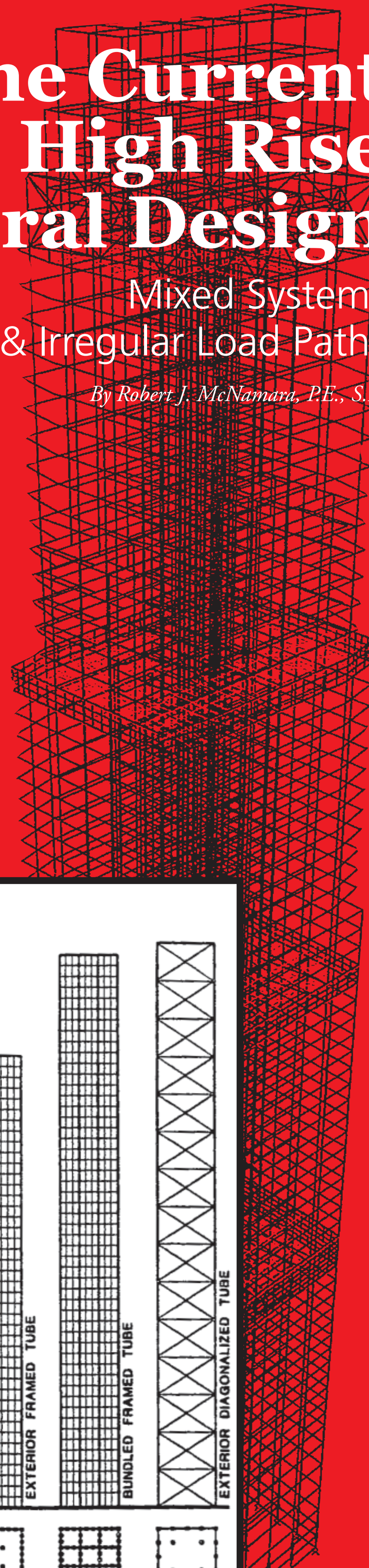

Some Current Trends in High Rise Structural Design

Mixed Systems & Irregular Load Paths

By Robert J. McNamara, P.E., S.E.

Systems - General

The lateral load resisting systems for tall buildings have been nicely organized into efficient types, ranked according to optimum performance for a given height or number of floors. These configurations are shown in the well-published diagram developed by The Committee on Tall Buildings and Urban Habitat, Group SC, 1980 (*Figure 1*). Well known systems applicable to any structure occupy the left side of the chart, and systems more applicable to tall and super tall structures occupy the right side of the chart.

This chart has provided direction to designers for optimum system selection and is still very useful today. Most tall buildings, at the time the chart was developed, had regular plan layouts and a regular vertical façade without significant set backs. The lateral systems were continuous vertically and did not deviate from the simple diagrams shown in the chart.

Many of these systems, especially those left of center of the chart, are well suited for approximate hand calculations. Design criteria such as lateral deflection limitations and inter-story drift indices were used in conjunction with the hand computations to produce very economical designs. These lateral load resisting systems (two to eight stories) usually contributed a small increment to the total structural cost. When designing taller buildings, the lateral systems became a much larger part of the structures cost and adherence to uniformity implied in the system shown in the chart was mandatory. The approximate analysis methods used also required that the organization of the system not deviate from the assumptions built into the methods used to analyze and design it.

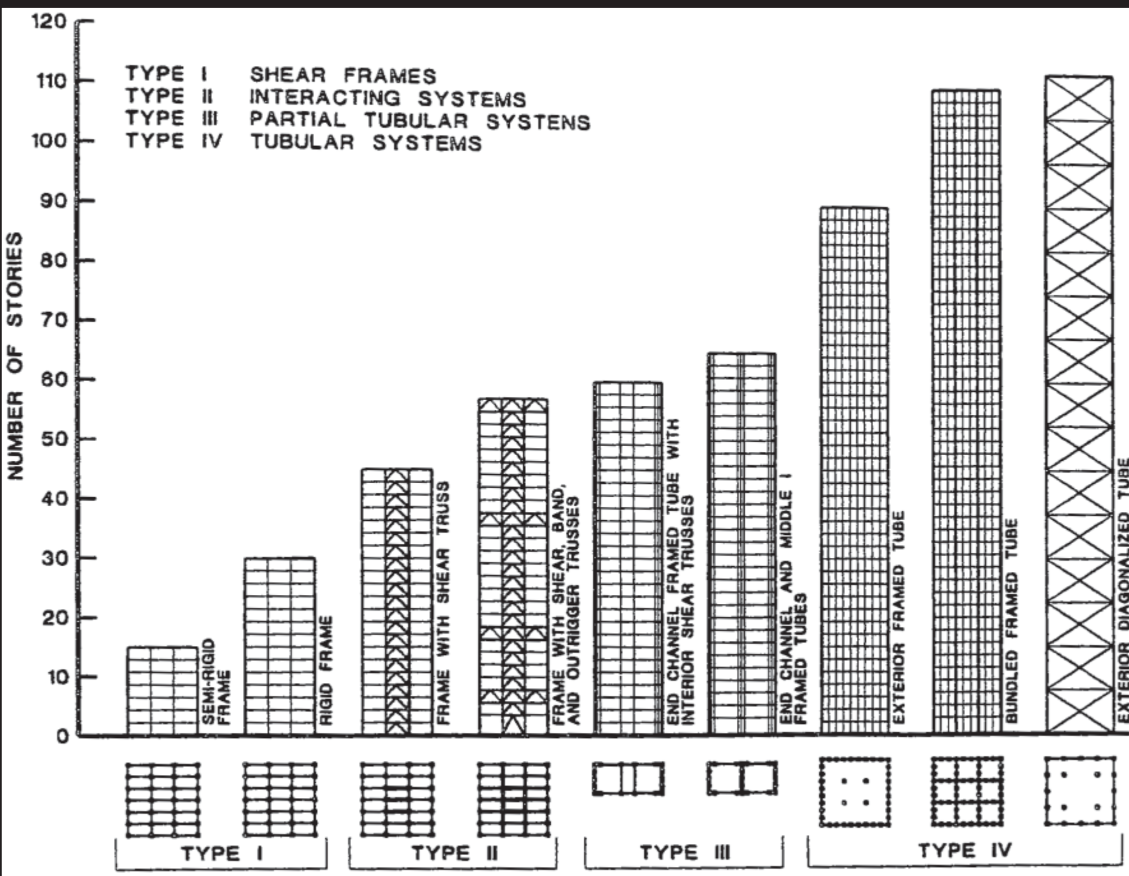

Figure 1 (CTBUH, Group SC, 1980.)

With the availability of sophisticated structural analysis and design programs, Engineers began to take liberties with the formal organization of the standard systems presented in *Figure 1*. Architectural forms began to deviate significantly from simple rectangular boxes. Plan forms no longer remained similar from floor to floor. Plan shapes became disjointed, wall surfaces faceted, curved, sloped, etc., all of which demanded the structural engineer create systems to accommodate the new building envelopes. The simple orderly systems categorized in the chart no longer worked with the architectural envelopes being developed for new buildings. One of the more important consequences of these new architectural forms was that the structural systems were no longer continuous vertically, and that systems that engaged the entire building geometry such as tubes became ruptured and discontinuous. The fundamental principles guiding the conceptual organization of the structure were not changed, but the load path which engaged the lateral systems became much less direct than that of the more traditional systems. Because of this, the usual analytical assumptions inherent in many of the commercially available computer programs such as rigid floors are no longer accurate. The deformations in previously assumed rigid elements have become an important aspect in the overall behavior and analysis of these elements, and must be addressed in the design.

To accommodate these new forms, engineers developed their own array of mixed systems. A blending of the various classical lateral systems to accommodate the irregularities and discontinuities was developed with the help of the sophisticated computer programs and new design methods. Moment frames were mixed with braced frames rather arbitrarily to create structural systems which conformed to the irregular architectural layouts. All of these systems work toward the same goal of delivering the lateral wind or seismic loads to the foundations, albeit rather indirectly. A good example of the mixed systems composed of various classical parts is shown in *Figure 2*. The structure is the First Bank Place in Minneapolis, MN designed by CBM Engineers, Inc. This structure is developed to accommodate the various architectural plan and façade changes with height. Clearly a very careful consideration of all the load path deformations and corresponding analysis assumptions is important for the actual structure to perform as the designer intended.

Another very important issue influencing the selection of structural systems was the gradual inclusion of seismic design requirements throughout the county. No longer is it appropriate for the designer to conclude that "wind governs" or "seismic governs" by comparing the gross base shear on the building. The nature and treatment of seismic and wind forces are quite different. Current seismic code design forces can only be rationalized by assuming damage to the structure. The actual forces generated by a seismic event are much greater than the code forces, and these forces are assumed to be reduced by the energy dissipated in structural damage. This is not the case for wind code forces. Wind code forces are derived from the wind velocities expected, and are to be resisted elastically and do not assume energy is dissipated in their development. The end result of this dichotomy for tall buildings is the total seismic design force, which may be numerically less than the wind force. However, the assumption that the structure can dissipate energy implies that the elements being required to dissipate energy meet critical detailing requirements. Damage must occur and be controlled. Connections now need to develop the full capacity of the member in order to dissipate the energy implied by the seismic design procedures. In most cases, it is the yielding of the connections that dissipates the necessary energy. It should be noted that the resulting damage from the 1994 Northridge Earthquake convinced many owners of the need for structural systems which approach the seismic risk from a more logical damage control point of view. Dissipating the energy required by the code procedures, coupled with non-ductile connections, produced a

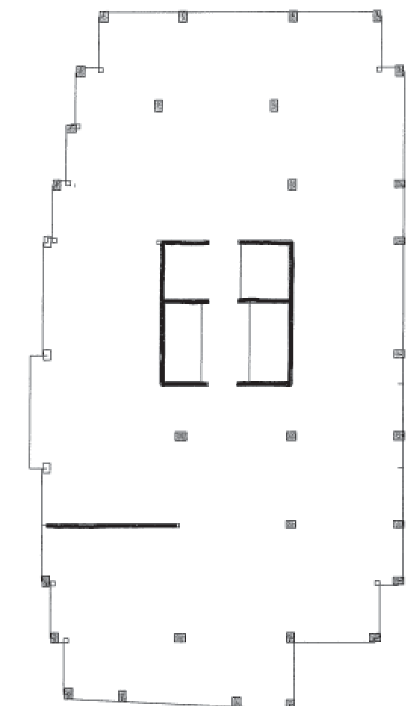

Figure 3a

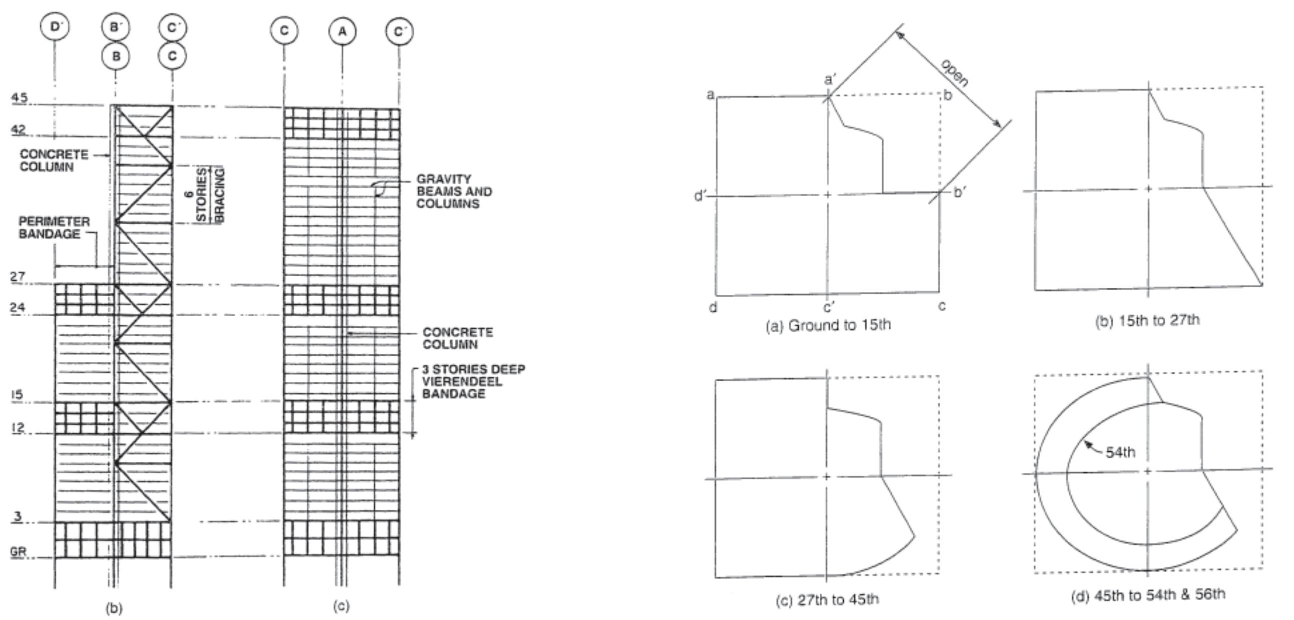

Figure 2

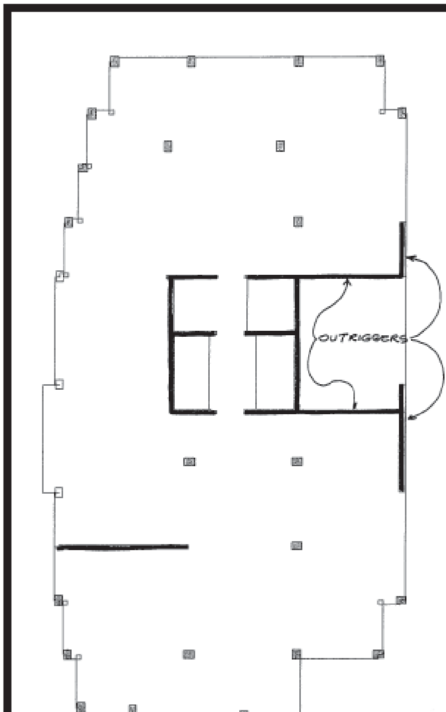

Figure 3b

damaged structure that proved to be too costly to repair for use after the Northridge earthquake. This code design approach and related performance problem has led to an increased interest in energy dissipating systems, and to systems where the dissipating elements are designed directly for the energy to be dissipated and the structural systems are intended to have little or no damage. It is with the introduction of these combined systems that the importance of the deformations along the load path becomes of paramount importance.

This article examines several projects that illustrate some of the structural solutions used in today's tall buildings. In most cases, the solutions derived for today's new forms are not new, but an adaptation of the tried and true systems outlined in the early 60's and 70's and idealistically diagramed in the chart shown in *Figure 1*. The adaptation has been made possible by the ease of use of structural analysis and design computer programs available on the commercial market. However, application of the analysis and design programs with a critical eye towards their inherent built in assumptions, such as rigid diaphragms, and deformations along the load path, must be a prime consideration in applying the programs to today's systems. Common assumptions relating to simple concrete member properties, such as cracked or uncracked section properties, also has an important effect on the overall behavior of the system.

Along with the current approaches comes a curious development of a new jargon, which seem to derive from the fashion industry. Hats describe outrigger systems, belts for outriggers without diagonals, etc. Similar terms such as bustles, bandages and zippers have found applications to structural systems and have become common nomenclature for the new combinations of systems.

Systems – Fancy Hats

An example of the variation on a traditional system is shown for a 30 story concrete tower currently under construction. The program requirements from the owner demanded a concrete tower with minimal floor to floor heights. A restrictive urban site resulted in an "L" shaped plan, with parking below the housing units. Economy of the concrete structure called for a gravity system with a minimum of beams. All of this meant that the lateral system would be confined to very slender shear walls of concrete surrounding the elevator core and a few isolated shear walls. The height to width ratio of the core alone was over 20 to 1, resulting in an extremely flexible structure. In order to develop an economical system with these constraints, the adoption of an outrigger system composed of deep concrete beams (albeit slightly irregular) mobilizing the core with exterior columns to resist the lateral loads was developed (*Figures 3a and 3b*). The outrigger is a "hat" girder. The complexity of the fancy hat girder is an extension of the outrigger concept shown in *Figure 1*, although not amenable to hand computations. The complicated arrangement of the stiff outrigger girders at the roof provides the necessary engagement of building columns resisting the overturning effect with the slender core and stiffening the lateral system. The deformations of the floor system have an important impact on the effectiveness of the hat system engaging the exterior columns. The resulting forces in the shear walls, engaged exterior columns, hat girders, foundations, etc. are very dependent on the assumptions used in the analysis for those elements. The outrigger engaged exterior columns can be in net tension, which significantly reduces their effective area for stiffness in the lateral system and accordingly reduces the effectiveness of the system. The design is best served using the hat system to engage the heaviest gravity loaded exterior columns to eliminate this undesirable consequence of the system performance being highly dependent on the element property assumptions (cracked or uncracked). This issue is also an important aspect in the analysis of the concrete system under the action of code seismic forces, where the selection of the response reduction factor is not obvious. Most common computer programs will not easily account for different element proper-

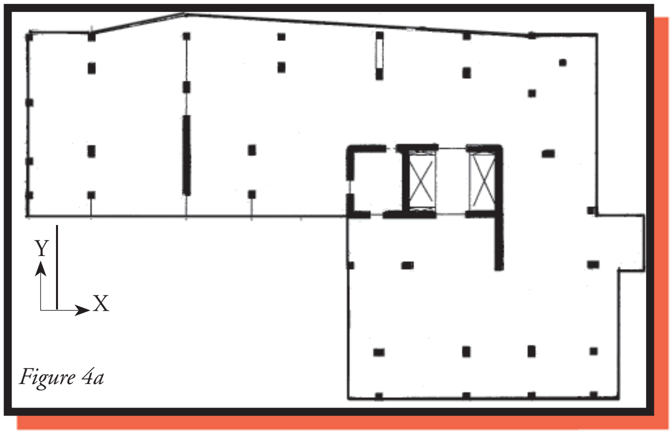

Figure 4a

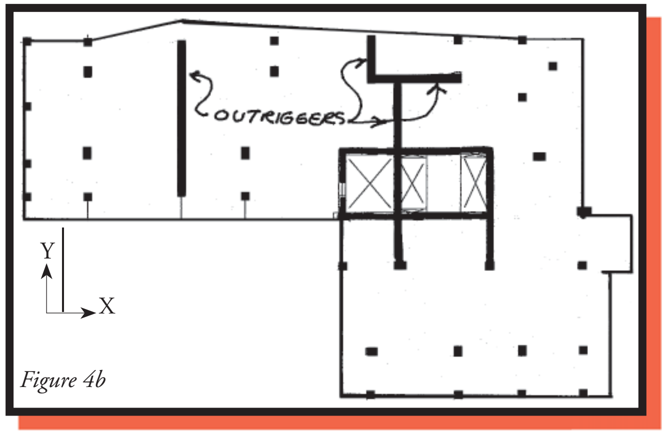

Figure 4b

ties, which depend on whether the element is in tension or compression.

Another example of a similar concept is shown in *Figures 4a and 4b* for a project currently in the design stage. Here, a series of deep beams serve as an outrigger system for another very slender concrete core. Again, the irregular "hat" serves to mobilize a larger portion of the overall structure, reducing uplift loads in the slender core and stiffening the structure to minimize lateral deflections.

In *Figure 5*, a circular plan for a 500-foot high office building is shown with wide column spacing around the perimeter, eliminating the possibility of an economical perimeter frame. The interior layout is that of a square central core. The core is a braced steel frame with a height to width ratio of 8. This large slenderness produced a relatively heavy steel frame. Another fancy hat system was created with steel truss outriggers as shown in the plan. The hat was also supplemented with outriggers near building midheight to add additional lateral stiffness to the system. This hat and outrigger addition provided significant overturning resistance and lateral stiffness to the internal core. The odd geometry of the diagonal core intersection presented interesting steel detailing problems, but overall the "Fancy Hat" resulted in a very economical structural steel frame. The connections in the exterior columns engaged by the hat trusses required special consideration along with the detailing of the load path through the hat/core interface.

Systems – Fancy Belts

A concept which replaces the outrigger idea, but behaves in a very similar manner, is to use a "belt" system which eliminates the outrigger diagonal. The traditional outrigger is necessary to mobilize more of the building geometry to resist lateral loads, namely the exterior columns. When the outrigger must be placed in the middle of the tower, the outrigger diagonal is usually problematic with interior planning of the user space. Traditionally, the outrigger has been restricted to mechanical floors and the roof. Alternatively, the diagonal brace can be replaced by a "belt" around the perimeter, which is a story deep vierendeel girder around the perimeter. The belt needs to be very stiff to eliminate the need for internal diagonals. The load path of the forces through the diaphragm floors into the belt and the deformations of the floor are complex and require a very a detailed analysis. Only through the use of present day sophisticated finite element computer programs can this type of structure be properly designed and detailed.

The tower shown in *Figure 6* is currently under design utilizing the belt concept to stiffen the structure and force the overall structure to act as a combined shear wall/tube system. No internal diagonals or floor spandrel beams are used. In order to reduce the effective height-to-width ratio of this structure, "belts" were required at several intermediate floor levels and steel outriggers were used at the top. All of this effort is to force the entire structure to act as a single unified "tube" system. The height-to-width ratio of the core walls alone is 25, much too slender for an economical structure. The height-to-width ratio for the overall structure

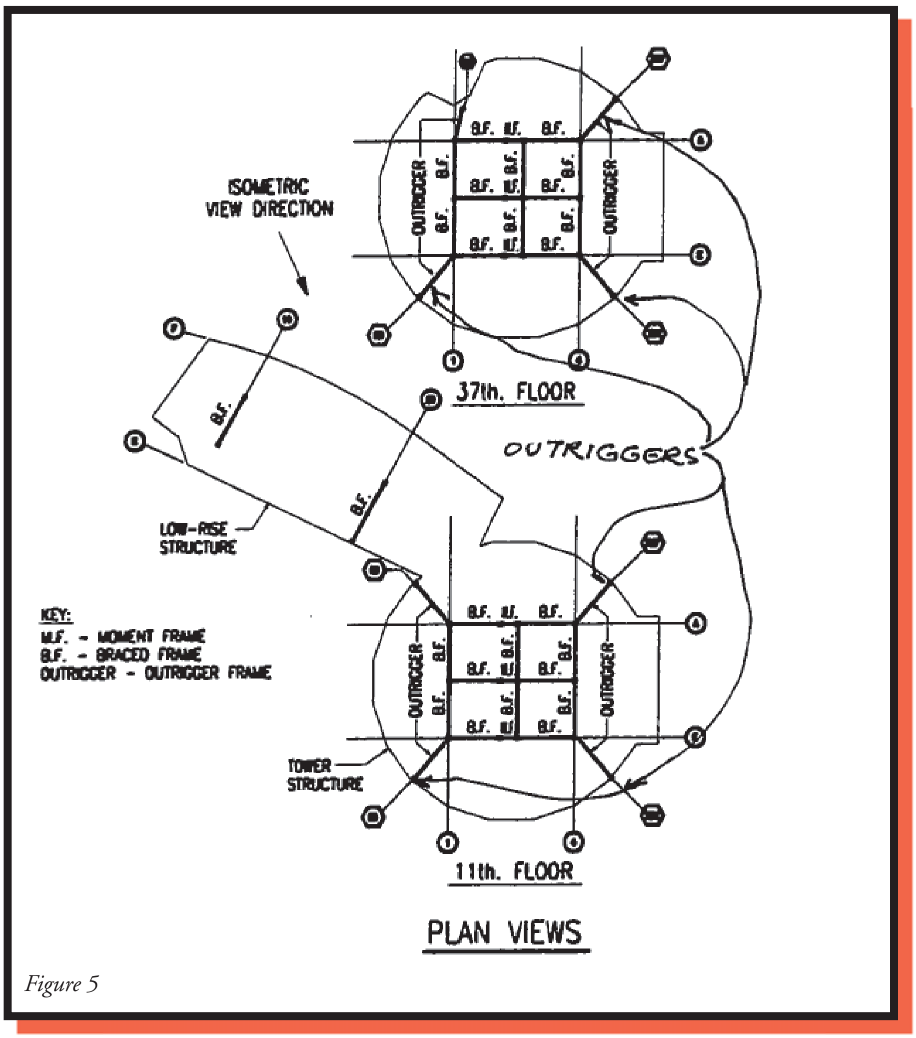

Figure 5

is 8, still slender but economically possible.

As an interesting side note, the tower preliminary design was done utilizing the Natural Hazard Aerodynamic Loads Database (NATHAZ) sponsored by the University of Notre Dame. The database at this site was used to determine target translation periods to control the expected motion levels of the upper (and most expensive) condo floors. The number and location of the belts in the structure were then studied to produce building periods matching those derived from the NATHAZ website (**http://www.nd.edu/**). The design was then tested in a wind tunnel at the University of Colorado, using a force balance model to predict the top floor accelerations. The approach using NATHAZ website methodology proved to be very useful in generating realistic preliminary target periods for the building, satisfying the motion comfort criteria. As a result of these studies, preliminary planning now allows for a Tuned Mass Damper to be included in the early planning and cost allowances. This tower is being designed in association with KLA of Colorado

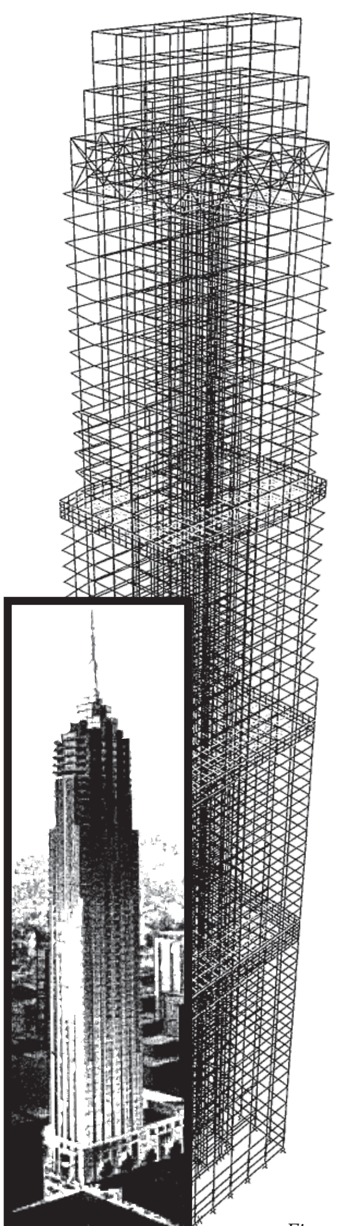

Figure 6

Future Trends

The fragmentation and rupturing of the traditional structural systems has produced new structural forms, which in many cases are the simple juxtapositions of classical systems. Frames are uncoupled and mixed with braced diagonalized systems. Systems are discontinued and switched from one type to another depending on the architectural forms. However, the nature of gravity and lateral forces of nature was not changed. A clear and distinct load path is still the most important aspect of any tall building's structural system. The forces for one system transferred to another must be carefully traced and accounted for. The usual "rigid diaphragm" and other similar assumptions imbedded in today's computer programs must be carefully examined for each of these new structural systems. As designers, we must ensure the structure can do what it is being asked to do. The imbedded assumptions in the sophisticated programs in common use today must be clearly understood, and any deviation from these assumptions and their effects on the overall behavior of the structure must be clearly known to the designer.▪

Robert J. McNamara, P.E., S.E. has been practicing structural engineering in the Boston area for over thirty-five years and serves as President of McNamara/Salvia Inc. He can be reached via e-mail at **rjm@mcsal.com**

***Structural Systems for Tall Buildings*, by the Council on Tall Buildings and Urban Habitat (1995), is published by McGraw-Hill Publishing Company.**