Technology Transfer in Building Construction—Case of Seismic Design

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Abstract: Many construction innovations incorporate technologies that have been transferred from one geographical area or discipline to another and subsequently modified for the new conditions. This paper analyzes an example of this technology transfer on a sample project: chevron bracing was first used in the structural system of a tall building located in a high seismic zone. This paper describes current technologies for structural systems and the evolution of the unique structural design used for this project. This paper discusses three types of barriers to technology transfer in the U.S. construction industry: building codes, conservatism, and organizational barriers. The focus of this paper is on examining how the project team overcame those barriers. This paper concludes that the teamwork should be based on a reciprocal relationship. Each team member must possess technical competency. It is also vital for each team member to expend efforts to understand not only the technical aspects of the project but the needs and concerns expressed by the other team members. This paper provides insights about the reciprocal relationship and the qualifications of the participants required to surmount barriers to technology transfer in the U.S. construction industry.

Introduction

In early 1990, the tallest building in an area rated seismic zone four was completed in Los Angeles. It is a 73-story steel structure, rising 1,018 ft (310 m) above street level, and containing 1,400,000 sq ft (130,000 m^2) of office space. The dual structural system consists of an exterior ductile-moment–resisting frame and an interior core braced with two-story chevron braces on all four sides (see Fig. 1).

This bracing scheme reduces the number of connections, which improves constructability. It also reduces the load path so that less steel is required and the number of potential architectural interferences is reduced. A building with equal performance containing the common structural system used in seismic zone four, a perimeter ductile-moment–resisting frame, would require an additional 5,500 tons of steel; the additional steel would have cost approximately $7,000,000 (Banavalkar 1988). Although the building contains multiple step backs or variations in the floor plans, the dual structural system using the spine concept incorporated in this project maintains its efficiency. This type of system allows designers more freedom to build tall structures with nonstandard shapes in high seismic areas.

Successfully obtaining a consent from the building-code regulators, the structural engineer for this project adapted a chevron bracing technology,

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frequently used in nonseismic areas, for application in a high seismic zone. This was not a revolutionary innovation, but the nudging of technology beyond its current boundaries, which pushed the evolution of seismic structural technology one step further. In summary, this project illustrates a success story of technology adaptation and transfers from one particular area to another, in which many traditional barriers that exist in construction were overcome.

This paper begins with a discussion of the current technology used in tall buildings in nonseismic areas as well as the structural systems used for tall buildings in high seismic zones. After briefly describing the participants in the project and the evolution of the building design process, the paper then discusses three types of barriers to technology transfer: building codes, conservatism, and organizational barriers. The focus will be on examining how the participants in this project overcame those barriers. The paper concludes with insights about reciprocal relationships between key participants and qualifications needed for the relationships to be successful in surmounting the barriers of technology transfer.

PERSPECTIVES ON BUILDING STRUCTURAL SYSTEMS

Structural Systems for Tall Buildings in Nonseismic Regions

A building may be considered "tall" when its structural analyses and design are affected by the lateral loads caused by wind as well as the sway caused by these loads (Taranath 1988). The three basic types of structural systems most frequently used include: (1) Braced frame systems; (2) framed tube systems; and (3) nontubular systems.

Braced frame systems contain a frame for vertical support and a bracing assembly for lateral support. The systems may be exterior braced frames (see Fig. 2) and interior braced frames (see Fig. 3) that use X-bracing or some form of eccentric bracing (Taranath 1988). The K, V, or chevron configurations are forms of concentric bracing.

In framed tube systems (see Fig. 4), closely spaced columns and deep spandrel beams are moment-connected so the building reacts like a single entity or beam; the columns act like the flange of the tube. There are many applications of this structural system in tall buildings.

Nontubular structural systems include shear wall frames, moment-resisting frames with braced cores, and other nontypical schemes. Shear wall frames combine a moment-resisting frame on the exterior that resists vertical loads with concrete or composite shear walls that resist lateral loads. The moment-resisting frame is made up of moment-connected columns and beams: The loads are transferred from one element to the next through the connections. The shear wall system is also frequently used in tall buildings. Another commonly used system comprises moment-resisting frames with braced cores. This is a steel scheme that uses a combination of moment-connected frames for vertical load resistance and core bracing for lateral load resistance (Taranath 1988).

Structural Systems for Seismic Regions

The structural systems commonly used in high seismic areas include: (1) The perimeter ductile-moment–resisting frame (DMRF); (2) the braced system with a moment-resisting frame; and (3) the shear wall with a moment-resisting frame (Ambrose and Vergun 1985).

A perimeter DMRF is a steel or concrete frame around the perimeter of

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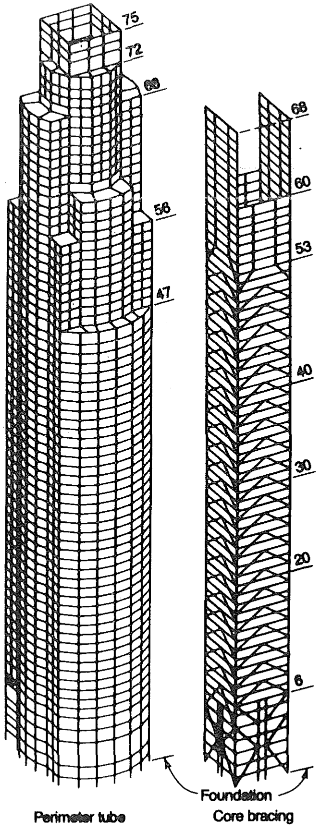

FIG. 1. Perimeter and Core (Courtesy of CBM Engineers, Inc.)

the structure, in which moments are transferred through the connections between members of the frame. The system must also be detailed to provide ductile behavior and meet qualifications listed in the Uniform Building Code (UBC). The advantages of the DMRF are:

- It can dissipate large amounts of energy.
- Due to the lower value of construction-type coefficient assigned to the system, the required design loads are less.
- Extensive experience with DMRF structures results in a large body of analytical and behavioral information about the system; thus, it is favored in the building codes.
- The system is architecturally attractive because it allows large open spaces within the exterior walls (Ambrose and Vergun 1985).

The disadvantages of the perimeter DMRF are:

- Because of the flexibility of the structure, there is a greater propensity for nonstructural damage.

- It is costly to increase the number or size of members to stiffen the structure to correct lateral deflection problems.
- Because the moment connections must be stronger, particularly in steel frames, construction cost and installation time at each connection are increased.
- There is a stability problem in slender structures from p-delta effects (i.e., stress induced by vertical loads acting on the laterally displaced building frame) (Ambrose and Vergun 1985).

Another commonly used structural system is a braced frame connected to a moment-resisting frame. The advantages of this system are better economy as well as less nonstructural damage, because it is a stiffer structure. The disadvantages of this system are higher inertial forces, because it has a small period or torsional moment, potential problems with the connections since they must be stronger than the bracing, and possible buckling of the braces (H. Krawinkler, unpublished interview, May 8, 1989).

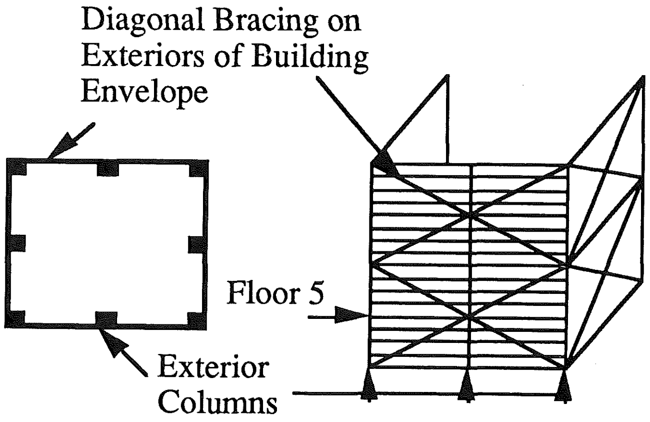

FIG. 2. Exterior Braced Frame

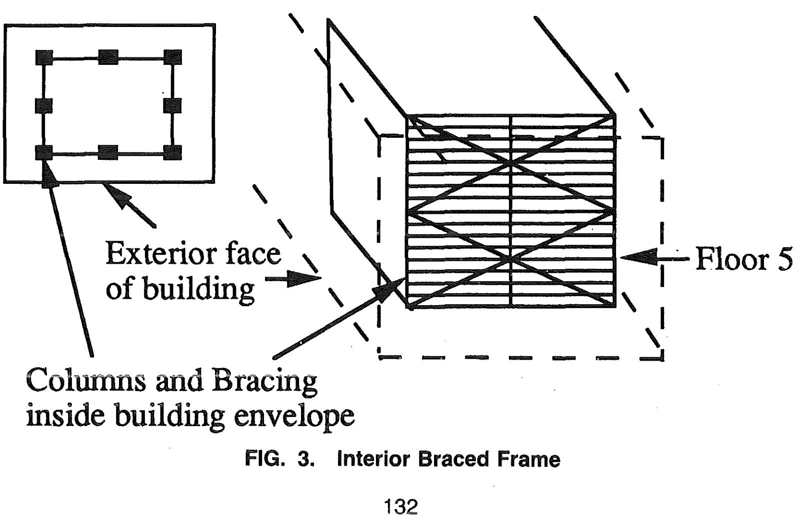

FIG. 3. Interior Braced Frame

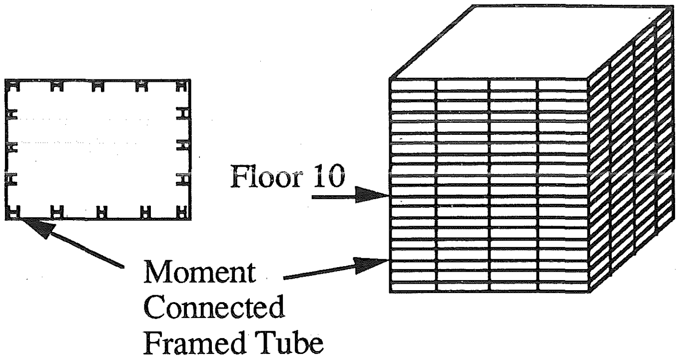

FIG. 4. Framed Tube

The third commonly used structural system in seismic areas is a shear wall with moment-resisting frame system. The advantages of this system are less nonstructural damage during an earthquake because of the structural stiffness, as well as ductility and stability provided by the backup system. The disadvantage of the system is that it will attract higher inertia forces due to a small vibration period (H. Krawinkler, unpublished interview, May 8, 1989).

Typical Use of Chevron Brace

The chevron brace is a configuration of concentric bracing. Structurally, it behaves the same as the V- and X-braces. It is commonly used in bracing systems for tall buildings in nonseismic areas. In high seismic areas, chevron bracing is typically used in low-rise buildings only.

Since the members in chevron bracing are shorter than those in X-bracing, chevron bracing can take higher compression forces. While X-bracing requires four or five connections, chevron bracing needs only three connection points; therefore, construction cost of chevron bracing is less (G. Luth, unpublished interview, May 9, 1989).

The major disadvantage of this chevron-bracing system is that, if one of the braces buckles, the beam above the brace may have large vertical deflections at the center. If a section of the brace does buckle, the strength of the system may deteriorate significantly because of the imbalance between the tension member and the compression member (*Recommended Lateral* 1987). This is the main reason building codes prohibit the use of chevron bracing in high seismic areas.

Development and Architectural Design of Project

The owner of this project is one of the largest builders in the country. The firm's annual volume is more than $300,000,000, and it is the largest commerial landowner in Los Angeles. Through a set of agreements with the city of Los Angeles, the owner acquired the rights to develop a building across the street from the Los Angeles Central Library, a national Cultural Heritage Monument. The owner provided funds for renovating the Central Library.

The owner wanted a distinctive high-rise building, a signature building in downtown Los Angeles. In 1980, the owner hired a world-renowned ar-

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chitectural firm, based in New York City. One of the partners in the architectural firm led the design team from conception to preliminary schematics, and through production of working drawings and administration during construction. Beginning in 1980, the architect consulted with the owner during the two years of development negotiations with the city of Los Angeles. In 1982, the architect began the conceptual design for the building.

The site has a rectangular shape that is not aligned with the Central Library (see Fig. 5). The architect considered it important to retain focus on the Central Library and respect the distinguished architecture of that building. They also wanted a connector, a pleasant pedestrian area, between the historic area of downtown and the recently developed Bunker Hill area. At a different level, they wanted the building shape to enhance the Los Angeles skyline. This building would be the tallest on the West Coast.

The architect prepared six proposals for the geometric shape of the building. Several of the shapes were circular to draw the pedestrian flow around the building from the Bunker Hill side to face the library. However, the

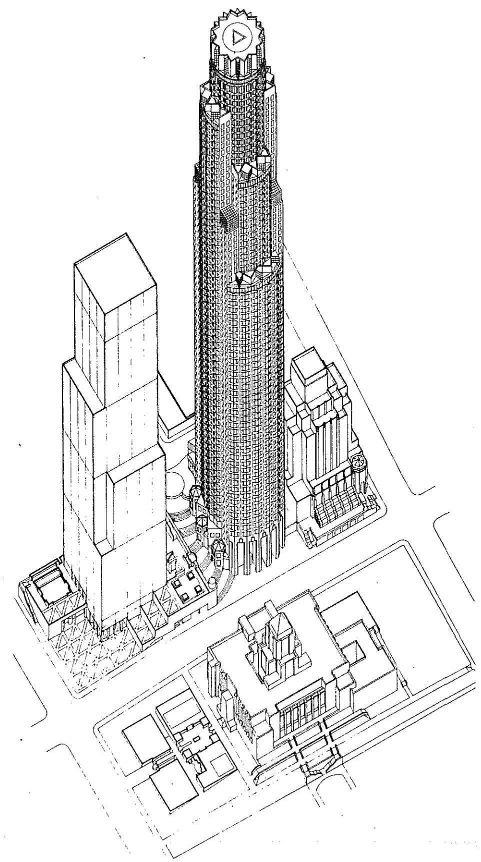

FIG. 5. Location of Project (Courtesy of Pei Cobb Freed & Partners and Fredenburgh/Architects)

circular shape had some constraints. It did not fit easily in the rectangular site, and the interior spaces were not conducive to efficient offices. The designers experimented with overlapping squares and circles to address these problems while retaining the dynamics of the circular shape.

The final proposed shape, a circle with overlapping rectangles at the flanks, provided an efficient base floor plate and allowed varying floor configurations from the setbacks (i.e., changes in elevation or changes in floor plan sizes) at the higher floors. The geometry also provided a distinctive and memorable shape on the Los Angeles skyline. This concept was refined and developed through the design process.

STRUCTURAL DESIGN OF PROJECT

Prior to the selection of a structural engineer, at the conceptual stage the architect considered a perimeter DMRF for the structural scheme. The owner thought the steel was too dense around the perimeter of the structure. The columns were spaced close together and descended to the lower part of the building, creating an impediment to the efficiency of a parking area. The owner sought more input regarding alternative structural schemes.

Representatives from a select list of structural engineers recommended by the architect were invited to interview with the owner for the structural consultant position. A small structural engineering firm that specialized in tall building design was selected and began the structural design of the building in 1984.

Owner's Demands for Structural Design

The owner, who was very sensitive to the commercial real estate market in the Los Angeles area, conveyed the following needs and requirements to the structural engineer.

- The owner were willing to pay for quality tenant space; cutting corners to save project cost was not wanted.
- The owner wanted an innovative, signature building. Thus, they wanted to preserve the architect's design concept—the overall shape of the building, including multiple setbacks at the top and the wide-open lobby.
- The owner, however, wanted a structural system that would be free from any controversy or criticism; the structural system of the building was to be the safest in Los Angeles area.

The structural engineer had never worked in the Los Angeles area, so he began exploring structural schemes on a very conservative basis. A general contractor joined the design team to provide construction input; the structural scheme evolved with the input of a design/construction team.

Conflicting Requirements of Ductility and Stiffness

For the structural engineer, the challenge was to meet the seismic-force demands and the wind-performance demands without compromising the architectural integrity of the building, as well as to achieve economy within the established design parameters. The structural engineer wanted to optimize the structural system in terms of both performance in wind and seismic force—in other words, stiffness and ductility. The structure should stay perfectly elastic during a maximum credible earthquake; it should also provide stiffness against wind for tenant comfort.

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The structural engineer began the design with some form of a perimeter DMRF knowing that, since the building was so tall, he would need to supplement this perimeter DMRF with some bracing in the core structure for more stiffness. Without the additional stiffness in the core structure, the cost of the structural system would be extremely high.

Several structural schemes that had a totally ductile frame with some forms of bracing in the core were considered. The wind-tunnel studies on these preliminary schemes indicated that the building was highly sensitive to wind motion, so additional stiffness was required for tenant comfort. The structural engineer started improving the systems, addressing the owner's and architect's demands as well as the stiffness and ductility requirements.

Evolution of Structural Design

The structural engineer evaluated a number of other bracing schemes, some using composite concrete columns and others incorporating a spine with X-bracing in the structure. The owner reviewed the schemes. The composite concrete concept was considered too revolutionary for the area and was discarded.

Initial Spine Concept

The structural engineer's experience indicated that, in buildings with multiple setbacks, an efficient structural system results from a common spine. He located the spine with an X-bracing system close to the exterior of the building. This system was significantly less expensive than the other alternatives, offered good stiffness, and limited tenant motion perception to satisfactory comfort levels.

However, the scheme was unconventional, so the owner hired a steel design consultant in Switzerland to review the design. The consultant reported that the building was not "totally infallible"; it did not have the level of ductility he thought it should have. These doubts, coupled with concerns about the detrimental effect of cross bracing in the lease area, led to rejection of the scheme. The architect also wanted a core completely free of bracing. The structural engineer continued to do studies of the core.

Bracing Schemes

To meet this request, the structural engineer developed a hybrid bracing scheme with columns in the lease space, but not in the core. This scheme met the architect's requirements, but is was more costly. The owner thought the system would adversely affect the marketability of the lease space.

The structural engineer started working with a dual system, a braced core with a perimeter frame. They considered several bracing schemes: diagonal bracing, cross bracing, and single-story chevron bracing. These schemes used intermediate columns on each side of the corridor leading to the elevator core, a departure from the spine concept.

Final Design Concept

The structural engineer pursued a system that held to his spine concept and used four heavily loaded major columns in the corners to efficiently resist the seismic load. This led to the basic configuration of the final scheme, a core consisting of four major columns and two-story chevron bracing linked to a perimeter DMRF. The core with the column provides stiffness to the building and the perimeter frame provides ductility. Interference with me-

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chanical system components was a major concern, so the two-story chevron braces were alternately located to eliminate both architectural and mechanical interferences. This scheme did not require columns in the leasing space and was approximately $2,000,000 less expensive than any of the alternatives.

Although the design met all the legal requirements, the uppermost occupied floor still had higher wind acceleration than the structural engineer wanted. They investigated two solutions: adding dampers to the building or readjusting the stiffness of specific members to increase the effective mass.

Since adding stiffness could affect the seismic load, the structural engineer chose to increase the effective mass by stiffening parts of the upper perimeter frame. This brought the wind-induced acceleration at the top of the building within acceptable limits. This adjustment of adding localized stiffness was done in such a way that the overall stiffness was not increased. The dual system with this adjustment was the final design used for the building.

Interaction with City of Los Angeles

The structural engineer began his relationship with the Los Angeles building code officials early in the design process by inquiring about code requirements. During the later part of 1985, the Uniform Building Code (UBC) was being revised. The proposed edition contained criticism of chevron bracing even in nonseismic areas. The structural engineer produced special design criteria for chevron bracing to address the safety and ductility concerns.

The structural engineer designed the floor beam for free span so the flow would not collapse even if one of the diagonals buckled. He then presented his analysis to the building code officials of Los Angeles as well as the Structural Engineers Association of Southern California to prove the safety of the structure designed under their criteria. Eventually, the 1988 UBC contained recommendations that arose from the analysis of this design. The owner also had the design reviewed by two other prominent structural engineers. There were no further criticisms.

Early in the design process, the owner hired one of the largest general building contractors in the country to provide preconstruction services. As the structural system evolved, the contractor provided cost information about the proposed schemes. The contractor later became prime contractor for construction of the structure. Construction began in 1987 and was completed in early 1990.

Overcoming Barriers to Technology Transfer on Project

The structural design of this project was not a revolutionary innovation. It was the transfer of existing technology used in nonseismic areas and the innovative modification of that technology for use in a high seismic zone. This process of transfer and modification occurs in many construction innovations. For example, plastics were developed outside the construction industry; yet, they are applied to formwork, piping, and accessories used in building construction. Laser technology was developed outside construction, but now provides major benefits in surveying and in the partial automation of construction operations. These existing technologies were transferred into the construction industry and they continue to be adapted and modified for use in the industry.

Existing Barriers to Technology Transfer

Technology transfer in construction, however, is not a simple process. In construction, several types of barriers hamper and discourage the movement of existing technology. Three key barriers are the presence of building codes, the conservatism of key participants in specific projects, and the organizational hierarchy created in the traditional contracting approach.

Building codes are written to establish a minimum standard of quality and performance for buildings in a specific area. These codes must cover every type of building and every site condition. It is impossible, however, to address the unique characteristics of each construction project, so the codes are written in general terms and interpreted by local officials for specific applications. In other words, the codes are based on the common practice for the area of application; this can be a barrier to importing a technology that is not common to the area. If the local officials do not have the technical expertise and are unwilling to seek expert consultation, then the code interpretation may restrict the potential innovator from transferring and modifying the "new" technology.

Another barrier to the technology transfer is the conservatism of the key participants in the project. In fact, the construction industry is very conservative. It cannot use the trial-and-error method for innovation because failures have grave consequences for public safety. An owner who will occupy the structure will not tolerate any unnecessary risk or potential liability caused by using a "new" technology. Many are also unwilling to spend the additional resources required to prove that the new technology meets their own criteria as well as those of the building codes.

Also, owners/developers must consider the marketability of the building in their technical decisions. They would not allow a technology that is controversial and thus could cause market resistance. The professional liability of the architect and the engineer also encourages conservatism. The litigious nature of our current society and the potential for large financial loss from any amount of culpability have made professionals wary of taking any avoidable risk. This conservatism is a barrier to the transfer and modification of existing technology for use in a new area.

A third barrier to the technology transfer in construction is the organizational hierachy established by traditional contracting methods. Traditionally, the owner hires an architect to complete the design process before the construction phase. The architect hires the structural engineer and other specialty consultants needed to complete the design. Since the engineer and consultants are working for the architect, there may be less incentive for challenging interaction and compromise between the parties. The engineers and consultants are not in a position of equal authority and this means that they will have to convince the architect that new technology is worth the risk of rejection by the owner or the risk of further modification of the design—before it is ever presented to the owner for review. This contractual dependence may encourage the filtering of ideas, which can be a barrier to the technology transfer.

In this project, the owner and the designers took specific actions to overcome potential barriers from building codes, conservatism, and organizational structures.

Overcoming Building Code Barrier

In 1985, proposed additions to the UBC came to the attention of the structural engineer. These additions contained criticisms of chevron bracing

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that would have restricted the use of this system for this project. The structural engineer met with the Seismology Committee of the Structural Engineers Association of California (SEAOC) and presented a case for applying special design criteria to allow the use of chevron bracing in tall building structures. He presented analyses of the reaction of the braces in the event of failure and convinced the committee that his criteria were safe. The committee modified its recommendations, incorporating some of his criteria ("Recommended Lateral" 1988).

The structural engineer also approached Los Angeles building code officials early in the design process. He communicated with them throughout the evolution of the design. He presented his analyses and convinced them the design was safe. Without the commitment and technical expertise of the structural engineer and the city's ability to evaluate the technical aspects of the design, the building code would have been a barrier to the transfer of this technology.

Overcoming Conservatism Barrier

The conservatism of the key participants in the building process can also be a barrier to technology transfer. The owners did not want a controversial design, but they allowed a full investigation of the ideas. They hired expert consultants to substitute the technical findings the structural engineer presented to them. Their definition of *controversial* did not mean new or innovative, but it meant the design could not be technically suspect. The owner was willing to pay for investigation of design alternatives to determine whether they met this criteria.

The architect had never worked in a high seismic zone before. This suggests that they would be very conservative on their first project. However, on this project *conservative* did not mean traditional. The architect did not limit the building shape to normal design for the Los Angeles area. They developed the conceptual design based on other criteria: The building's interaction with the surrounding environment and its enhancement of the Los Angeles skyline. They did address the special seismic conditions by working with the structural engineer to accommodate the seismic requirements while maintaining the integrity of the design concept.

The structural engineers had limited work experience in a high seismic zone. The way they developed the seismic design criteria reflected their conservatism. They consulted with experts in seismic design and performed wind-tunnel studies to establish the performance criteria of the design schemes. Their conservatism did not prevent them from importing technology they had used in other locations, but it did require extensive analysis and testing. The structural engineer had the ability to present the analysis and convince the building code officials that the design was safe.

Overcoming Organizational Barrier

The owner contracted with the architect, structural engineer, contractor, and other consultants separately. Each party worked for the owner from the beginning of the design process, and they all participated as equals in the design evolution. The owner encouraged the parties to function as a team and present a range of options on major design decisions from which he would make the final decision.

With this type of contractual arrangement, i.e., separate contracts, each party reports to the owner directly and is contractually tied to the owner, avoiding the filtering of options that can occur when one of the parties is

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working for another. Unlike the traditional process, a team of equals is created.

Conclusions and Practical Applications

The barriers to the technology transfer were surmounted in designing an innovative structural system for this project because of the teamwork of the professionals from formulation to construction. This teamwork was based on a reciprocal relationship. One person did not invent the new idea and unilaterally convince the others to implement it. The design evolved to incorporate each participant's needs.

For this relationship to be successful, the participants need specific types of qualifications. Each team member must possess technical competency. The entire team does not have to be composed of experts; the technical information may be provided by a few team members or by expert consultants. Each participant, however, must be able to understand and respond to the technical information presented to them. They must be able to use technical merit as a criteria in their decision making.

The reciprocal process also requires that each participant invest resources. It takes time, money, and personnel to interact as team members and to work through the competing demands of the other members. If a participant does not have the technical expertise to fully analyze an alternative, resources are required to obtain the information needed for analysis. It is vital to expend efforts to understand not only the technical aspects of the proposal, but the needs and concerns expressed by the other team members. Each member must participate fully in the analysis and the major decisions; this requires a commitment of resources.

The barriers of technology transfer can be surmounted through a reciprocal relationship between key participants in the building process. This reciprocal relationship requires qualified participants: Each participant must have a basic technical competency and must be willing to expend resources needed to be active members of the decision-making process.

This project also illustrated the important role of the champion on construction projects. The broad view of the owner and the reciprocal relationship between team members created a favorable climate for the work of a champion. The structural engineer functioned very effectively in this role; he developed an innovative design concept and convinced the project team and others with authority over the project that the design best met all project objectives. The role of the champion involved technical analysis, advocacy of the design consideration of multiple objectives, and integration of the team members.

Practical application of the insights from this example of successful innovation involves at least three actions by owners, designers, and contractors. First, set up project environment that facilitates a collaborative approach to both project definition and problem solving. This requires bringing all the major players aboard early and giving objective consideration to concerns regarding design, construction, and use of the facility. Second, challenge and require the project team to identify and evaluate alternative design solutions. The owner will most likely have to pay for this, but each team member should feel a responsibility to suggest innovative approaches. Third, reject conventional wisdom regarding barriers to innovation in construction. Though formidable, these barriers are surmountable, as demonstrated in this case. Making the required effort can bring significant project benefits and enhance both the capability and reputation of the firm involved.

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