TRENDS AND INNOVATIONS IN HIGH-RISE STRUCTURES

by

Christopher D. Lubke

B.S. Civil Engineering
Texas Tech University

Submitted to the Department of
Civil and Environmental Engineering in
Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in
Civil and Environmental Engineering
at the
Massachusetts Institute of Technology

June 2003

Signature of Author: ______________________________
Department of Civil and Environmental Engineering
May 12, 2003

Certified by: ______________________________
Jerome Connor
Professor of Civil and Environmental Engineering
Thesis Supervisor

Accepted by: ______________________________
Oral Buyukozturk
Professor of Civil and Environmental Engineering
Chairman, Departmental Committee on Graduate Studies

TRENDS AND INNOVATIONS IN HIGH-RISE STRUCTURES

by

Christopher D. Lubke

Submitted to the Department of Civil and
Environmental Engineering on May 12, 2003 in
Partial Fulfillment of the Degree Requirements for
Master of Engineering in Civil and Environmental Engineering

ABSTRACT

High-rise structures have been evolving in several different areas. The great heights of today's tall buildings can be attributed to a combination of innovative structural schemes as well as advanced construction materials. Structural systems have progressed from basic rigid and braced frames to more complex systems that involve framed tube structures, outrigger braced structures, and mega-braced frames with mega-columns and mega-braces. Advancements in concrete technology have decreased the weight, increased the strength, and increased the ductility of the material. Lighter and stronger concrete allows for smaller member sizes and more interior space. Recent trends have shifted to composite (steel/concrete) structural elements. These elements are able to use the best attributes of each material for the advantage of the structure. Composite columns are frequently used, consisting of either a concrete filled tube or a steel section encased in concrete. The structural systems, construction materials, and other design issues of the Jin Mao Tower and the Petronas Towers are discussed.

As structural systems improve and become more efficient, one must also be concerned that the structure maintains a significant amount of redundancy to prevent progressive collapse in extreme events such as earthquake or fire. To ensure that the building is resistant to fire, engineers are tending to move toward a performance-based design scheme rather than a prescriptive design for fire. This gives the engineer more flexibility in the design of the structure. For times when the fire cannot be controlled, designers are focusing on new alternative methods of egress from tall buildings including: skybridges to other structures, exterior deployable escape chutes, and flying rescue platforms.

Thesis Supervisor: Jerome Connor
Title: Professor of Civil and Environmental Engineering

ACKNOWLEDGMENTS

I would like to express my appreciation to the Department of Civil and Environmental Engineering. The academic fellowship that was granted to me by the department made my attendance at MIT possible. The excellent faculty and staff helped to make my experience here a very rewarding educational experience.

The people that I appreciate the most, who have been right there beside me through it all, are my fellow M. Eng. students. You helped me work through the difficult times and enjoy the good times. The friendships that I have made will carry on for years to come.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

LIST OF FIGURES

List of Figures (cont.)

TRENDS AND INNOVATIONS IN HIGH-RISE STRUCTURES

BY CHRISTOPHER D. LUBKE

1. INTRODUCTION

Since the square footage of land is very limited in an urban environment, high-rise structures are a highly efficient scheme of maximizing the use of one particular land area. The taller that a building is, the more revenue can be generated from that area. Therefore designers are continually pushing the limits of the height of buildings and the amount of usable space inside the structure.

One method of increasing the height of the building is to improve the structural systems to resist the loads acting on the system more efficiently. Recent designs have involved the use of mega-braced frames that rely on a few very large members to resist a majority of the loads. But, with a fewer number of members, the structures may become less redundant and more vulnerable to unexpected events. Recent studies have been conducted in evaluating the vulnerability of structures.

Another way to extend structures to new heights is to improve the properties of the materials that are used to construct the structure. Many buildings are combining steel and concrete throughout the structure to utilize the most attractive aspects of each material.

New consideration is being given to the issue of fire safety in high-rise buildings. Recent trends are moving away from the prescriptive-base fire design to comprehensive performance-based design in order to give the engineer more flexibility in the building design. New technologies are also evolving to improve the method of egress from tall buildings.

2. *LOADS*

There are two types of loading on any structure: gravity loads and lateral loads. The gravity loads are the same for a high-rise and low-rise structure except high-rise buildings accumulate much more load near the bottom of the structure. Lateral loads, including wind and earthquake, are generally the critical issue associated with tall buildings.

2.1. WIND

Wind loads become a critical element associated with tall buildings. Because it acts as a pressure, a large force is exerted on the large building surface. The intensity of the pressure increases with height. The moment arm to the resultant of the wind pressure as shown in Figure 1 also increase with height.

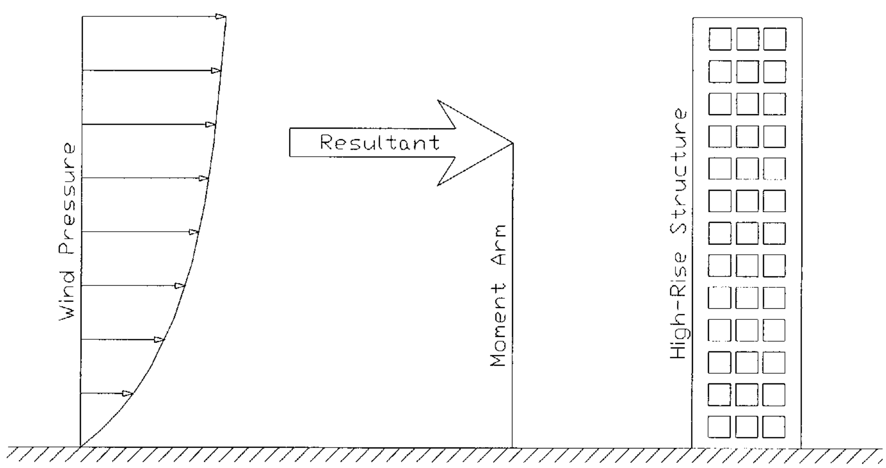

Figure 1. Schematic of Wind Loading on a Structure.

When considering wind loads on high-rise structures, one must be focused on the dynamic effects of the wind. Motion may be induced into the building either along the direction of the wind or perpendicular to the wind direction. The excitation in the along-wind direction is created by the gusty nature of the wind. The perpendicular motion occurs as a result of vortex shedding on alternating sides of the structure (Figure 2). The maximum lateral deflection created by the wind generally occurs in the along-wind direction, while the peak accelerations of the structure occur in the cross-wind direction.

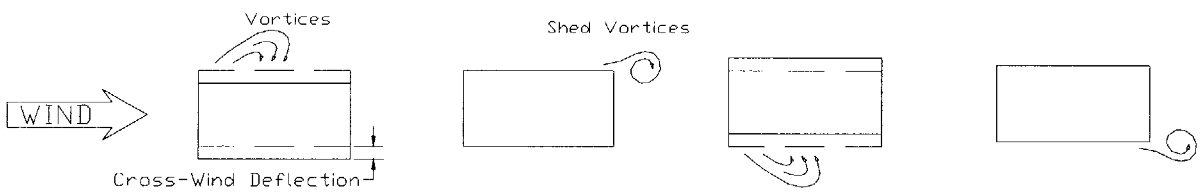

Figure 2. Effect of Vortex Shedding on a High-Rise Structure .

The forcing frequency in the along-wind direction is dependent of the characteristics of the wind in a particular area. A wind gust may have a duration between 2 and 10 seconds depending on the surrounding terrain and meteorological trends. The period of a high-rise building can be estimated by

$$T = 0.1 \cdot N$$

where N: number of stories in a building.

Therefore, tall buildings will have periods in the range of 5 to 10 seconds (natural frequencies between 0.1 and 0.2 Hz.) When the wind gusting frequency nears the natural frequency of the building, the lateral deflections along the wind direction will exceed the static deflections created by the wind pressure on the building.

The frequency of the vortex shedding can be estimated by:

$$f = \frac{V \cdot S}{D}$$

where f: vortex shedding frequency

V: meanwind speed at the maximum height of the building

S: Strouhal number (shape and velocity dependent)

D: diameter of the structure.

When the forcing frequency of the vortex shedding approaches the transverse natural frequency of a building, excessive lateral crosswind deformations may occur, if the structure does not have any significant amount of structural damping. After the structure begins to resonate with the vortices, the forcing frequency tends to "lock-on" to the transverse natural frequency of the structure. Therefore, small changes (±10%) in the wind velocity will not change the behavior of the vortex shedding phenomenon. The vortices will continue to shed corresponding to the oscillations of the structure until the wind velocity has changed beyond the "lock-on" range.

Since the frequency of vortex shedding phenomenon is critical for range of values near the transverse natural frequency of the structure the approximation of the forcing frequency does not have to be extremely precise. This important to a designer since high-rise buildings are generally complex shapes, and the Strouhal number must be determined experimentally.

2.2. EARTHQUAKE

Earthquakes are able to damage a structure not by a direct force as with wind or gravity loads, but by intense vibration. As the building vibrates, inertial forces are developed within the structure simply because there is mass in the structure. Therefore the more mass that a building has, the more susceptible it is to damage cause by an earthquake. Another problem associated with earthquakes is the nonlinear, P-Δ, effects on vertical elements such as columns and walls. When these elements are push out of plumb by the lateral ground motion, they become unstable under vertical loading and more susceptible to buckling.

Earthquakes produce a spectrum of accelerations that are transferred through the soil. For analysis of the structure, one wants to generate a response spectrum of a given design earthquake. The response spectrum shows the maximum response of a damped single-degree of-freedom mass-spring system with respect to the natural period of the system. The response can either be the absolute acceleration, pseudo relative velocity, or relative displacement of the structures. All three characteristics can be represented on a tripartite logarithmic plot.

When performing an earthquake resistant design, it is not necessary to limit the amount of acceleration for human comfort. The goal is to minimize the amount of lateral drift to prevent yielding and buckling of structural members and distress in architectural components such as interior partitions or window glazing.

Since some amount of lateral drift is inevitable during an earthquake, a designer will want to make a structure as ductile as possible. Ductility allows a structure to undergo inelastic deformation without creating a failure or collapse. Concrete is typically a very brittle material, but with proper reinforcement, it can endure large deflections before failure.

Earthquake loads exerted on a structure can either be determined statically by an equivalent force method or dynamically. The 1994 Uniform Building Code requires a dynamic analysis for tall buildings (over 240 ft) in order to evaluate the effects of vibration modes above the first mode. To see the effects of the higher modes, it is necessary to model the structure as a multi-degree of freedom system. This can be accomplished by lumping the mass of the structure at discrete levels corresponding to the floor levels of the building. Then the response of the structure can be analyzed for a particular ground motion depending of the stiffness and damping properties of the structure.

3. *Structural Damping*

High-rise structures are susceptible to dynamic loading and motion problems. To reduce the effects of the dynamic loads, a designer can either increase the stiffness of the structure or implement a damping scheme to dissipate the motion. The damping controls how quickly a vibration induced into the structure is attenuated. Damping can reduce the amount of lateral displacement as well as the lateral acceleration of the structure. When a load acts on a structure, a certain amount of energy is imparted to the structure in the form of strain energy or kinetic energy. Damping is the mechanism that is able to absorb or dissipate this energy. Therefore, there are several different types of damping.

A certain amount of damping is present in almost every structure. In a steel building, structural damping dissipates energy through friction of bolted connections as the connected members are strained. Welded connections do not provide as much structural damping. Concrete buildings develop structural damping as the concrete members undergo micro-cracking. As the micro-cracks are produced, strain energy is release from the structure. Under extreme loading, hysteretic damping comes into effect. This type of damping involved energy dissipation by inelastic deformation or yielding of structural elements.

The naturally occurring damping in a structure is typically not sufficient to meet the demands of a high-rise building. Therefore various devices have been developed that can be installed in a structure to increase the amount of damping. The most basic type of damper is a viscous damper. This device typically involves a piston forcing fluid through an orifice. The force imparted by the device is proportional to the velocity of the piston. These devices are compact and can be installed easily. They can be spliced inline with the cross-bracing of a braced frame structure. As the structure tries to rack, the bracing will be extended and the damper will be actuated.

Other devices can be put in place to utilize hysteretic damping. The objective of these devices is to yield under intense loading before the structure yields. Once the hysteretic damper begins yielding under intense cyclic load such as an earthquake, energy will be dissipated. The dampers may consist of a ductile steel core that is surrounded by a larger jacket to increase the bending rigidity. The bending rigidity allows the device to function in tension and compression (Connor, 2003).

Engineers have also been able to implement damping devices in structures that are "tuned" to the natural frequency of the individual structure. These tuned mass dampers (TMD) involve a large mass that is allowed to move with respect to the structure. The a translational TMD travels on tracks and roller, and a pendulum TMD is simply a mass suspended by a series of cables or rods to form a pendulum. The translational TMD is connected to a spring and damper system that controls the tuned frequency of the device. The frequency of the pendulum damper is modified by selecting the appropriate length of the pendulum.

TMD can be implemented with a new design or used to retrofit buildings that develop unexpected motion problems. One problem of these devices is that they often occupy large amounts of space in a building. TMD have been implemented to reduce motion problems in the John Hancock Tower in Boston, the Citicorp Center in Manhattan, and the Crystal Tower in Osaka just to name a few.

4. *Progression of Structural Systems*

The maximum height of a building is simply governed by the ability of the structure to resist the loads that are acting on it as discussed in the previous section. The method that is used to resist these forces is dependent on the distribution of structural members as well as the properties of the members themselves. Structural systems and material properties are continually evolving in order to more efficiently resist the loads acting on the structure and maximum the amount of usable space inside the building.

4.1. Rigid Frame

The most basic type of framing system is the rigid frame or moment frame system. This scheme consists of moment resisting connections at girder and column joints. The resistance to lateral forces is achieved through bending of girders and columns by the rotation of joints as illustrated in Figure 3. Rigid frames are effective in reducing the maximum moments in the girders under gravity loads. The main problem with rigid frames is that the majority of the lateral deflections of the system are cause by frame racking rather that axial deformation in the columns, or cantilever bending. In order to reduce the lateral deflection, one must increase the bending rigidity of the beams and columns. Typically in high-rise office buildings, large spaces are desired therefore long beam spans are necessary. As the length of the beam increases, the bending rigidity decreases by a power of three. Therefore, the rigid frame is not an efficient system for resisting lateral deformations when the height of the building exceeds about 25 stories (Smith, 1991).

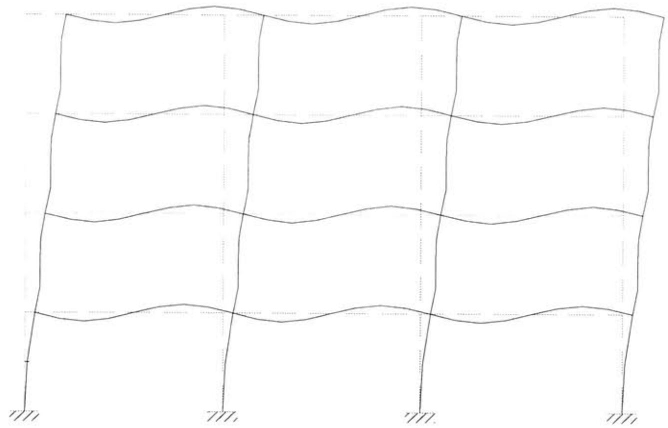

Figure 3. Shear Racking of a Rigid Frame.

The rigid frame can be used with a steel or concrete structure. This type of system lends itself to concrete construction. Since beams and columns are cast simultaneously, the beam-to-column joints are continuous and therefore more resistive to rotation.

4.2. Braced Frame

The braced frame improves on the efficiency of the rigid frame by reducing the amount of bending rigidity of the columns and girders required to resist lateral deformations. As the frame system undergoes shear racking, the diagonal dimension of an individual bay is lengthened, or shortened. If members are extended diagonally across the bay, the lateral drift will be resisted by tension or compression in the diagonal members, and the external columns will resist the tension and compression created through bending as shown in Figure 4. When diagonals are placed on all levels of a frame, the lateral deflection of the frame will tend to behave more as cantilevered beam in bending. Therefore a braced frame is more efficient than a rigid frame since the girder and column elements do not have to resist the lateral loads by rotation of the joints. This bracing scheme can also be achieve in a concrete structure by filling in bays of the frame. As the bay tries to rack, a diagonal compressive force will develop in the filled area.

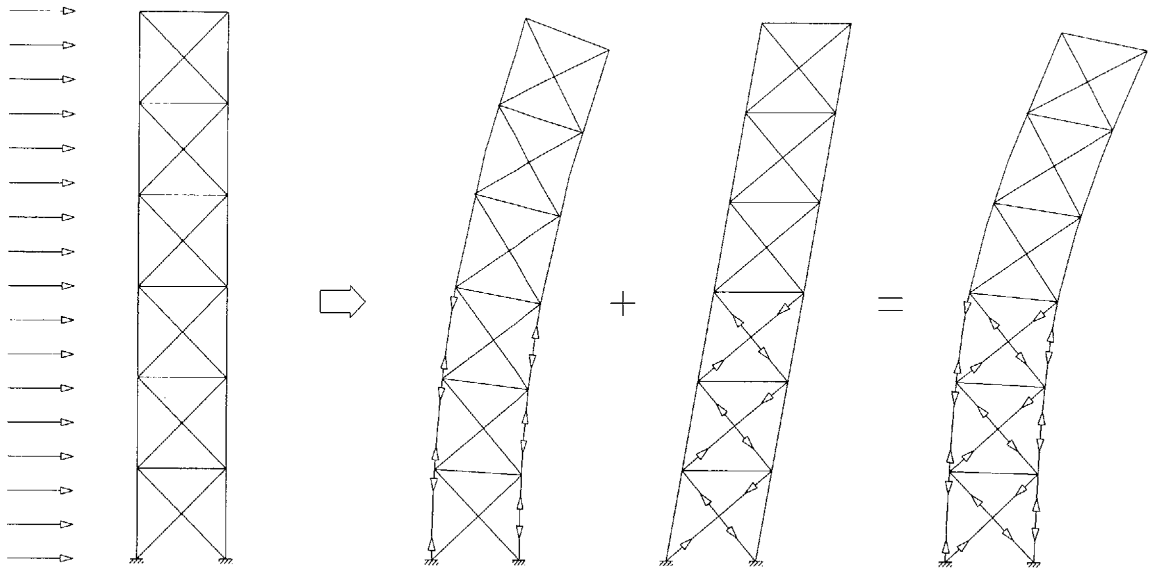

Figure 4. Behavior of a Braced Frame

4.3. ECCENTRICALLY BRACED FRAME

The eccentrically braced system is more ductile than a concentrically braced frame system as discussed earlier. Therefore, it is especially useful in areas with high levels of seismic activity. The diagonal bracing is not connected at the intersection of the beams and columns (Figure 5), but rather away from the column at some eccentricity. The eccentricity is sometimes referred to as a fuse or a link. Under seismic loading, it is necessary for a frame to dissipate energy. One way to dissipate sufficient amounts of energy is through yielding of structural elements. Under intense lateral motion, as the frame racks, the fuse can be designed to yield in shear and dissipate some of the energy generated by the earthquake. Therefore this system is very ductile with respect to lateral loading. And, since the fuse is generally very short, the deflection due to bending of the beam is generally very small. Thus, the elastic stiffness of the system is almost equivalent to that of a concentrically braced system. The problem with the system is that once the system has yielded there are residual deformations in the structure. Therefore, major structural element must be repaired or replaced.

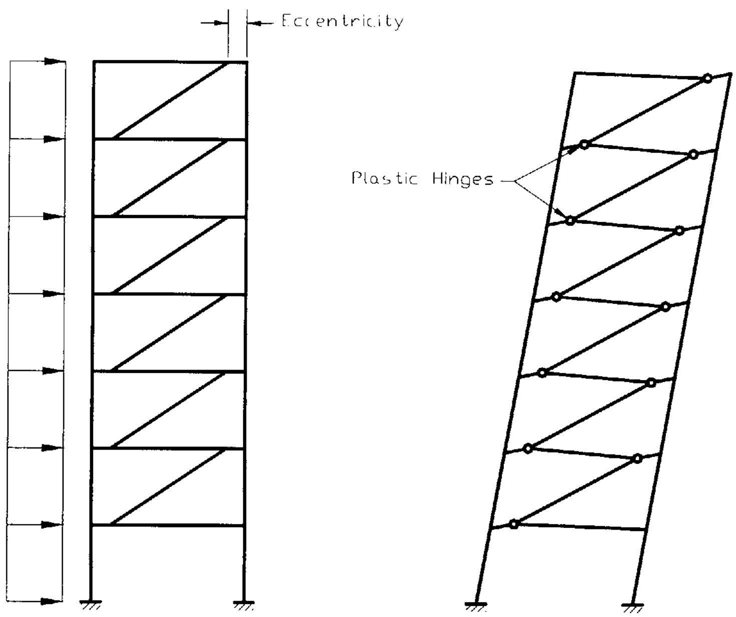

Figure 5. Behavior of Eccentrically Braced Frame.

4.4. Staggered Truss

A staggered truss system (Figure 6) behaves very similarly to a braced frame, but it in certain circumstances, can increase the amount of space between bracing. This type is system is especially useful for hotels or apartments that have regularly spaced units. The trusses serve a dual purpose: to prevent lateral deformations as in a braced frame, and to carry the gravity loads of the floors. The trusses are very efficient carrying the gravity loads since they are essentially beams that have a depth equal to the inter-story height. One truss member supports both the floor below and the floor above, therefore for one particular column row, a truss member is only needed every other floor. The staggered trusses rely on a floor diaphragm to transfer the shear from one level to the next (Figure 6) since the truss member are offset by at least one column row from floor to floor.

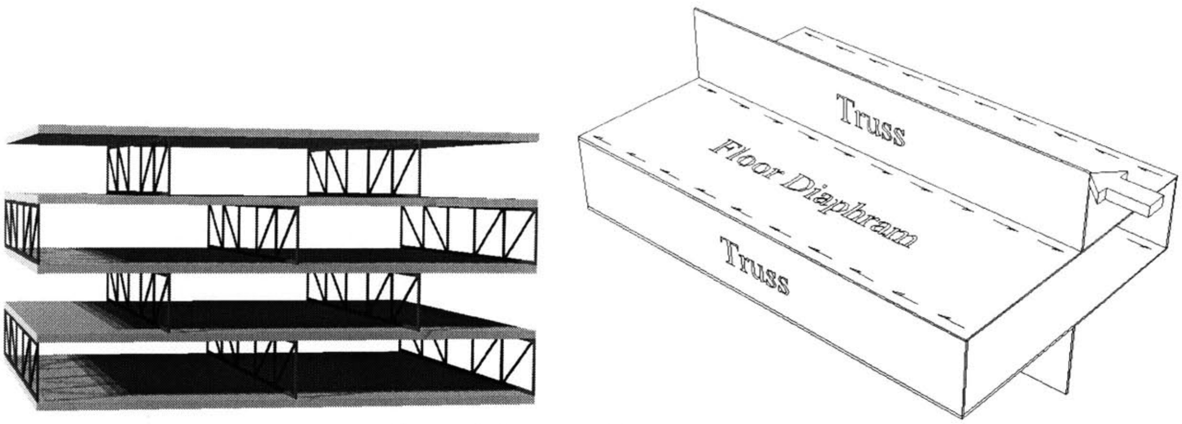

Figure 6. Staggered Truss System.

4.5. CORE STRUCTURES

Another common framing practice is using vertical core elements to resist lateral shear and bending deformations. Typically the core will consist of solid concrete walls that are placed around elevator banks near the center of the building. This type of system is desirable from an architectural standpoint since the primary lateral load resisting elements are hidden in the interior of the building that allows for greater flexibility in the space around the core. The extreme case of a core supported structure involves all of the gravity and lateral loads being carried by the rigid core as shown in Figure 7. The floors for the building are either individually cantilevered from the core or groups of floors can be cantilevered as a unit. Since the core element is not deep in respect to bending, it is not an efficient element in resisting the lateral loads. And, supporting the floors loads by a cantilever with one concentrated moment at the core is also highly inefficient (Smith, 1991).

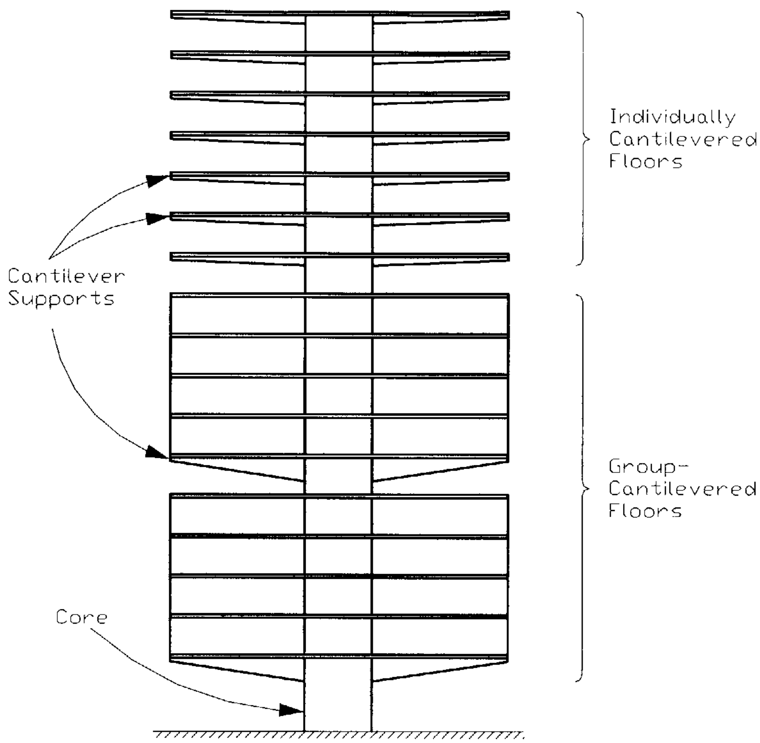

Figure 7. Schematic of Core Supported Structure.

4.6. FRAME-SHEAR WALL INTERACTION

Another type of system is a shear wall frame system. This system is quite efficient because the shear wall and frame react to lateral loads in different manors. The actions of the two different systems tend to oppose one another by the modes of deformation that creates interlacing forces between the systems (Figure 8). The shear walls acts as a deep cantilevered beam under lateral loading. The curvature of the shear wall is small near the ground and increases along the length of the member. The frame deflects by shear racking, producing a linear deflection along the height of the structure. Therefore, at the base of the building, the shear wall has very little curvature, therefore it is restraining the frame from lateral displacements. At the top of the structure, the curvature of the shear wall is restrained to the angle of the linear shear of the frame. This type of structural system is applicable for structures of 40 to 60 stories (Smith, 1991). The relative stiffnesses of the shear wall and the frame need to be constant for this principle to work. Discontinuities in the shear wall also present problems. Openings in the shear walls cause them to behave as a frame in shear unless proper reinforcing is placed around the opening.

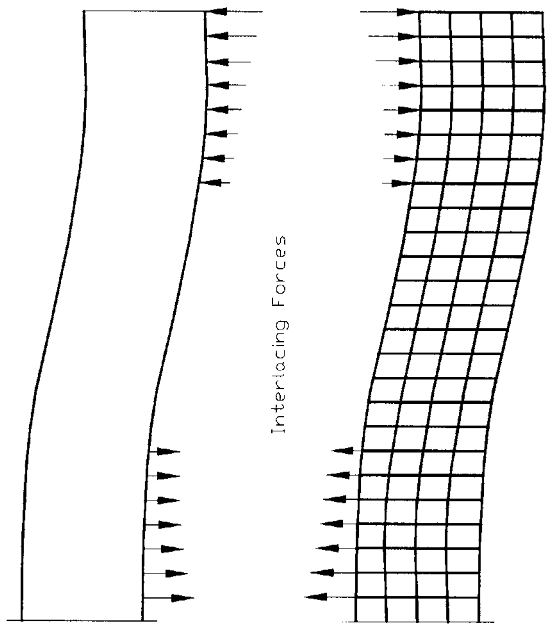

Figure 8. Behavior of Shear Wall-Frame Interaction.

4.7. *Outrigger Braced Structure*

As the height of a building increases, one wants to maximize the bending rigidity of the structure by increasing the moment of inertia of the overall structure in order to minimize the amount of lateral drift. This is accomplished by placing many of the structural elements around the perimeter of the structure. One ways of mobilizing perimeter structural elements is to use the outrigger and belt truss system. This system generally consists of a stiff central core with stiff outriggers cantilever out from it (Figure 9). The outriggers are then tied to exterior columns. Therefore whenever the central core begins to bend, the outriggers will want to rotate. The rotation is restrained by axial action of the exterior columns. Cables could also be used for tying the outrigger arms together vertically or tying them to the ground.

For this scheme to be effective, it is necessary to have very stiff outriggers, so truss members with depths of one or two floors are generally required. The truss members can be continued around the perimeter of the structure, to form a belt truss, to incorporate more of the axial elements, columns or cables, into the structural scheme. The outrigger effect can also be achieved by extending diagonals from the core down and across two floors to the perimeter columns. The outrigger system dramatically increases the bending rigidity of the structure, but the shear rigidity is still dependent on the resistance of the core.

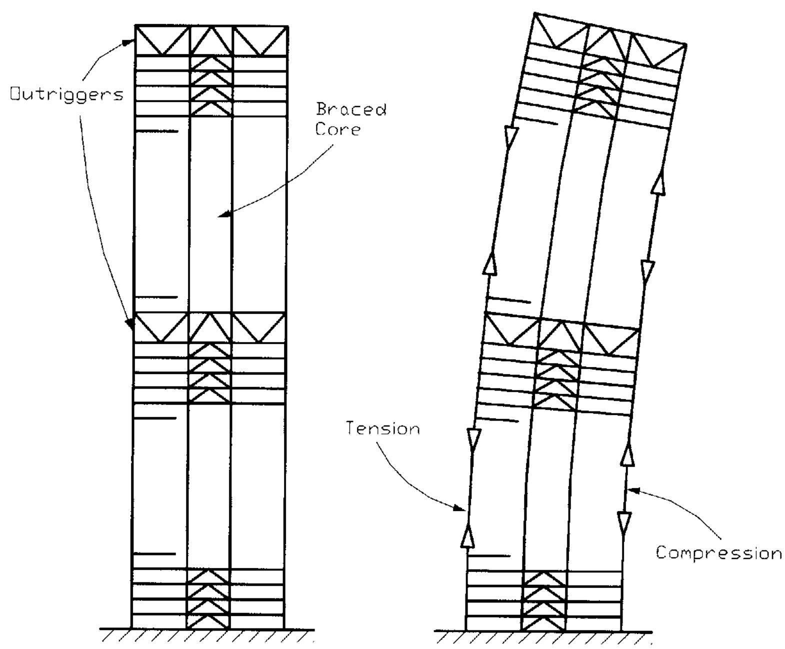

Figure 9. Behavior of Outrigger Braced Structure Under Load.

An outrigger structure can be modeled a cantilevered beam with rotational stiffeners at the location of the outrigger arms. The rotational stiffeners reduce the amount of rotation in the cantilevered beam at discrete locations that results in an overall reduction in the amount of lateral displacement at the top of the member. The outriggers also reduce the internal moment of the cantilevered beam. The outrigger model, a comparison of displaced shapes, and a comparison of moment diagrams for the modeled structure is included in Figure 10.

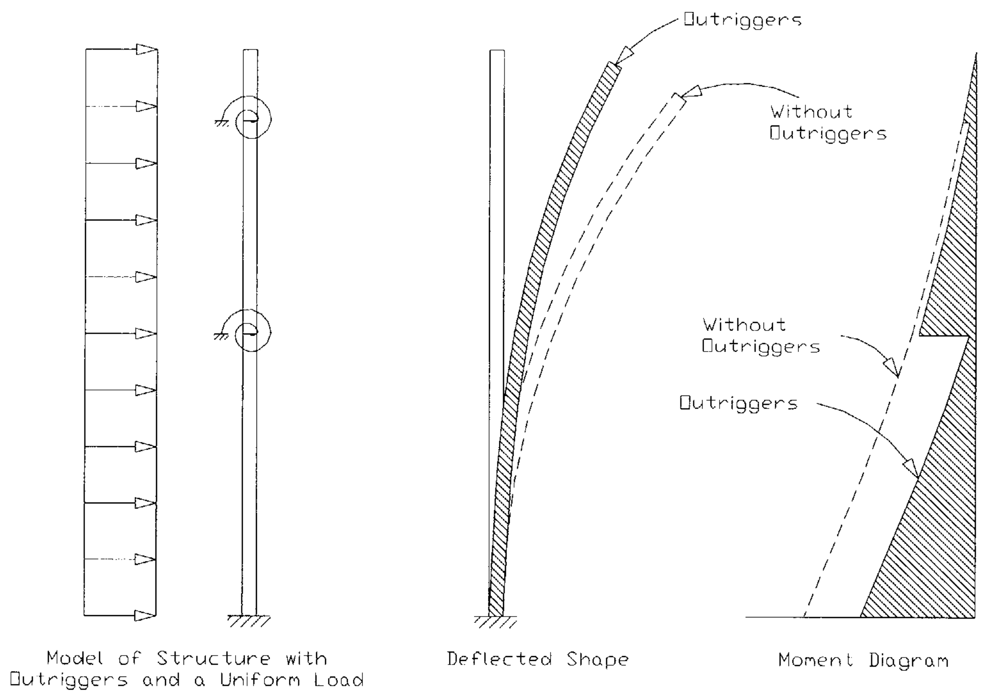

Figure 10. Model of Simplified Structure With Outrigger Bracing.

4.8. TUBE STRUCTURES

The framed tube structure involves many closely spaced columns around the perimeter of the building. The columns are connected by deep spandrel beams to reduce the effects of shear racking. The structural behavior of the framed tube structure is analogous to a cantilevered wide-flange beam. When lateral forces are imposed on the structure, the faces normal to the wind act as the flanges to resist bending. The sides of the structure function as a web to resist shear. The columns of a tube structure are usually oriented such that the stronger axis of bending is parallel to the exterior wall as shown in Figure 11. This increases the structural resistance to shear racking.

The most important factor in framed tube structures is the shear lag phenomenon. This creates increase stress at the corners of buildings (Figure 12), and reduces the bending stiffness from the idealized beam bending theory. The efficiency of the system is not achieving its maximum potential since the system is not fully utilizing the axial capacity of the columns normal to the direction of bending. This type of framing can also result in large lateral deflections due to shear racking even with the deep spandrels.

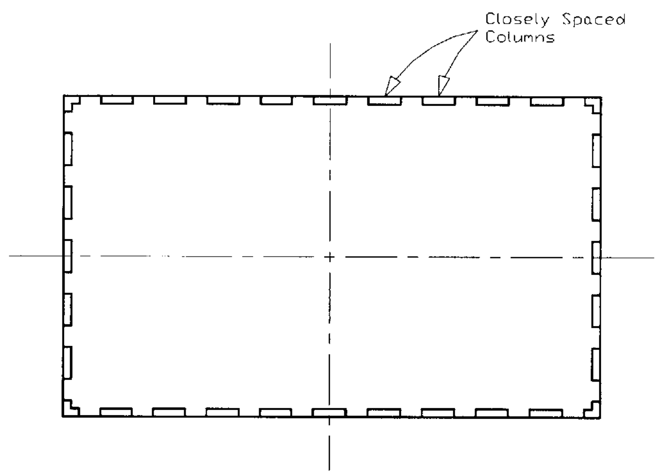

Figure 11. Plan View of Tube Structure.

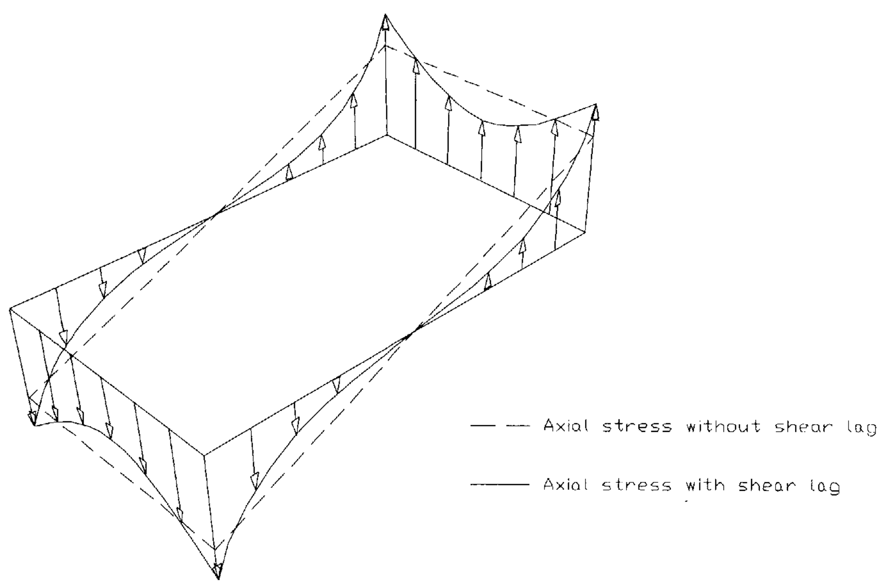

Figure 12. Illustration of the Effects of Shear Lag.

Much consideration has gone into the analysis of the effects of shear lag. Lee (2002) developed a method of analysis in order to quickly estimate the effects of shear lag. This is necessary during preliminary design phases before a full mathematical model can be analyzed.

By adding large truss elements around the perimeter of a tube structure (Figure 13), creating a braced tube structure, the bending stiffness can be increased. Diagonal truss elements diminish the effect of shear lag to produce a more efficient tube system. Since shear lag is not a problem, the size of columns and spandrels can be reduced and the column spacing can be increased. The efficiency of a tube structure can also be increased by grouping multiple tube structures together to form a bundled tube structure as shown in Figure 13.

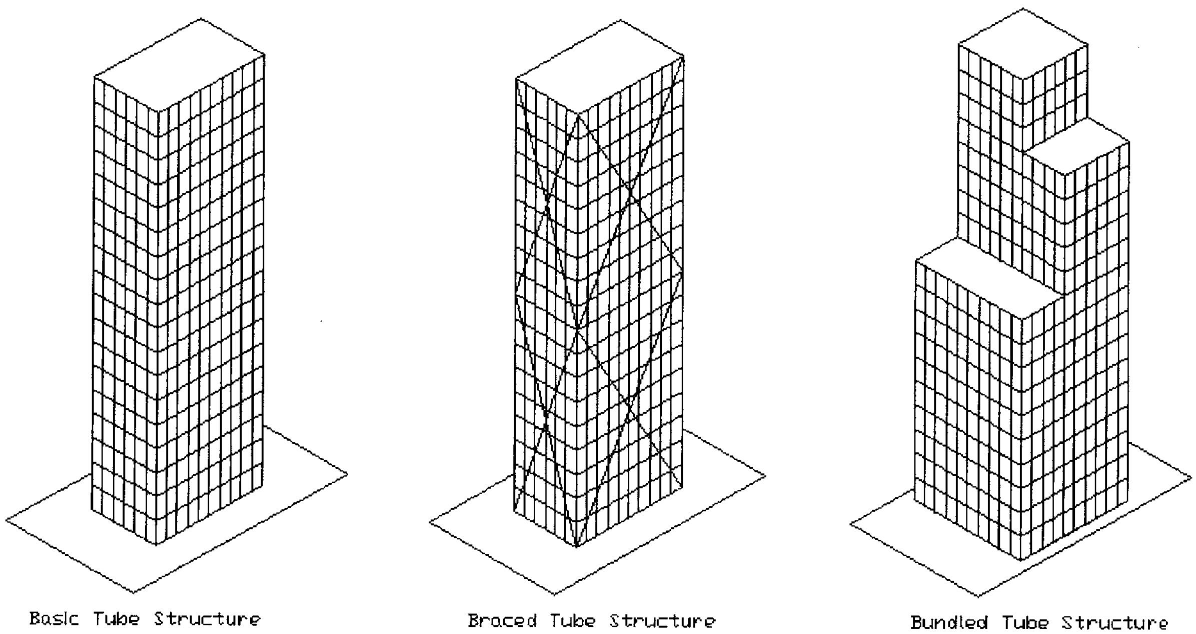

Figure 13. Schematic of Tube Structures.

4.9. HIGH-EFFICIENCY MEGA-FRAMES

Dr. Fazlur Kahn has shown that the most efficient system involved a rectangular trussed tube with only four corner columns (Taranath, 1998) as illustrated in Figure 14. The mega-columns and large mega-braces around the perimeter of the structure carry a majority of the gravity and lateral loads. Interior columns are only need to setup the floor system of the structure. Transfer girders are needed to collect the loads from the interior and transfer them to the exterior columns and bracing. These transfer elements can be implemented as various heights throughout the structure to allow groups of floors to have a framing system that is appropriate for the use of the floors. Office spaces generally require large spans between the columns, where as apartments units can have closely space columns for a more intimate environment.

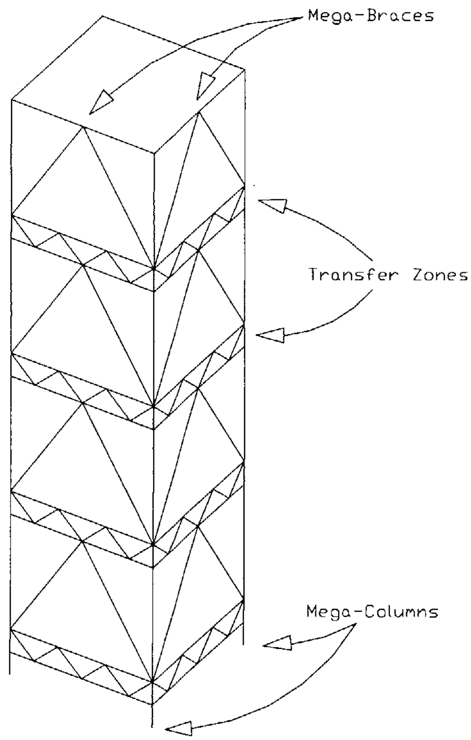

Figure 14. High Efficiency Structure.

4.10. TRENDS OF STRUCTURAL SYSTEMS

For pure concrete buildings, the progression of the structural system has dramatically increased the height to which concrete high-rises can be built. Figure 15 shows the limiting heights of the various structural systems when built out of concrete (Ali, 2001).

In the past, the structural system has been limited by the modeling techniques. The structural system had to be uniform so the structural analysis could be approximated accurately (Smith, 1991). Very complex systems could not be accurately evaluated by hand and computer processing power was limited. Since computer technology has been evolving, so has the complexity of structural systems. Current trends show many modern high-rise buildings are using a combination of structural systems throughout the building to form hybrid structures.

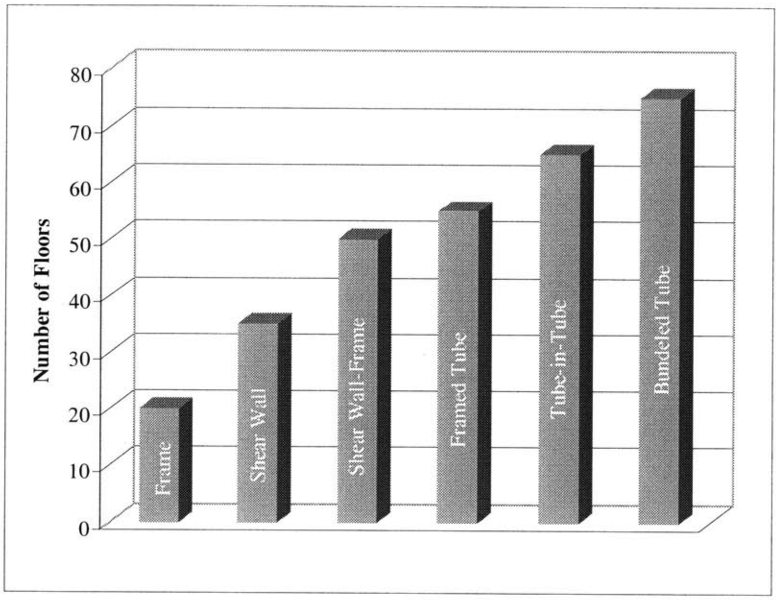

Figure 15. Maximum Height of Concrete Structural Systems (Ali, 2001).

5. *ADVANCEMENTS OF MATERIALS*

In the early 20th century, the maximum height of buildings was severely limited. Buildings did not extend to great heights until the development of structural steel. Steel has a relatively high strength to weight ratio, is easily erected, has long spanning ability, and can be used is many different types of structural schemes. In the mid- 1900's, reinforced concrete was not very attractive structural material for use is very tall buildings because it is very labor intensive and time consuming. Recent innovations in concrete material, forming, and placement has made reinforced concrete a much more viable option for high-rise buildings. Combining steel and concrete in high-rise buildings has also allowed the structures to sore to new heights in recent years. Figure 16 shows the breakdown of the 200 tallest buildings (data is taken from ATop@ 2003) according to the construction material that was used. It shows that a majority of the buildings are constructed of steel, but the concrete and composite structures do not appear in the top 200 until the 1970s as shown in Figure 17.

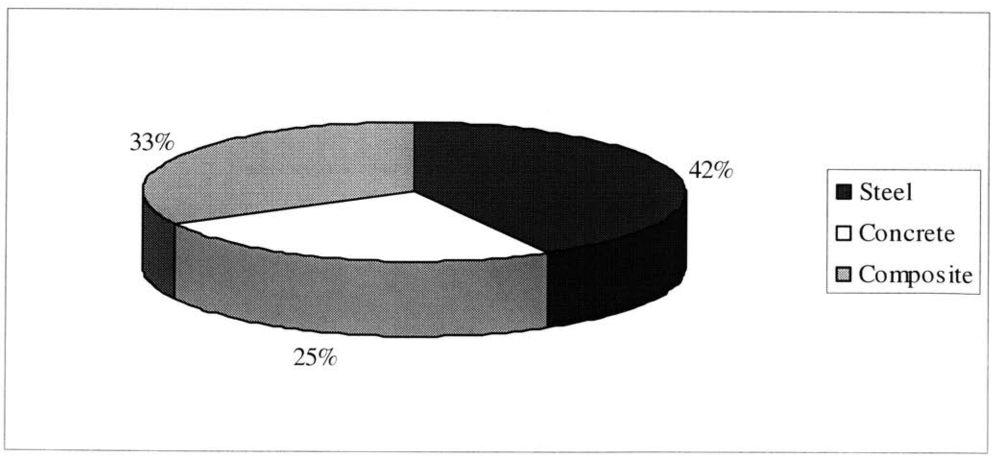

Figure 16. Tallest 200 Buildings.

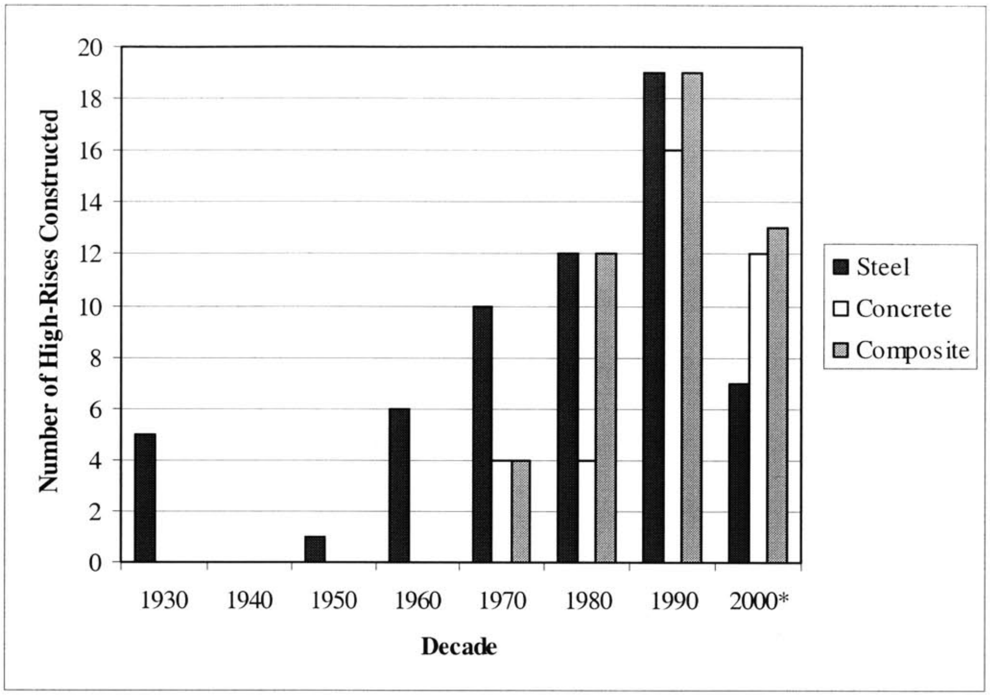

Figure 17. Tallest 200 Buildings by Decade

Improvements in the properties concrete have created a drastic shift in the use of concrete in high-rise buildings. One can see in Figure 17 that the number of concrete high-rises amongst the top 200 buildings dramatically increased between the 1980s and the 1990s. New types of forming, such as slip forms and jump forms, allow the construction on concrete structures to progress more efficiently. Improvements on the strength of concrete reduce the amount of material need and therefore reducing the weight of the structure. A light structure results in smaller columns and less load exerted on the foundation. Higher strengths of concrete also improve the durability of the material.

New high performance concrete reduces the amount of time to maturity from seven days to just 24 hours (Mir, 2001). It can also be designed to increase the ductility of the structure. Ductility is an important characteristic for reinforced concrete structures during extreme loading events such as earthquakes. One method of improving the ductility is by adding various types of fibers to the mixture. Fibers could be steel, fiberglass, or polypropylene. Slurry infiltrated fiber concrete (SIFCON) is another method being developed for improving the ductility of concrete. This consists of a layer of fibers that is infused with a concrete slurry. The fibers occupy about 10% of the volume of the material which is much higher than other concrete mixed with fibers. This material has deflection characteristics similar to that of a steel slab (Walraven).

Within the past decade, high-rise structures have begun to fully integrate steel and concrete throughout the building to maximize the efficiency of the structure. By combining steel and concrete, one can use the material that is most effective for one particular region of the structure. Steel has the ability to span large distances and can be easily and quickly erected, while concrete is very durable and easily formed to custom shapes. Figure 18 shows that composite (steel/concrete) structures have been the tallest structures in recent years when compared to steel and concrete structures.

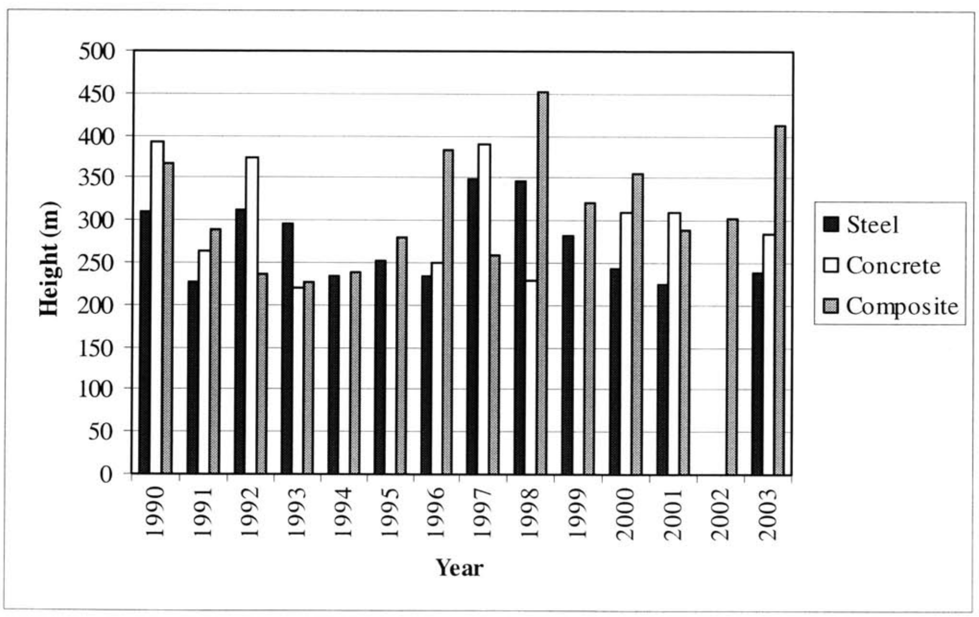

Figure 18. Height of 200 Tallest Buildings.

Composite decks and composite girders have been used for several years. Composite decks employ a light-gage steel corrugated deck to supports the concrete slab and functions as tension steel on the bottom of the slab. Composite girders use steel shear studs along the top of the girder to develop composite shear action at the interface between the steel and concrete.

One of the most widely used composite elements is the composite column consisting of a steel pipe or tube filled with high strength concrete. A composite column could also involve a steel element that has been embedded in concrete. The first type is generally easier to construct since the steel pipe serves as the formwork. In both cases, typically the steel section is sized to support the construction loads. The concrete casting lags behind the steel erection and the concrete only needs to reach maturity by the time significant loading is added to the structure.

The steel section encased in concrete is generally only used for exterior columns since the transfer of formwork from one story to the next is easier along the exterior of the structure. This type of composite column also requires additional transverse reinforcement to provide the necessary ductility for cyclic loading such as earthquakes.

The concrete-filled column is very efficient in construction since no formwork is necessary and longitudinal and transverse steel can usually be eliminated. This type of element could also be employed as a diagonal member. Several performance issues of these composite columns have yet to be answered. Further study is needed on the bonding action between the steel and concrete. In some instances, shear studs have been employed on the inside of the steel pipe to insure that the composite action is achieved. Little is known about local buckling of the steel along the length of the member or the performance of the member when loaded beyond the point of yielding.

Research has been done on the concrete filled columns concerning the biaxial stress of the steel section. When an axial load is imposed on the composite member, the steel is strained circumferentially as wells as axially when the concrete tries to expand. This biaxial state of stress decreases the maximum force that can be exerted on the member. To avoid this problem, Aboutaha et. al. (1998) suggests the use of steel confined reinforced concrete columns. These columns involve a typical reinforced concrete column with a steel pipe section around it, but the steel section is terminated just short of beam joints. Therefore, the steel pipe does not undergo direct axial compression and the strength characteristics of the steel are improved. In this situation, the steel is function only as a confinement jacket for the concrete and not as an axial loaded column.

Continual research and advancement of construction materials greatly benefits the extents to which high-rise building can reach. Materials are becoming lighter and stronger therefore making structures more efficient in resisting the loads acting on the structure

6. *Efficiency vs. Redundancy*

Innovations in high-efficiency structural systems, such as mega-braced frames, using composite elements with high strength materials have resulted in fewer columns carrying a majority of the load. As the efficiency of a structural system is maximized, the degree of redundancy is reduced. The structure becomes very vulnerable to unpredictable events. Even though the vulnerability of the structure is increased, the composite elements may be sufficiently robust in order to resist unpredictable events individually (Abdelrazaq et. al,).

Redundancy can be defined in a number of different ways. Bertero et. al. (1999) was able to distinguish between the redundancy associated with a pseudo-static earthquake analysis and a dynamic earthquake analysis. The degree of redundancy for a pseudo-static case is the number of plastic hinges "that must yield or fail to produce the impending collapse of the structure under the action of monotonically increasing lateral deformations" (1999). Therefore, a push-over analysis of the structure under the equivalent static lateral forces can be used to determine the degree of redundancy. Figure 19 shows examples of the degrees of redundancy in a frame for the pseudo-static loading case. For a dynamic case Bertero et. al. (1999) determined that the degree of redundancy is dependent on a time history analysis of the structure under earthquake ground motions. It is the number of plastic hinges the must fail concurrently to create a structural collapse.

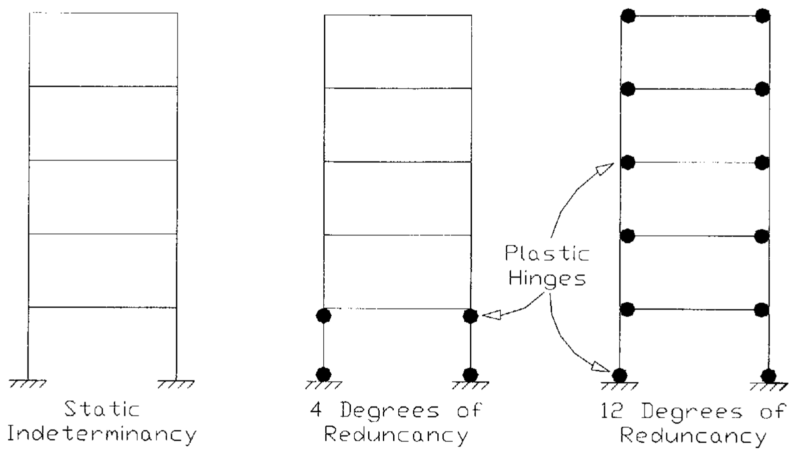

Figure 19. Static Redundancy Under Earthquake Ground Motion.

Structural innovation has resulted in projects that extend beyond the limits of typical design code. Therefore it becomes the responsibility of the engineer to assess the amount of risk that is inherent in the structure and apply an appropriate design to insure that the occupants of the building are safe. Extensive study has been done concerning the assessment of structural vulnerability and risk. In the design of high-rise buildings it is essential to resist progressive collapse by a small, or disproportionate, amount of damage. The University of Bristol has developed a structural vulnerability theory that examines the connectivity of the structural elements in order to identify failure modes. When combined with structural response and reliability analysis, an assessment of risk and susceptibility of progressive collapse can be determined (Blockley, 2002).

Melchers (2002) suggests the need for structural engineers to implement risk assessments for buildings similar that which are done for hazardous facilities such as nuclear power plants. This would allow the engineers to evaluate the potential of “low-probablitity—high-consequence” events such as acts of war or terrorist attacks. As high-rise buildings grow taller and taller, the consequence of such events is also increased.

7. *Performance-Based Design for Fire*

When designing a building, one is required to ensure that the structure can withstand the forces that are acting on it in order to keep the occupants safe. Therefore, it is also necessary to study the effects of the structure during a fire and design the structure to withstand the blaze and not allow a catastrophic collapse.

Generally, fire resistive requirements of a structure are based on the types of materials composing the structure. Building products are tabulated with various fire ratings, and depending of the type of occupancy, the fire rating must be kept under a certain level. This prescriptive type of design does not directly consider the structural integrity of the members and is difficult to tailor to specific structural designs. Current trends in fire safety regulation are moving toward performance-based regulation. According to Kokkala (1996), a performance-based approach can allow for a 5% savings on total construction cost without compromising any of the safety of the building. As technology is rapidly developing, computer simulation of the behavior of fires is improving. Such analysis allows the engineer the study the effects of a particular structure under an arbitrary fire situation. This is an integral part of performance-based design for fire protection.

Solomon et. al (2002) determined that there are several elements of performance-based design that will benefit the engineers and designers. A design can be highly specialized to serve a specific function or hold some aesthetic quality. The engineer can reduce any unnecessary redundancies of a prescriptive code that does not benefit the fire protection system. A performance-based design also allows for more innovation of fire protection methods to be developed.

There are several elements that need to be considered during the structural design of a building when conducting a performance-based fire safety regulation. When building materials are exposed to the extreme heat of a fire, the mechanical properties of the materials are changed. These changes generally results in lower strengths and stiffnesses of the structural elements. Additional internal forces are also exerted on the members due to the extreme high temperatures. All of these issues decrease the total resistance of the element to structural loads.

Since the occurrence of a fire has a relatively low probability, building codes have implemented factors that reduce the amount of total load that each element is required to resist while exposed to a fire. And, since a fire is considered to be an extreme event, it is not necessary to design for deflection under extreme heat conditions.

Redundancy is essential to implement in a structure in order to withstand fire damage. Fire damage is usually localized but could cause failure of major structural elements in the small area. If the structure has redundancy incorporated, the forces that were carried by the failed structural member can be redistributed to other elements that have significant reserve strength. Any amount of redundancy is generally effective since the structure is generally not under extreme loads in the event of a fire. To be effective during a fire, a redundant structure needs to be very ductile in order to accommodate large deflections.

The effects of fire damage are largely dependent on the type of structural material and the amount of fire protection that is provided to the structural elements. Steel elements can be extremely vulnerable to fire since steel has a high thermal conductivity and the members are usually thin. Therefore the heat propagates throughout the member quickly and causes a reduction in stiffness and in strength. Thermal expansion of steel members can cause damage to the structure away from the blaze. Figure 20 shows the deformations that can occur from a fire in one isolated area of a building. As the beams expand and force the columns to deflect out of plane, non-linear P-Δ effects become critical. All joints must remain intact to allow for such deformations.

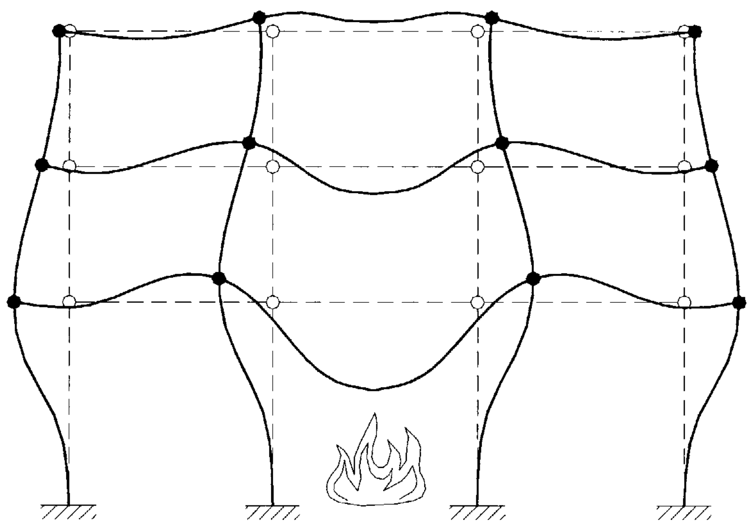

Figure 20. Deformations of a Frame Structure Created by an Isolated Fire.

There are several ways to improve the fire-performance of a steel structure. One method is to surround the steel with concrete. Besides reducing the temperature effects, the concrete also prevents corrosion, improves durability, and can be designed to be load bearing as well. This type of construction can be difficult to form around interior columns and is expensive if only considered as a fire protectant.

A substantial amount of research has also been conducted on fire exposure of concrete-filled composite columns. The concrete is very beneficial to the performance of the member. It is able to absorb the heat that is transfer to the steel and slow down the rate of heating of the steel. The concrete can also carry the axial load of the column as the steel section begins to lose strength the temperature increases. It has been determined necessary to have holes drill at every floor in order to allow the steam from the concrete to be released and prevent bursting of the steel (Buchanan, 2001).

Another fire protection system involves encasement with gypsum or calcium silicate board. These boards are easy to install and provide a good surface for interior finishing. Replacements is usually required if the boards are exposed to a fire.

Spray-on fire resistant systems are usually the cheapest and easiest to apply to steel members. The effectiveness of spray-on systems is strongly dependent on the adhesiveness of the material to the steel elements. The spray-on material could either be a cement-base with fiber reinforcement or intumescent paint that swells up when heated. Areas that are vulnerable to damage must be protected to insure that the material is not removed. The intumescent paint is more attractive for exposed members since the cement-based concoction is very thick and messy. Intumescent paint cannot be casually inspected since one cannot easily determine the thickness of the paint layers.

Concrete is generally less susceptible to fire damage than steel since it has a low thermal conductivity. But, concrete becomes vulnerable when the temperature is high enough to cause the cover to spall off. High strength concrete seems have more problems with explosive spalling than normal weight concrete. Lightweight concrete has more fire resistance than normal weight concrete. Since the lightweight aggregates are products of a high temperature process, their properties are nearly constant at elevated temperatures (Buchanan, 2001). Fiber reinforced concrete can behave well when exposed to fire depending on the type of fibers that are used. Polypropylene fibers melt and form passages for the steam to escape from the concrete and therefore spalling is reduced.

8. *EMERGENCY EGRESS*

Since the event of a fire is somewhat inevitable, and it would not be economically feasible to design a building to be totally fireproof, extensive consideration has been given to the exiting procedures in high-rise buildings. When dealing with very tall buildings, the typical exit path down a stairwell may consist of 50 or more stories of decent. During an emergency situation, the stairways become congested and the rate of decent is slowed. It has been proposed to implement wider stairways and corridors on the lower floors of skyscrapers to allow for the accumulation of traffic near the bottom floor to flow easier. But, this obviously uses an exorbitant amount of space and is not economically attractive.

So how can appropriate paths of egress be provided? Several new methods are being considered that have not be used in the past. In areas that are highly urbanized, one may consider extending escape routes to other adjacent buildings. This would be a relatively simple fix that could serve as escape routes for either building. This would also be a passive system that would not require any mechanical maintenance. Having a sky bridge to an adjacent building would also allow for occupants of the floors above the damaged level to evacuate the building safely.

Recent study has also focused on using various types of egress paths along the exterior of the building. Deployable chutes could be installed along the perimeter of the building inside a removable spandrel panel just below the floor slabs. The chutes would be fabricated from a fire proof, high tensile strength textile. In an emergency the chutes could be deployed manually or automatically. Manual operation would be desirable in the event of power failure. Since fires or other emergencies are usually limited to a couple of floors the escape chutes may only need to extend four or five floors to allow occupants to avoid the damaged area. They could also be deployed at multiple levels to allow for a continuous escape route to ground level if necessary. One could also consider using deployable devices that extend across to adjacent buildings. The occupants could then use the standard egress paths of the other building.

A technique that would be simple to implement is the use of perimeter wall rescue vehicles. This type of vehicle is what is normally used for window washing and other exterior maintenance. The unit is simply lowered from a support structure at the top of the building to collect trapt occupants and lower them along the façade of the building to the ground level. These systems are usually driven with a mechanical wench system that would be inoperable in a power outage; therefore manual systems need to be considered.

Another more complicated method of egress from tall buildings could utilize emergency rescue platforms. These vehicles would essentially be a hovering platform that is controlled like a helicopter. A greater amount of risk is associated with the successful transfer of building occupants to the flying platform than the other evacuation methods.

The new World Financial Center in Shanghai will incorporate refuge floors every fifteen levels. These floors will be essentially fire proof and contain no furniture. There sole purpose will be to act as a safe haven for the occupants of the building until further evacuation procedures occur.

There are many alternatives for evacuation of very tall buildings currently under consideration. All of the systems discussed provide another egress option for the occupants in case the primary path, usually down a central core, is damaged. Providing this additional path of egression is the same as implementing rdundancy the structural system. Having a more redundant structure will lead to a safer and more reliable structure.

9. *CASE STUDIES*

9.1. PETRONAS TOWERS, KUALA LUMPUR, MALASIA

The Petronas Towers (Figure 21), the world's tallest buildings, were completed in 1998 in Kuala Lumpur. The towers extend to 1,483 ft (452 m) with 88 floors above ground and 5 floors below ground. The programming of the building is divided among office, retail, and entertainment space. The structural engineering was complete by Thorton-Tomasetti Engineers.

Figure 21. Photograph of Petronas Towers (Bocaling, 2000).

The lateral structural system involves a reinforced concrete core and mega-columns that connected by ring-beams along the perimeter of the building. The concrete core has a maximum dimension of 75 ft at the base of the towers and tapers to 62×72 ft. The columns have diameters up to 7.8 ft (2.4 m). The concrete used in the structure have compressive strengths from 5,800 up to 11,600 psi. The mass and stiffness of the concrete was appropriate for the lateral system, but steel was used for the floor system to speed up the construction process and take advantage of the spanability so interior columns would not be required. A 2-story deep outrigger connects the core to the perimeter columns at level 38 to increase the efficiency of the lateral system. The structural scheme holds the lateral drift angle to 1/560.

Since the two towers are in close proximity, it was necessary to conduct wind tunnel test to evaluate the coupled effects of the wind between the two towers. With a design 3-sec mean wind speed of 78 mph (35.1 m/sec) at a height of 33 ft (10 m), the maximum acceleration was only 20 milli-g. This is below the acceptable level of acceleration of 25 milli-g. The fundamental period of the towers was determined to be 9 sec.

9.2. Jin Mao Tower, Shanghai, China

Completed in 1998, this 1381-ft (421-m) tall mix-use high-rise structure is the tallest building in China and the forth tallest building on the planet behind only the Petronas Towers of Kuala Lumpur and the Sears Tower of Chicago. The 88 floors of the Jin Mao Tower (Figure 22) are composed of 50 stories of office space, 36 floors of a hotel, and two floors for a restaurant and an observatory. The architecture of the building utilized traditional Chinese forms and employees a tapered tiered scheme similar to that of Chinese pagodas. The architecture and structural design was performed by Skidmore, Owings, and Merrill.

Figure 22. Photograph of the Jin Mao Tower (Shanghai, 2003).

The lateral rigidity of the tower was achieved by employing a steel/concrete composite structure. The structural scheme involves a combined core structure and outrigger bracing scheme. The exterior columns are composite mega-columns composed of a steel sections encased in a rectangular concrete section. The dimensions of the mega-columns range from 3×11 ft to 5×16 ft. The concrete has compressive strengths ranging from 5000 to 7500 psi. The mega-columns are connected to the reinforced concrete core by 2-story deep steel outrigger trusses at three levels: 24-26, 51-53, and 85-87.

The earthquake loading that the structure was designed for was similar to the 1994 UBC, Zone 2A earthquake. The structural design was controlled by the dynamic wind behavior of the structure. The wind loading consisted of 100-yr return wind speed, which is equivalent to a 10-min sustained wind at 75 mph (33.5 m/s). Aeroelastic wind tunnel tests were performed to asses the magnitude of accelerations that the building would experience under the wind loading. An inherent structural damping of 1.5% was assumed for the testing. The results showed the fundamental period of the building to be 5.7 sec, and the accelerations for a 1-yr wind was only between 3 and 5 milli-g (g = 32.2 ft/sec^2, 9.81 m/sec^2). A 10-yr wind only produced accelerations on the order of 10 milli-g. Load return periods were tested since accelerations from wind loading are a serviceability requirement. The accelerations are well below the acceptable level of acceleration at 25 milli-g; therefore the designers decided that mechanical dampers were not necessary for this building.

The drift of the tower under a 50-yr return wind loading and 2.5% damping is only 1/1142. The drift angle is estimated to be 1/857 after two nearby proposed high-rises are constructed. Even under an equivalent 3000-yr wind, the drift is only expected to be on the order of 1/575. This tower is obviously very rigid with respect to lateral loading since typical acceptable drift angles are on the order of 1/200.

The Jin Mao Tower is a good example of a modern high-rise structure that uses a combination of structural systems and materials. The integration of steel and concrete is a hybrid structural scheme maximizes the efficiency of the structure in resisting the gravity and lateral loading.

10. Conclusion

High-rise buildings have progressed in a number of ways: advancement of the structural system, improvement of the materials, and better egress strategies. Such progress allows for buildings to be built taller and safer. Advancements of computer technology has allowed for the development of hybrid structures that were previously difficult to model. Fiber reinforced concrete ads a significant amount of ductility to concrete, and it can be very resistant to fire when polypropylene fibers are used. Recent trends are attempting to move away from the typical prescriptive design for fire resistances and focus on performance-based design. And, for instances when the fire cannot be controlled, new egress strategies such as deployable chutes will allow the occupants to evacuate quickly and safely. As long as all of these areas continue to be developed, one can only guess at what heights that future high-rises will reach.

A1. References

Abdelrazaq, A. K., and Sinn, R. C. "Robustness and Redundancy Design for Tall Buildings."

Abouthaha, R. S., and Machado, R. (1998). "Seismic Resistance of Steel Confined Reinforced Concrete (SCRC) Columns." *Struct. Design of Tall Build.* John Wiley & Sons. New York, NY.

Ali, M. M. (2001). "Evloution of Concrete Skyscrapers: from Ingalls to Jin Mao." *Elctrnc. J. of Strct. Engng,* EJSE, 1(1).

Baker, W. F. (2001). "Structural Innovation." Sixth World Congress on Tall Buildings and Urban Habitat. Melbourne, Australia.

Bocaling, A. (2000). "Petronas Towers." <http://www.greatbuildings.com> (May 11, 2003).

Bertero, R. D., and Bertero, V. V. (1999). "Redundancy in Earthquake-Resistant Design." *J. of Struct. Engng.*, ASCE, 125(1), 81-88.

Blockley, D. I., Agarwal, J., Pinto, J. T., and Woodman, N. J., (2002). "Structural Vulnerability, Reliability, and Risk." *Prog. Struct. Engng Mater.* John Wiley & Sons. New York, NY.

Buchanan, A. H. (2001). *Structural Design for Fire Safety.* John Wiley & Sons. Chichester, UK

Kokkala, M. (1996). "Fire Safety of Buildings: Trends and the Roel of CIB W14."

Lee, K., Lee, L., and Lee, E. (2002). "Prediction of Shear-Lab Effects in Framed-Tube Structures with Internal Tube(s)." *Struct. Design of Tall Build.* John Wiley & Sons. New York, NY.

Melchers, R. E. (2002). "Safety and Risk in Structural Engineering." *Prog. Struct. Engng Mater.* John Wiley & Sons. New York, NY.

"Top 200 Skyscrapers Worldwide." (2003). <http://www.skycrapers.com> (May 2, 2003).

Shanghai Municipal Government. (2003). "Jin Mao Tower (1)." <http://www.sh.gov.cn> (May 11, 2003).

Smith, B. S., and Coull, A. (1991). *Tall Buildings Structures.* John Wiley & Sons. New York, NY.

Solomon, R. E., and Hagglung, B. (2001). "Performance Code Requirements in the Tall Building Environment." Sixth World Congress on Tall Buildings and Urban Habitat. Melbourne, Australia.

Taranath, B. S. (1998). *Steel, Concrete, & Composite Design of Tall Buildings.* Second Edition. McGraw-Hill. New York, NY.

Walraven, J. "Challenges for New Materials in Concrete Structures." 13th FIP Congress.