for structural peer review, many building owners and others (including some structural engineers) still challenge the need for, or the intent of, these requirements. Individual cases have demonstrated that there are many professional and procedural issues to face. And, while meeting the letter of the requirements, a peer review can be ineffective if it is not properly conducted according to the intent of the provisions. Peer review is now a logical part of the design/construction process made necessary by the evolution of the construction industry.

Historical Development

Building Failures & Structural Design in the United States. The current process of the structural design of buildings has evolved over the last century. In times past, building design involved:

- Simple methods and codes;
- Large factors of safety;
- Straightforward communication among all participants; and,
- Clear lines of responsibility.

Today, building design has become a complex business of producing high-performance structures involving:

- Complicated building codes and design specifications;
- Low factors of safety;
- Design/construction teams with many parties and unclear lines of responsibility; and,
- Often extreme financial and time pressures.

While the incidence of catastrophic, life-threatening failures has been relatively low, there were a rash of such failures from the late 1970s through the late 1980s, suggesting that something had gone awry. Among the major failures are the following:

Hartford Civic Center. In January 1978 the roof of the Hartford Civic Center Coliseum collapsed. Fortunately, no one was in the building at the time of the failure, but just a few hours earlier 6,000 persons had been assembled in the building for a sports event. An investigation revealed that a design error involving improper bracing of top chord compression members was the likely cause of the roof collapse.[1]

Willow Island Cooling Tower. In April 1978 a large section of a reinforced concrete cooling tower at Willow Island, West Virginia, collapsed while under construction, killing 51 construction workers. The collapse occurred because construction loads from a formwork system were imposed on the structure before the concrete had gained sufficient strength to support the loads.[2]

Kemper Arena. In June 1979 the roof of the Kemper Arena in Kansas City collapsed. Like the Hartford Civic Center, the Kemper Arena was densely occupied just before the failure but was essentially empty at the time of the failure. A high-strength bolted connection that linked the roof's space frames was subjected to a wind-induced rocking motion that was not accounted for in the design. This motion fatigued and loosened the bolts, causing them to fail under an intense wind and rain storm.[1]

Harbour Cay Condominium. The Harbour Cay Condominium in Cocoa Beach, Florida, collapsed in March 1981 while under construction, killing 11 construction workers. The building had been designed by two retired NASA engineers. One of them, who had performed most of the building's design, had little experience with building design. The other allowed his professional engineering seal to be affixed to the plans even though he was not familiar with the building's design.[3]

Hyatt Regency Walkways. In July 1981 two suspended walkways at the Hyatt Regency Hotel in Kansas City, Missouri, collapsed, killing 114 people and injuring hundreds of others. Investigations after the failure revealed that a critical hanger-rod-to-walkway-beam connection was never structurally designed. Responsibility for the connection was lost in communication between the structural engineer and the fabricator's detailer. Compounding this error was a construction-phase change in the walkways' hanger rod arrangement that essentially doubled the load borne by the critical connections.[1]

L'Ambiance Plaza. In April 1987 the partially completed 16-story L'Ambiance Plaza Apartment building in Bridgeport, Connecticut, collapsed while under construction. Twenty-eight construction workers were killed. While the cause of the failure was never conclusively determined, investigations by many organizations revealed several gross deficiencies in the structural design and the construction of the building. These problems were the result of a serious breakdown in communication, the unclear assignment of design responsibility, lack of quality assurance programs and other safeguards to public safety.[4]

While there are a myriad design and construction quality issues in all of these failures, a common quality step lacking in all of them is independent verification of the adequacy of the structural design. In typical United States practice, the assurance of the quality of a structural design rests almost entirely with the engineer of record. There are no regulatory checks as there are in other industries, such as airlines or pharmaceuticals. Many years ago, plan reviews by local building departments often provided thorough reviews of building structural designs and, in some cities like Los Angeles, building departments still provide comprehensive reviews. Generally, however, municipal building departments have neither the staff nor the funds to provide meaningful reviews of today's complex structural designs.

One characteristic of catastrophic building failures is that they tend to be low-frequency, high-consequence events. They are disasters that are infrequent, and while they receive great attention when they do occur, they are forgotten by many shortly thereafter so that high priority on their avoidance is lost. Consequently, building owners and the general public frequently do not value the importance of sound structural engineering.

In an industry where financial competition and time pressures are severe, responsibility is not well defined and communications may be unclear, this is a recipe for disaster. The structural engineering profession realizes that it has an obligation to take a stronger role in assuring public safety. That obligation is better served by exercising some form of self-regulation rather than by having such regulation imposed on the profession by others. Peer review can help mitigate these disasters.

Early Resolutions of Industry Organizations. After the spate of structural failures from the Hartford Civic Center through the Hyatt Walkways, a number of national conferences were held that were attended by experts on structural failure investigation and avoidance. Some of these conferences were:

- "Building Structural Failures—Their Cause and Prevention" (Santa Barbara, California, November 6–11, 1983)
- "Reducing Failures of Engineered Facilities" (Clearwater Beach, Florida, January 7–9, 1985)
- "Construction Industry Roundtable Meeting" (Kansas City, Missouri, March 1985)
- "Structural Failures II" (Palm Coast, Florida, December 6–10, 1987).

Out of the careful deliberations of each of these conferences came experts' recommendations for actions needed in the design and construction industry to mitigate the chances of catastrophic failure. The similarity among the recommendations that came from each conference is striking. All advanced the need for structural peer review.

American Consulting Engineers Council (ACEC)/American Society of Civil Engineers (ASCE) Guidelines. ACEC and its affiliated organization, the Coalition of American Structural Engineers (CASE), have developed several programs and guidelines for peer review. ACEC conducts Organizational Peer Reviews. In this type of review the quality of an engineering firm's professional practice is examined independent of a particular project through a quality audit. CASE has developed a comprehensive set of guidelines for Project Peer Review (CASE Document 5-1992).[5] That document contains not only a comprehensive suggested summary of services for peer reviews, but also provides recommended terms of agreement between the owner and structural engineer for project peer review services. ACEC and ASCE formed a joint task committee to develop a policy and set of proposed guidelines for project peer review. The resulting recommendations, ACEC Publication 1021, were introduced in 1990.[6]

Requirements in Connecticut. Public Act 89-255, which went into effect on July 1, 1989, requires an independent structural engineering review of large structures that exceed an established threshold limit. Excerpts from this legislation are reproduced below:

> *"Threshold Limit.* Any structure or addition thereto (1) having four stories, (2) sixty feet in height (3) with a clear span of one hundred fifty feet in width, (4) containing one hundred fifty thousand square feet of

total gross floor area, or (5) with an occupancy of one thousand persons.

"Procedure. If a proposed structure or addition will exceed the threshold limit as provided in this section, the building official of the municipality in which the structure or addition will be located shall require that an independent structural engineering consultant review the structural plans and specifications of the structure or addition to be constructed to determine their compliance with the requirements of the state building code to the extent necessary to assure the stability and integrity of the primary structural support systems of such structure or addition. . . . Any fees relative to such review requirements shall be paid by the owner of the proposed building project. The building official may prequalify independent structural engineering consultants to perform the reviews required under this subsection. . . . If fabricated structural load-bearing members and assemblies are used in such construction, the professional engineer licensed in accordance with chapter 391 responsible for the design of such members or assemblies shall sign a statement of professional opinion affirming that the completed fabrication is in substantial compliance with the approved design specifications."

While the scope of the required peer review is not as clearly defined as in the MSBC, the objective of the Connecticut requirements is similar. A professional organization, the Connecticut Engineers in Private Practice, has developed guidelines for the reviewing engineer.

Requirements in Other Countries. In West Germany "proof engineers" have practiced a form of project peer review for over fifty years. Design reviews by independent proof engineers are mandatory for major structures. The proof engineers are neither building inspectors nor project peer reviewers; they are federally licensed, independent peer consultants who are retained by municipalities. Proof engineers are licensed in three fields: metals, concrete and masonry, and wood construction. Their responsibility is to ensure that the design complies with all government regulations.[7]

For the owner to obtain building permits at the different stages of construction, several proof reports are required from the proof engineer. These reports verify the soil conditions, the architect's design and the structural integrity of the design. For complex structures, detailed checks of computations, drawings and any temporary support are also required. The cost of the review adds 0.6 to 1.0 percent to the construction cost, depending on the nature of the construction.[8]

In Belgium, the Bureau de Controle pour de la Securité de la Construction en Belgique (SECO) supervises all phases of design and construction. SECO is a nonprofit institution organized like an engineering consulting firm. It represents all Belgian insurance companies which, in turn, support it financially. When an owner seeks insurance for a proposed building, he or she submits the design to an insurance company. Before the insurance company will write a policy, SECO reviews the design. A technical board of 11 university professors arbitrates any differences of technical opinion between the designers and SECO's engineers. If the owner does not adopt the suggestions of SECO, the insurance company will not insure the building.[7]

France employs a peer review system very similar to the Belgium's SECO system.

Boston Second Engineer Check. On January 25, 1971, a 16-story apartment building known as 2000 Commonwealth Avenue in Boston collapsed while under construction. Four workers lost their lives. Investigations revealed a number of problems with the design, detailing and procedures used in the concrete construction. This building's failure prompted a program of project peer review in Boston. Many regulations for the design and construction of buildings for certain "Affidavit Projects" — one of them being a requirement for peer review of certain complex structures or systems — were formulated as a result of that collapse.

The threshold criteria for defining which buildings would be subject to peer review and the requirements of the review itself were not well defined. The Chief of Plans and Permits Division of the City of Boston Building Department was to determine whether or not the project was complex and subject to review. The chief set forth official recommendations and the bases for such recommendations in a memorandum to the Commissioner of the Building Department, who could approve or disapprove the action. The commissioner further defined this criterion as follows:[9]

> For this purpose, a complex structure shall mean any building or structure whose construction cost is a million dollars or more [in 1971 dollars]. This is not a hard and fast rule, but it will serve to indicate to owners and designers that a second examination by a professional engineer is required by the building department.

The building owner could select the reviewer and underwrote the cost of the review. The examination could only be performed by an independent professional engineer or architect who was registered in the Commonwealth of Massachusetts.

After the examination, the reviewer would confer with the designer to report the findings. Any problems with the design were resolved to the mutual satisfaction of the designer and the reviewer. Thereafter, the reviewer would prepare a letter to the commissioner stating that the reviewer had "checked the details, computations, stress diagrams, and other data necessary to describe the construction and basis of calculations, and further stating that, in [the reviewer's] judgment, the requirements of the City of Boston Building Code have been met with respect to the design."[9]

The required procedures and scope of the review process were similarly vague. Again, the commissioner elaborated:[9]

> I expect [the reviewer] to make a determination that the foundation design will support the structure. [The reviewer] should check the building for dead and live loads, and spot check the designer's assumptions, and check a percentage of the calculations, using something in the order of five or ten percent of these.... When the examining engineer has completed [the] review of the design of the structure, I want [the reviewer] to write a letter to the building department to the effect that [he/she] has reviewed the design based upon a spot check of some of the critical parts of the design saying something to the effect, "Based upon a spot check, I believe that the structure is designed in accordance with the provisions of the City of Boston Building Code."

Reaction to the Boston project peer review procedure was mixed. Some felt it was worthwhile and some did not. The perceived variability in success seemed to be due to a lack of clarity in the review regulations and the fact that owners could select reviewers largely on the basis of fee. The Boston procedure was superseded by the MSBC requirements in 1992.

The Massachusetts Requirements

The proposal to develop mandatory state-wide requirements for structural design peer review was initiated by the Chairperson of the Board of Building Regulations and Standards (BBRS). The chair became concerned over the increasing seriousness of reports of non-conforming seismic design practices in new structural design. The chair brought his concerns to the Boston Association of Structural Engineers (BASE). In considering the chair's request, BASE judged that non-conforming design was a concern for all life-safety aspects of structural design, not just earthquake resistance. As a result, BASE developed a comprehensive proposal for peer review, which was first submitted to the BBRS in February 1991.[10,11] The Boston Society of Civil Engineers Section/ASCE and ACEC acted as BASE's sounding board by commenting on draft versions of the document. The BBRS adopted the BASE recommendations with some modifications, and the requirements for peer review became effective on June 19, 1992.

The purpose of the MSBC requirements for project peer review is to enhance public safety of new construction. Toward this goal, the peer review should "verify that the design of primary structure is conceptually correct and that there are no major errors in the design" [Article 1, Par. 113.8.].[12]

Not all structural designs must be reviewed, only those where risk to public safety — because of size or occupancy of the building — is substantial. Structures for which the MSBC requires review are:

- Buildings that are five stories or more in height above the lowest floor, including stories below grade.
- Buildings that enclose a total volume of 400,000 cubic feet, including stories below grade. The volume is measured using the outside dimensions of the building.
- Structures in Use Group A, or structures that are partially in Use Group A, that will be used for the public assembly of 300 or more persons for civic, social or religious functions, recreation, food or drink consumption, or awaiting transportation.
- Structures of unusual complexity or design as determined on a case-by-case basis by the BBRS. A building official may apply to the BBRS for such a determination on a specific structure.

The only exemption is granted to temporary structures that are to be erected for a period of 180 days or less.

The MSBC requires that the owner retain the reviewing engineer. Mandatory qualifications for the reviewer are as follows:[12]

> The reviewing engineer shall be a professional structural engineer, registered in Massachusetts, qualified by experience and training and who shall have had structural design experience with buildings or structures similar to that covered by the application for the building permit. The reviewing engineer shall be impartial, and shall be independent of the architect of record, structural engineer of record, and contractors and suppliers who will be involved in the construction of the structure. [Appendix I, Par. I-2.1]

The reviewing engineer verifies that the plans and specifications submitted with the application for the building permit complies with the structural and foundation design provisions of the MSBC. The review must entail the following activities:

- Check to assure that the design loads conform with the MSBC;
- Check that other design criteria assumptions conform to the MSBC and are in accordance with accepted engineering practice;
- Review geotechnical and other engineering investigations that are related to the structural design to determine if the design properly incorporates the results and recommendations of the investigations;
- Check that the organization of the structure is conceptually correct; and,
- Make independent calculations for a representative fraction of systems, members and details to check their adequacy. The number of representative systems, members and details should be sufficient to form a basis for the reviewer's conclusions.

The reviewing engineer is not obligated to obtain and check the design calculations of the structural engineer of record, but may request a copy of these calculations for reference. If the design criteria and assumptions are not stated on the design drawings or in the project specifications, the structural engineer of record must set these forth in writing to the reviewer.

The MSBC requires a report and follow-up as indicated below:

- The reviewing engineer shall prepare a report to the building official stating whether or not the structural design shown on the drawings and the specifications conforms with the structural and foundation requirements of the MSBC. That report should include a summary of all deficiencies, if any, that cannot be resolved with the structural engineer of record.
- The structural engineer of record must review the report of the reviewing engineer and notify the building official in writing, whether or not there is any agreement with the conclusions and recommendations of the reviewing engineer.
- Unresolved disputes between the structural engineer of record and the reviewing engineer should be submitted by the building official, the owner, the structural engineer of record or the reviewing engineer to the Structural Peer Review Advisory Board for resolution.
- Any changes to the structural design subsequent to the original submission of the plans and specifications should be shown

on revised drawings and specifications, submitted with an amendment to the application for permit. The reviewing engineer must review the changes on the revised drawings and specifications. If the original report does not account for the changes in those drawings and specifications, a supplementary report relating to the changes and prepared by the reviewing engineer should be made to the building official.

The MSBC allows for special review and approval of the permits to construct foundations. Sufficient documentation must be made available so that the reviewing engineer can review the criteria and structural concepts for the whole structure as well as be provided with complete independent calculations for the part of the foundation covered by the permit.

Procedural & Professional Issues

There are some misunderstandings among building owners and others regarding the purpose of the Massachusetts peer review requirements. The peer review:

- Is *not* an exhaustive check of the structural design;
- Is *not* intended to mitigate the occurrence of minor failures or serviceability problems (*e.g.*, excessive vibrations or deflections);
- Is *not* intended to identify potential cost savings in the design;
- Does *not* involve elements of the building other than the principal structural system; and,
- Is *not* an opportunity for the building owner to engage the liability insurance of another engineer.

Scope & Cost. While the MSBC sets forth five tasks incumbent upon the reviewer (as stated in the previous section here), there is still substantial latitude and judgment given within the scope of review. Consequently, the thoroughness and effectiveness of the review can vary. Peer reviews by very experienced engineers can be very effective and efficient means of spotting gross problems. A seasoned eye is invaluable. The wise owner will select a reviewer largely on the basis of experience and qualifications rather than fee. There are no guidelines for the cost of a peer review, but where the review does not involve the resolution of an unusual incidence of problems, it can usually be performed for a small fraction of the design fee of the structural engineer of record.

Timing. The provisions of the MSBC require that the plans and specifications for the building permit be reviewed. Accordingly, most peer reviews are usually performed near the completion of the structural design (around the 90 percent design stage). The BASE Commentary recommends starting the peer review at the end of the preliminary design phase.[11]

The timing of the review must be carefully considered. If the review is performed too late in the process, construction can be delayed and the correction of any deficiencies can be expensive. A building permit is not issued until the review has been completed and any outstanding issues have been resolved. If disputes cannot be resolved between the engineer of record and the reviewing engineer, then the dispute is brought before a Structural Peer Review Advisory Board. Such arbitration can further delay a project.

Very large projects benefit from early peer reviews of criteria and concepts performed at the end of the design development phase. Detailed checking of member adequacy is performed once the construction documents are well advanced. There is a small fee premium to perform an early-start peer review, but it is generally cost effective for large or complex projects, since changes can readily be effected at that stage.

Dispute Resolution. Disputes may arise in the review process over differences of opinion between the reviewer and the structural engineer of record regarding the adequacy of one or more particular elements of the design. Recognizing this possibility, the MSBC allows for the mediation of such disputes by the Structural Peer Review Advisory Board.

The structural engineer of record, the reviewing engineer or the owner of the building submits any unresolved disputes cited to the Structural Peer Review Advisory Board on a form provided for this purpose. The board then convenes a mediation hearing within 30 days of receiving the application. It must render a decision in writing within 30 days following the mediation hearing.

In spite of having an established procedure for redressing disputes, the profession and all involved parties can be best served when the engineer of record and the reviewer establish a direct line of communication and a working relationship that can be used to resolve such disputes without intervention. Each party must approach this type of working relationship with the highest degree of professionalism and with a spirit of cooperation. The owner need not be involved in, or apprised of, the content of such technical discussions unless they impact schedule, construction budget, engineering fees, or some other direct concern of the owner. If the reviewer and the engineer of record cannot come to an agreement within this framework, the owner may direct that the more conservative opinion be adopted, or the owner may engage a third engineer to help resolve the dispute.

Responsibility & Liability. The MSBC states that:

> The structural engineer of record shall retain sole responsibility for the structural design, and the activities and reports of the reviewing engineer shall not relieve the structural engineer of record of the responsibility.

It is appropriate that a single party retain sole responsibility for the design — to do otherwise would obfuscate the lines of responsibility and present opportunities for mistakes. CASE Document 5-1992 presents recommended terms for contracts between owners and reviewing engineers that appropriately limit the liability of reviewers.[5]

Qualifications of the Peer Reviewer. Technical qualifications and experience are not the only important qualifications of a peer reviewer. Also paramount are high standards of professionalism and skill in resolving disputes. From an owner's perspective, perhaps the greatest risk that peer review presents to the project is the possibility of a protracted mediation process caused by differences of opinion between the engineer of record and the reviewer. Strong communication skills, a willingness and ability to understand alternative points of view, and a commitment to a successful review process are key qualifications. In selecting a reviewer, an owner should look for an experienced and knowledgeable engineer with a demonstrated record of conducting meaningful and effective reviews.

Segmented Design Process. Special problems are introduced when a segmented design process (that releases various portions of the design for construction in a fast-track mode) is adopted. Sufficient documentation must be made available so that the reviewing engineer can examine the criteria and structural concepts for the whole structure as well as the complete independent calculations for the part of the foundation covered by the permit.

Opportunities Lost. Peer review cannot ensure that a structural design will be fully free from errors — not only because the review is less than exhaustive, but also because design problems can go undetected for other reasons. For example, it is common for contract documents to delegate the design of some elements of the structure to specialty subcontractors through performance specifications. Examples are post-tensioning design, precast concrete design, structural steel connections, and steel bar joists. Such specialty contractor design is typically performed after the peer review has been completed, so such elements are not subjected to peer review. Gross problems with specialty contractor designs led to some of the severe structural deficiencies at the L'Ambiance Plaza Apartments. Although the MSBC peer review provisions do not require it, such specialty contractor designs should also be subject to peer review.

It also is common for some parts of the structural design to change during construction, again some time after the peer review has been completed. While MSBC peer review requirements dictate the resubmission for review of any revised plans in such circumstances, this resubmission is infrequently done.

When Major Changes Are Required. On occasion, the reviewing engineer may encounter a structural design that is so grossly riddled with errors that the reviewer has no reason to have confidence that those elements that were not

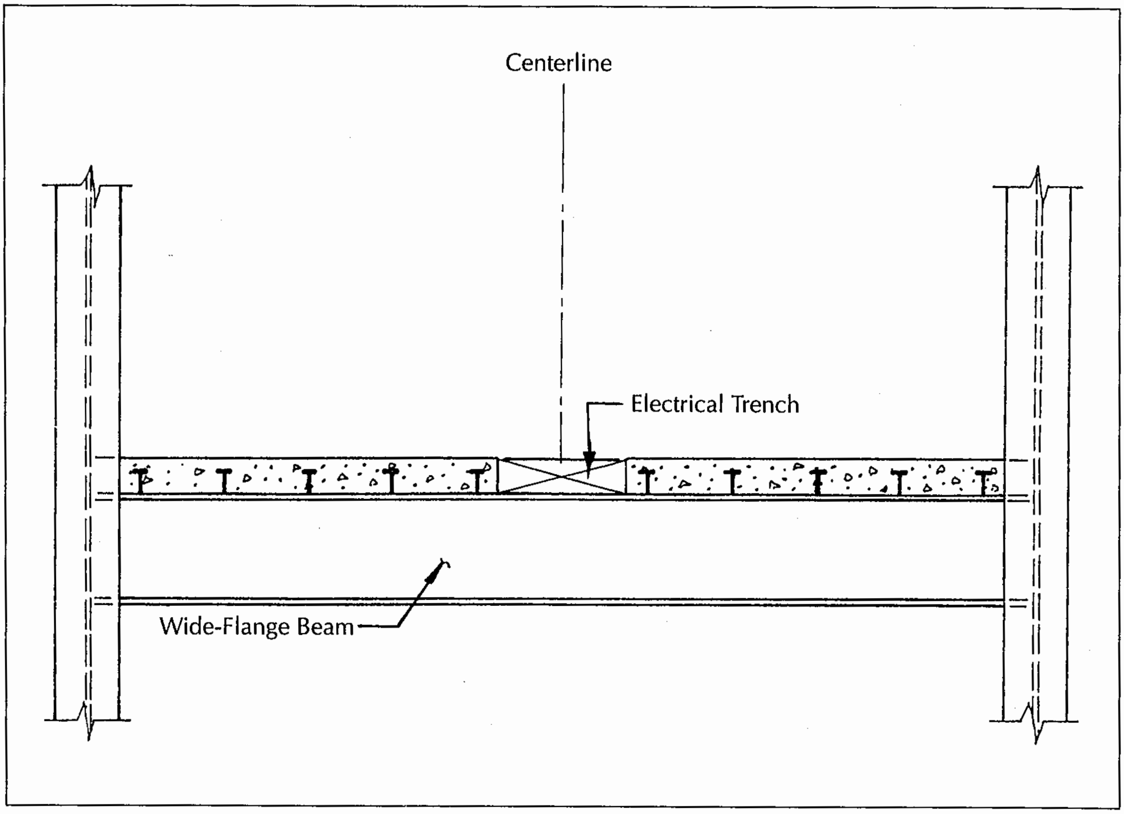

FIGURE 1. Composite action is destroyed by an electrical trench at mid-span.

reviewed could be reasonably free from errors. Consequently, the reviewer may feel that he or she cannot prepare a report in good faith representing that the structural design conforms to the MSBC. This situation dictates major corrective action be undertaken for the project. Such corrective actions can have severe financial and time consequences on the project, presenting a dilemma to the reviewing engineer for which there is no guidance in the MSBC. Remediation of the design in this case may involve one or more of the following:

- The structural engineer of record agrees to perform a full design check to correct all deficiencies, and resubmits the design for a new review.
- The peer reviewer is directed and paid by owner to make a full, exhaustive design check.
- A third engineer is retained to fully review the design and identify all areas needing correction.

Case Studies

A number of examples illustrate the benefits of, and types of problems exposed by, a peer review.

Office Building. The peer review for this six-story high, approximately 200 by 300 feet in plan, structure was not performed according to the MSBC peer review provisions, but was initiated by the owner after a partial failure occurred early in construction. The review of the structural design of this steel-framed structure revealed a number of problems.

The steel floor beams were designed to act compositely with the concrete slabs. Due to poor coordination between the structural and the mechanical/electrical drawings, an electrical trench was located perpendicular to the beams near midspan of the beams, essentially destroying composite action and greatly comprising the strength of the beams (see Figure 1).

Beam-column connections at the roof level were designed to be moment resisting, and the

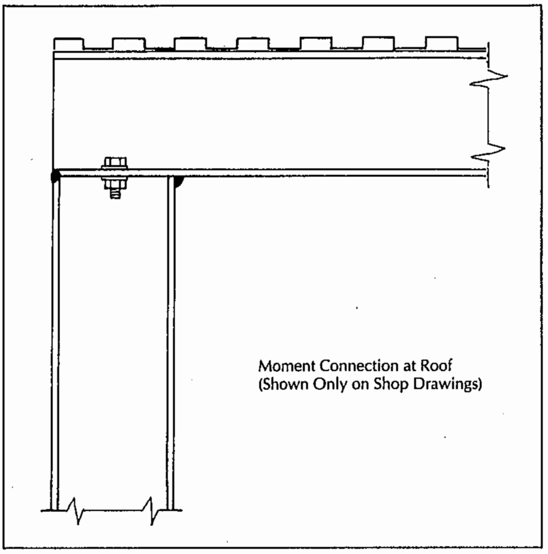

FIGURE 2. No stiffener plates were provided at the connection to transfer moment.

connections required stiffener plates to transfer the design moments. However, the connection design did not provide such stiffeners (see Figure 2).

A column adjacent to the stairwell opening in the floor slab was left unbraced by the slab opening. The column had no appreciable resistance to wind load (see Figure 3).

The building's structural system for resisting lateral wind and seismic loads consisted of moment-resisting frames, but not all of the columns had moment connections to allow them to participate in the lateral system. Consequently, the bracing required for the non-participating columns placed additional P-Δ forces on the participating columns. The building's original structural design did not consider P-Δ effects at all (see Figure 4).

Shopping Mall. This case study describes a peer review that was not performed according to the MSBC peer review requirements, since the project was located in another state. The peer review commenced at the beginning of construction.

The project involved a substantial renovation and addition to an operating retail mall. A small part of the work involved adding a cantilevered steel and concrete walkway to the side of an existing concrete wall. The walkway ran parallel to the wall. Shortly after construction of the walkway, the contractor and owner noticed that the walkway sagged over the length of its cantilever, and the connections of the walkway beams to the concrete wall were pulling away from the wall. The owner retained an independent reviewing engineer to investigate the problem. That investigation, as well as an investigation by the engineer of record, revealed that the cause of the walkway distress was a design error in the bracket connections that anchored the walkway support beams to the wall. The brackets were designed for shear, but the designer neglected the tension induced in the connection by inclined support struts that propped the ends of the walkway beams (see Figure 5).

Before implementing repairs for these failed walkway connections, the owner directed the

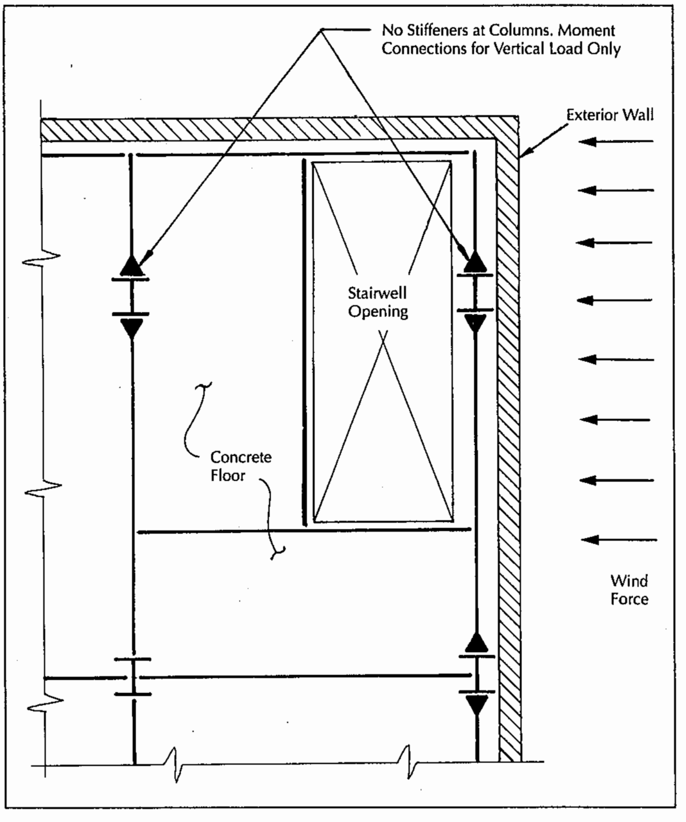

FIGURE 3. An unbraced column at the stairwell opening.

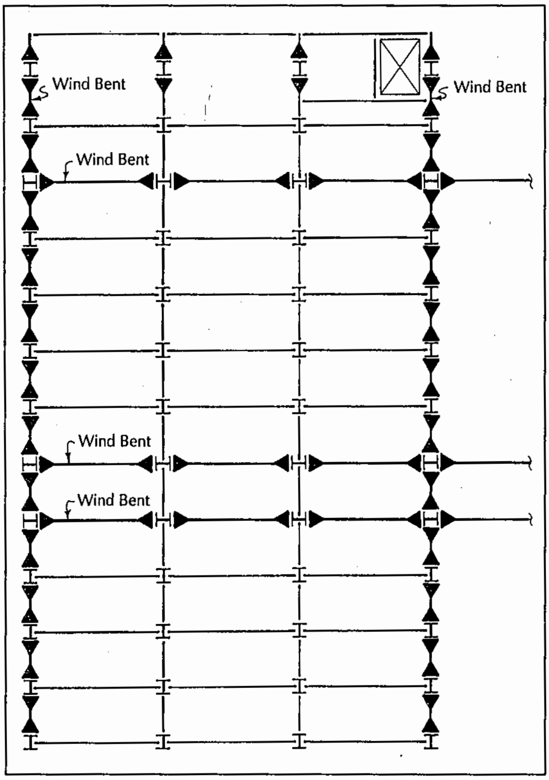

FIGURE 4. Only three of the 12 transverse frames have moment-resisting joints for resisting lateral wind and seismic loads.

structural designer and the reviewer to independently check the design of the other elements of the walkway. These checks revealed several other problems, causing the owner concern over the quality of the structural engineer's design of the mall renovation in general. At that time, construction of the project (worth tens of millions of dollars) was in an early phase, but fully underway. Any errors revealed in the structural design could have had a major impact on the project, and time was urgent. Because some of the construction had been completed, some remedial work would have to be performed on work in place. In other areas it was not too late to change the design. The owner, the structural engineer and the reviewer agreed to the following plan:

- The structural engineer would review the entire design and identify any necessary remedial work.
- The reviewer would check two representative areas of the structure comprising about 10 percent of the project.
- The reviewer was under instructions not to reveal to the structural engineer of record which areas would be reviewed.
- All agreed to meet after all assignments had been completed to compare results.

After a month all parties met. The structural engineer had found several additional design errors. The reviewer found many more errors in the representative areas the reviewer checked. A few are mentioned below. These problems were not necessarily the most severe, but are interesting for the challenges they presented.

The design of the roof trusses supporting sloped skylight areas of the main mall is shown in Figure 6. The single angle web members were connected to the chords with single bolts. Most of the trusses were fabricated and some were erected at the time of review. The peer reviewer felt that the use of single bolt connections in this application, especially considering the eccentricities involved in the connections, was imprudent. The structural engineer believed that the connections were adequate. All agreed to resolve this problem by welding the

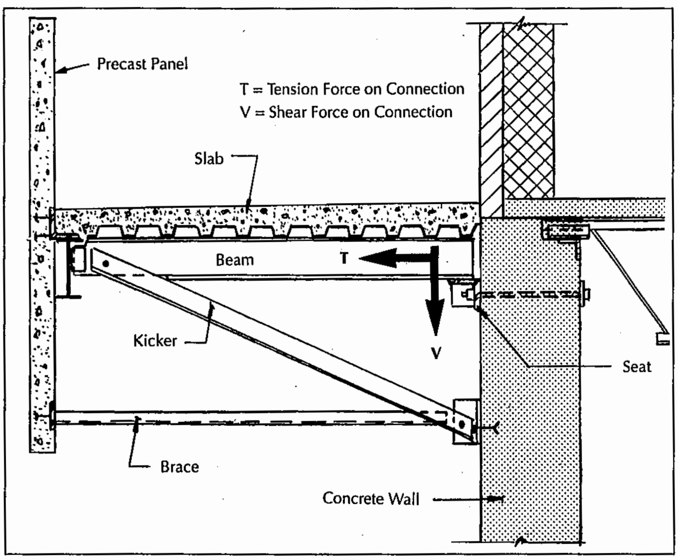

FIGURE 5. The design of the beam seat ignored the tension force imposed by the inclined strut.

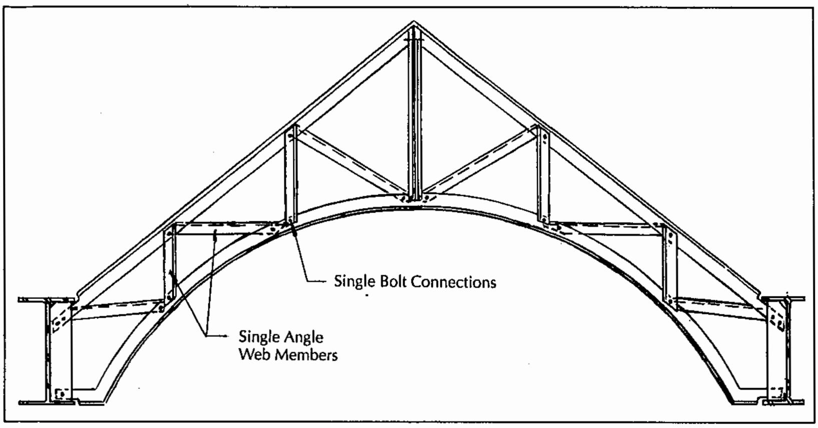

FIGURE 6. Typical roof truss for the shopping mall project.

most highly stressed of the single bolted connections near the ends of the trusses.

One unusual feature of the structure was a set of large space trusses that spanned open court areas of the mall as shown in Figure 7. The primary gabled arch trusses were supported on ring trusses forming the perimeter of the opening. The ring trusses were supported, in turn, on columns. For architectural reasons, the ring trusses were unusually deep compared to their span, making them quite stiff. As a consequence of this unusual stiffness, the structure was very sensitive to differential foundation settlements at the supporting columns. Small foundation settlements overstressed several of the truss members. The structural engineer did not consider the effects of foundation settlement in the original design.

Another problem that was revealed is shown in Figure 8. In order to provide raised skylight areas over parts of the existing mall roof, the existing roof bar joists were to be cut and suspended from new longitudinal support beams on each side of the skylight openings. There were several problems with the design of the connections of the truncated joists to the new beams, caused principally by the eccentricities and the lack of lateral stability of the connections.

As a result of the multitude of design problems that the peer review uncovered, the owner lost confidence in the original structural design. However, the owner was reluctant to relieve the engineer from the project, given the fact that construction was well underway. The owner commanded the peer reviewer to per-

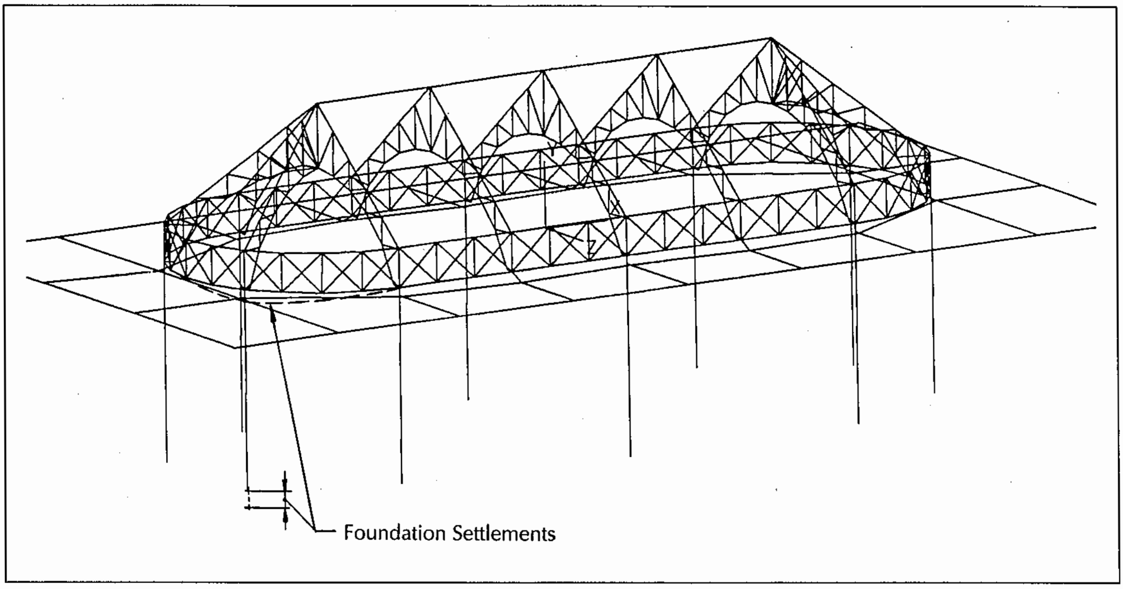

FIGURE 7. Small foundation settlements overstress truss members.

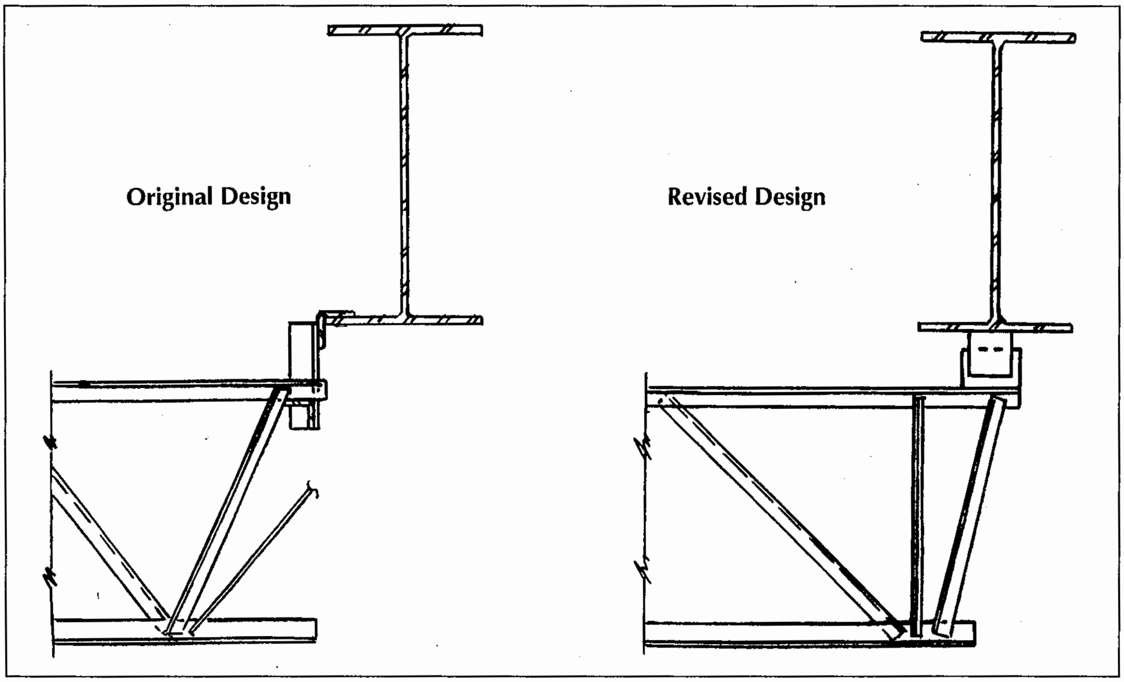

FIGURE 8. Connections were redesigned to eliminate eccentricities and lack of lateral stability.

form a complete design check of the work, which was done. This full design check revealed further problems that were corrected as the work proceeded.

There were other problems with the quality of the structural work on this project due to poor construction techniques, critical demolition procedures that were not engineered or otherwise thought out, ineffective inspection and lax submittal procedures. Much of these problems stemmed from a lack of clearly defined responsibility and lines of communication on this very complex construction project. The owner, construction manager and peer reviewer made a thorough review of, and revision to, the quality plan early in the construction process. In spite of all of the problems, the project was completed on time.

Hospital Building. This six-story hospital building was a reinforced concrete structure (approximately 270 by 150 feet in plan) braced by shearwalls. The structure was designed to accommodate three future stories. A number of problems were revealed by the peer review.

Cantilevered grade beams were required to support ten levels (nine stories and a roof). The design incorrectly considered the top steel to be fully effective in providing shear reinforcement for the cantilever portion of the grade beam rather than providing additional uniformly-spaced horizontal reinforcement. The top steel was not fully effective due to the lap splices that were detailed (see Figure 9).

The designer's lateral load distribution to the shear walls was incorrect. The shear walls were designed only for tension forces, neglecting very large compression forces. The shearwall reinforcement of the original design called for 15 #11 bars with no ties. After correcting the errors, the shearwall reinforcement was 63 #11 bars with ties (see Figure 10).

The typical floor framing consists of 10-inch thick two-way flat slabs with a dead weight of 125 pounds per square foot (psf) and 16-inch one-way slabs with a dead weight of 200 psf. There are 3.5-inch slab depressions in the 10-inch two-way slabs. The designer did not consider the additional weight of 75 psf for the 16-inch slabs or the additional 40 psf for finishes in the 3.5-inch slab depressions. The dead load was underestimated by 25 to 50 percent for the design of some columns. The dead load was

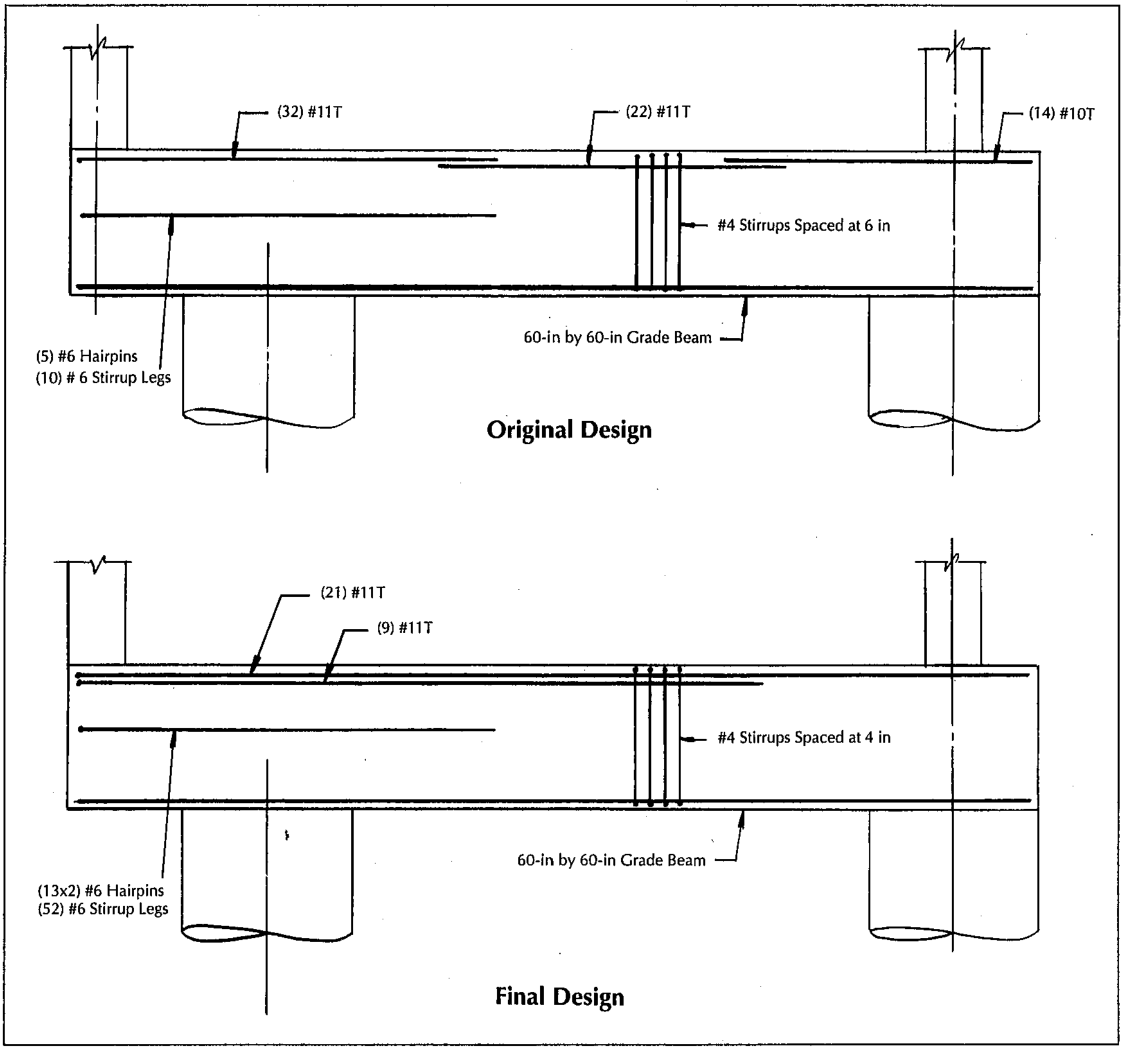

FIGURE 9. Cantilever grade beams were redesigned to correct inadequate stirrups and lap splices.

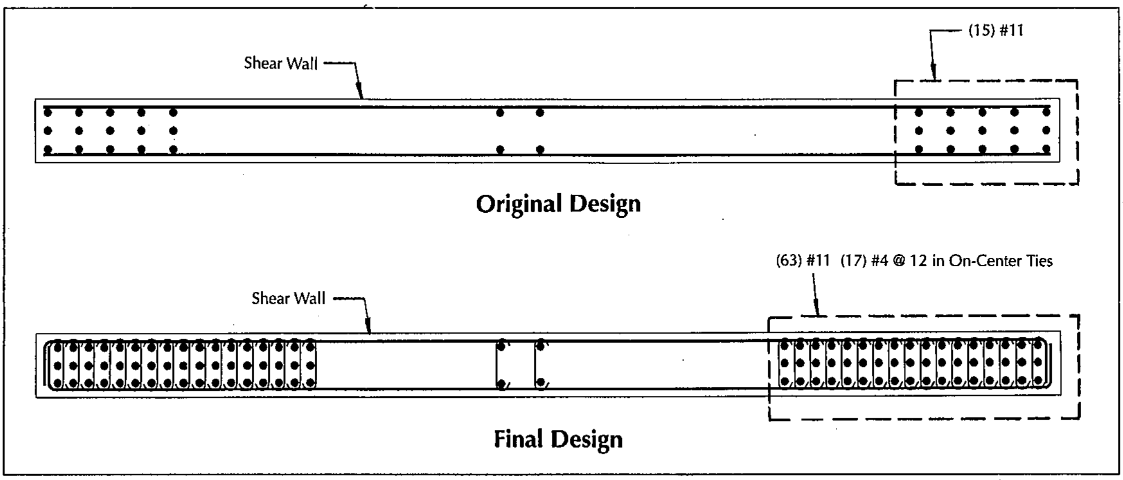

FIGURE 10. Shear walls were redesigned to account for compressive forces.

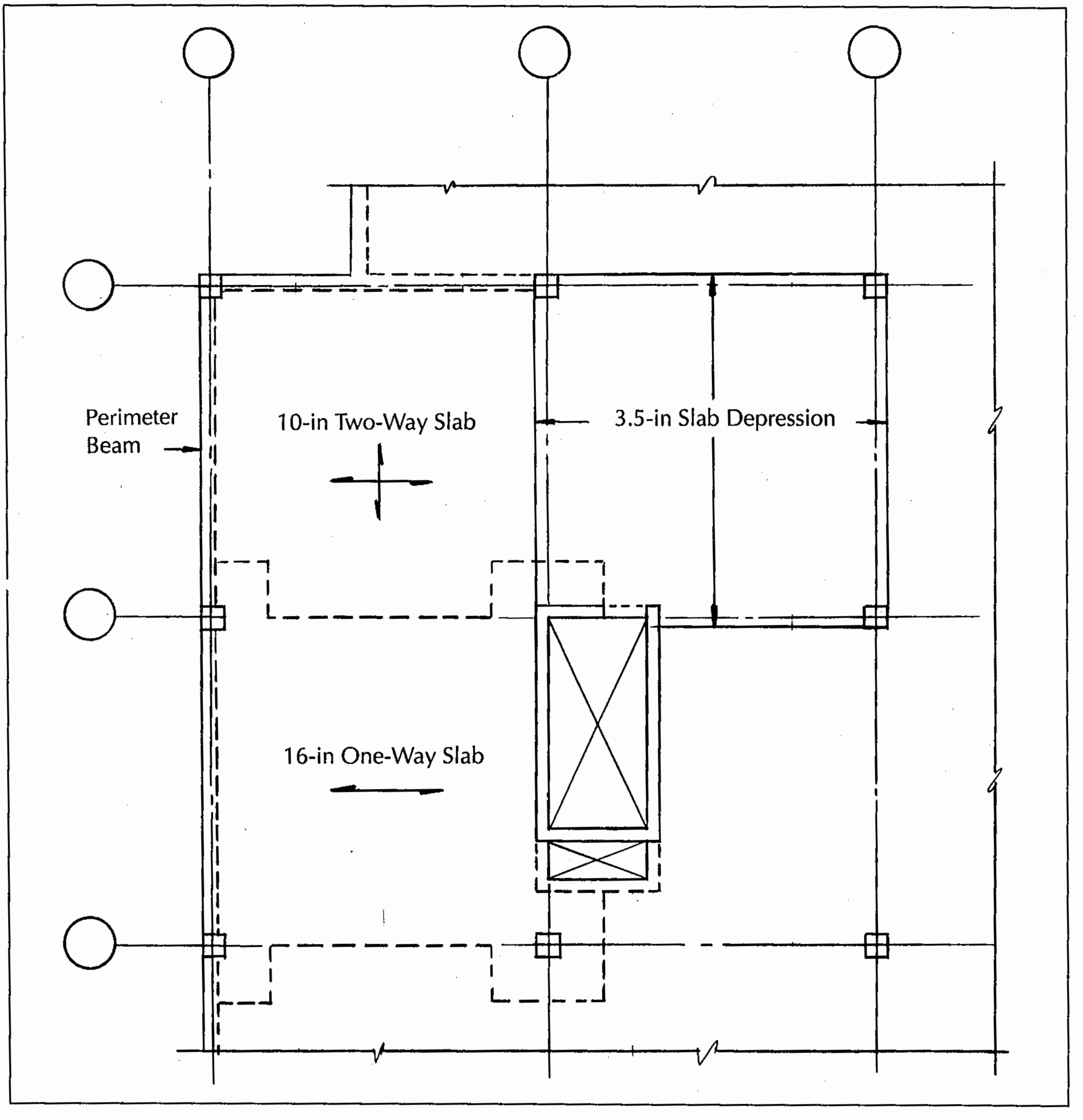

FIGURE 11. Typical floor plan for the hospital project.

underestimated by 25 percent for the design of the floor slab at the depressions (see Figure 11).

Caissons supporting shear walls were required to resist large tension loads (2,000 to 3,000 kips) with large shear loads (100 to 300 kips). The analysis of the caissons for shear was incorrect, and the design did not account for the reduction in the allowable shear capacity to account for tension. Additional stirrups were required in the area of high shear starting from the surface of the rock to several feet below. Shear studs on the steel embeds to transfer tension loads were missing in the lower half of the caissons (see Figure 12).

The six-story structure was supposed to be designed to accommodate three additional stories in the future using the roof as a story as shown on architectural drawings, but the structure was actually designed for only two future stories. This error was caused by miscommunication between the project engineer and a designer not familiar with the design criteria for the project. The project engineer directed the designer to design the structure for two future

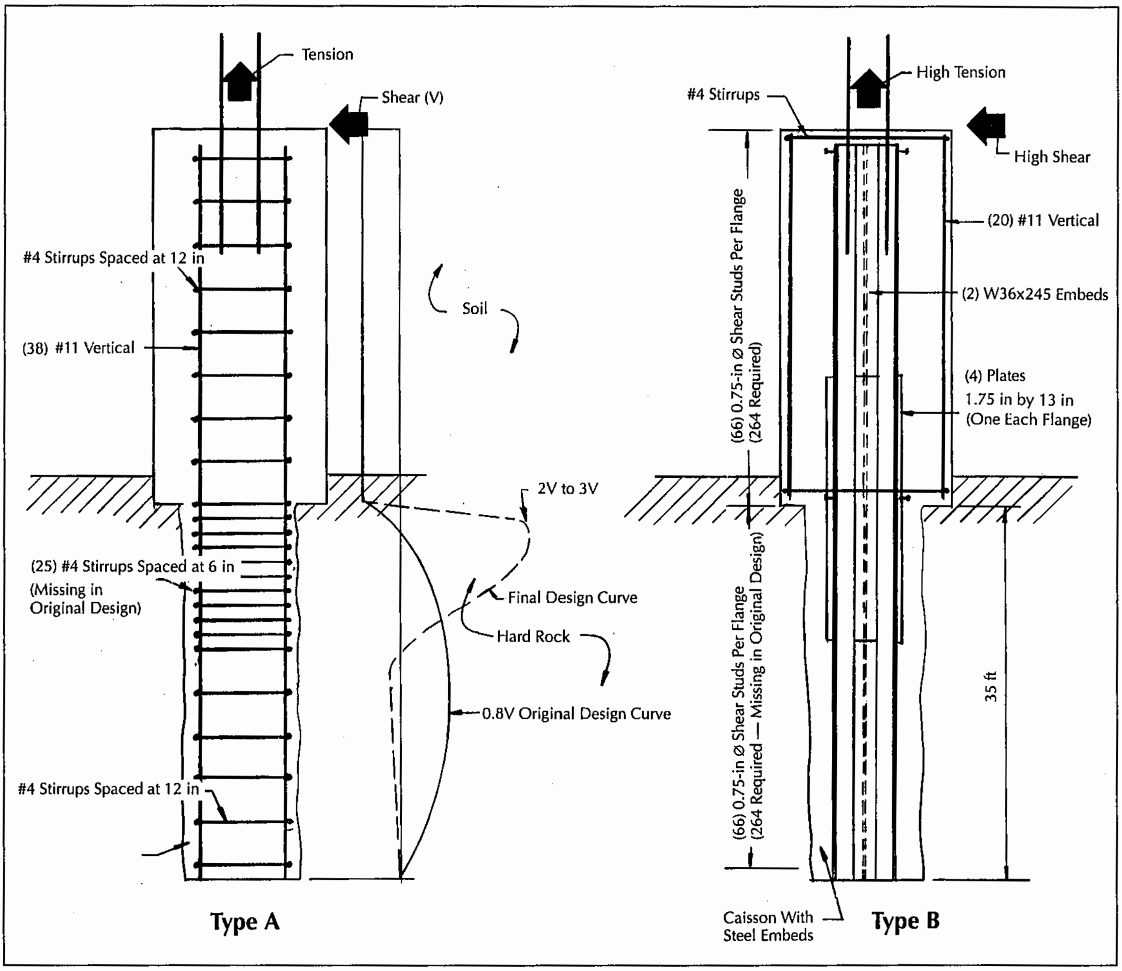

FIGURE 12. Caissons were redesigned to account for tension forces neglected in the original design.

stories. The designer was not aware that two additional framed levels and a roof level were required to accommodate three future stories and did not look at the architectural drawings. All the columns and shearwalls were redesigned to support the weight of the missing story.

A large combined foundation mat was designed to resist the overturning imposed by three shear wall stair towers. The design analysis did not consider the unsymmetrical shape of the mat and significantly overestimated the overturning resistance of the mat. After the peer review the mat was redesigned to include 60- by 90-inch continuous grade beams spanning to adjacent columns to provide additional overturning resistance (see Figure 13).

Conclusions

While Massachusetts is one of the first states to adopt mandatory structural peer review for threshold structures, the need for peer review is receiving more consideration nationwide. The need is based on the recognition that the complexity of current design codes and specifications, the complexity of modern design and construction teams, the use of higher performance structures with lower factors of safety, and the severe business and time pressures increase the probability of catastrophic life-threatening failures. A rash of catastrophic building failures since the early 1970s demonstrates that this concern is valid.

Peer review can be effective in reducing errors in new structural designs, but the process

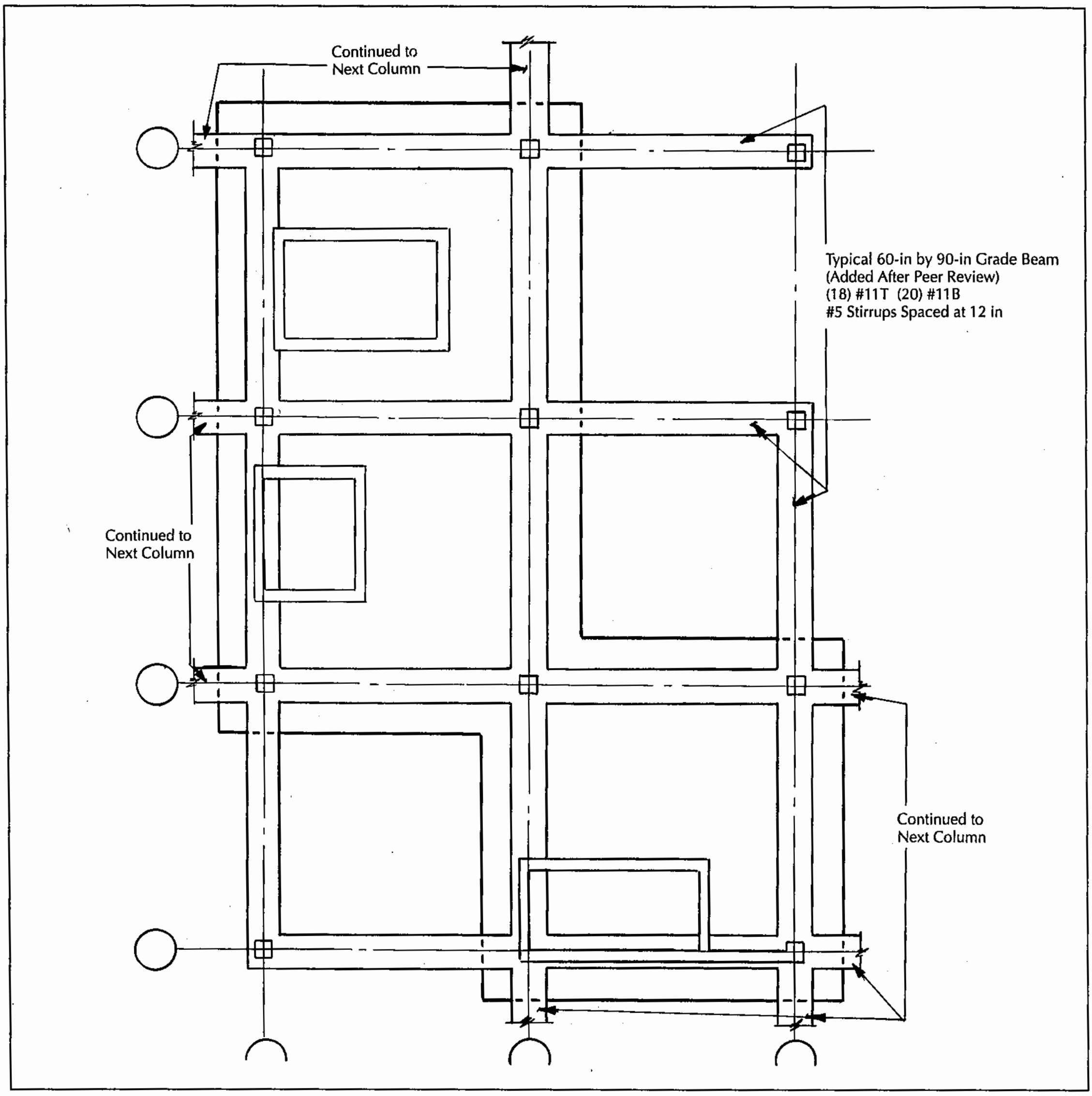

FIGURE 13. Plan of the mat foundation for the hospital building.

poses several challenges in execution. The peer reviewer must be selected not only for technical competence and experience, but also for skills in problem resolution. The scope and timing of the review also can be critical to the project's success. Segmented design processes and changes to the design during construction present opportunities for errors to go undetected by the review.

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