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New Practices in Concrete Buildings

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Special Problems of Tall Buildings (Shear Walls, Stability of Columns, Effect of Thermal Gradients, Construction Problems)

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The current popularity of high-rise structures throughout the world makes them an approporiate subject for this Congress of the International Association for Bridge and Structural Engineering. The first part of this paper summarizes the current state of the art, illustrates many of the things currently done and some of the problems thereby encountered. The second part specifically summarizes three types of important questions, hoping they may serve as stimuli for discussion and for future research. Certain types of problems are encountered uniquely in high rise structures that are not met in other structures.

Part I

High rises are sometimes defined as buildings above some 15 or 16 stories in height, but rather than define them in terms of the number of stories, the reporters prefer for purposes of this report to define them as buildings in which the height of the structure is such that prediction of its stability, internal stresses, reactions and movements are necessary and require rigorous analysis of both superimposed vertical and lateral loads and effects of shrinkage, creep, and temperature to assure adequate and safe performance for their intended purposes.

The economic, aesthetic and functional merits of both steel framed and concrete framed high rise buildings are debated now and will be continually debated in the future. At this time, neither material can be singled out as the ideal material for the structural framing of a high rise building. Only after careful study of the particular project can the designer select a framing material and system and conclude that they are the best solution for the project. Valid conclusions can only be made for a specific project at a specific time in a specific location. The validity of the conclusions will be largely dependent upon the skill, ingenuity and knowledge of the designer. Thus, it is most important that problems which must be solved to produce valid designs be clearly defined, and reasonable and prudent solutions for these problems be available to the designer.

High rises are built for various reasons such as: (1) a desire to make more effective use of land areas, i.e., to get more rentable square feet of floor area per unit land area, (2) to group people closer together in specialized communities for more efficient intercommunication, (3) for prestige and publicity purposes, (4) because of the possibility of higher rentals if all ancillary services are closely available, (5) more efficient use of public services for water, light, sewers, deliveries, and so on, (6) from a desire to get above the congested streets and have some air, openness, and a view as well as to escape street noises, insects, dust and dirt. Continuing expansion shows that the economic feasibility of such structures is assured.

Then what does determine the economic height of a structure? A prime consideration is vertical transportation. At some point the elevator shafts preempt most of the rentable floor space in the lower stories. Vertical travel is improved in a variety of ways, such as: (1) operating elevators at higher speeds, up to 370 meters a minute, (2) by better controls for speedy acceleration and deceleration, (3) by running some cars express part of the height of building and local only between designated floors, (4) by having two-story or even three-story walk-up apartments within the building with elevators stopping only at alternate or every third floor, (5) by operating two cars in the same shaft with a vertical safety chain suspended from the upper car to prevent collision, and (6) running elevators on the outside of the building. Even so, the amount of otherwise rentable space displaced by elevators is a major determinant.

The amount of space occupied by stacks for plumbing, heating, ventilating and electric services is of considerable importance. High velocities, mechanical rooms at intermediate floor levels, high voltages and similar devices are considered in order to minimize lost rentable floor space. At somewhere around 16 to 18 stories, there is often a sharp break in the bids due to the necessary provisions for mechanical and structural requirements.

Walls are made as thin as practicable, e.g., insulated steel panels in lieu of masonry. Column sizes are made as small as possible by using high strength materials. Columns are spaced and shaped to fit into intersections of partitions and similar out-of-the-way spots to keep room areas clear. Columns must be far enough apart to permit unobstructed rooms of adequate size between them or they might be exposed and free-standing in a larger room.

As the designer reduces structural sizes, he becomes more and more involved in problems of allowable sidesway ("drift"), vibration, and related phenomena. If column stacks can extend vertically from footing to roof, the volume of the building and its cost are minimized. If there are different occupancies on different floors, such as apartments over stores over garages, it is not a simple planning problem to get vertical stands of columns. Transfer girders are sometimes required to carry column loads from one pattern of columns to a different one. Such girders are often half a story to a full story in depth and require that much more cubage to enclose them. Sometimes service rooms can be worked in around them. Striving for a single plan of intercolumnation in floor plans that differ widely is worthy of considerable study. All these problems are largely architectural, although very much the concern of the structural engineer.

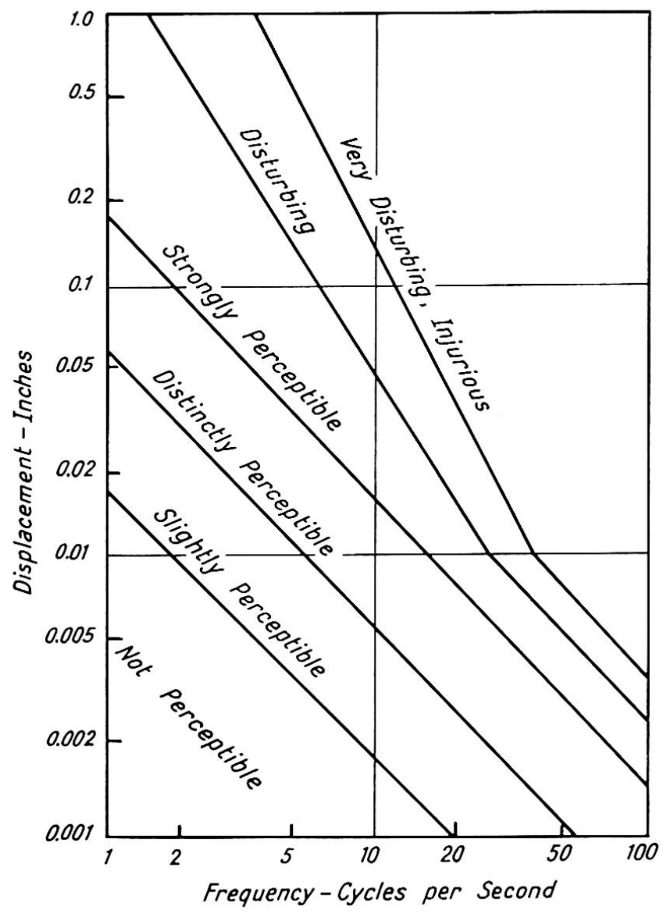
All high rises have certain structural problems in common. The loads are concentrated rather heavily over a limited land area, giving foundation problems, resulting usually in: (1) spread footings with high soil bearing intensity, (2) mats or rafts, (3) piles, (4) caissons, or similar devices. Careful subsurface soil investigations are made in advance of the development of plans. Estimates are made of probable settlements and the magnitudes tolerable by the structure.

Sometimes the supporting of the loads within the allowable bearing capacities is closely dependent upon the dead weight of the structure itself, and refined design techniques to minimize this dead weight become very important, as does the use of lightweight materials, including lightweight aggregate concrete.

Fire resistance is another characteristic that must be built into any high rise structure regardless of the materials used. Simple and sure means for emergency egress become increasingly hard to provide as the number of stories increases. Hence, all of the construction materials should be as fire-resistant as practicable. Three- or four-hour ratings are usually demanded by building codes and should provide sufficient time to vacate the building in an emergency.

Because most high rises are narrow in proportion to their heights, resistance to wind and seismic forces must receive primary attention. There are various ways of stiffening the three-dimensional rectangular-shaped skeleton framework of a high rise building, such as: (1) stiff joints between flat plate or flat slab floors (or between joists, beams or girders) and columns, making the entire structural frame a vertical Vierendeel truss cantilevered upward from the earth, (2) substitution of diagonal bracing for these stiffened quadrangles, (3) use of special braced bents or shear walls especially to resist lateral forces. Such provisions are time-consuming enough to analyze when the columns continue vertically upward in a single pattern. If set-backs occur or if the grid pattern of the column centerlines varies from floor to floor, even if only offset within successive planar sections, the design work is considerably increased. If such offsets are combined with others at right angles and outside the successive planar sections, the computational work is rendered even more complicated. Transfer girders are often short, heavily loaded beams that may involve analysis as deep beams. Torsion can not always be eliminated, and where it is not, a torsional appraisal must be made. In particular, the original planning must recognize such bracings, shear walls, transfer girders, and similar provisions and supply spaces in which they may be accommodated.

Even the psycho-physiological effects upon occupants must be considered. It is becoming apparent that lateral accelerations and deflections that can be safely tolerated by the structure may be annoying to occupants. Some medical research upon the reactions of human beings to various amounts of movement and rates at which cyclical movements take place has been done. The accompanying figure summarizes enough of these details to indicate the direction studies are taking to define humanly tolerable lateral movements.



Effects upon partitions, ceilings, external claddings, and floorings must also be considered, not only to guard against unsightly cracking, but also to avoid deflections and warpings that prevent doors and windows closing properly. It is necessary to provide for unavoidable vertical deformations of columns under load with suitable expansion connections. (Steel columns 300 meters high, stressed throughout to 2000 kg/cm^2, with Young's modulus 2,100,000 kg/cm^2 will necessarily shorten some 30 cm in height so that relatively unstressed steel panel walls, for example, must provide an aggregate of this amount of movement in jointings.)

Methods of analysis will be pretty much the same regardless of materials. Because of the large number of repetitions of floor loads, they should be established carefully—live loads high enough to provide requisite safety, low enough to provide economy, minimize loads on the foundations and permit construction at all. While established by local building codes for any given structure, the recommendations are now undergoing very careful appraisal. Construction loads can easily exceed those of subsequent occupancy, so they must be taken into account in the design or arrangements made to spread them out in a manner that will keep them within design assumptions. Partitions, especially when of masonry, and when there are many ducts and shafts, should be estimated realistically and not lumped into an arbitrary and possibly excessively low allowance per square foot. Dead loads should be evaluated with some care and not arbitarily assumed. A high stack of riser pipe supported by a tight clamp at a specific floor can produce a concentration of considerable magnitude and the floor system on either side must take this into account.

The effects of live loads can be reduced by a factor probabilistically determined and dependent upon the number of floors and the floor area supported and the relative magnitudes of live and dead loads. Structural analysts influenced somewhat by designers of aircraft and space vehicles and by scientists are coming more and more to understand and use statistical approaches to their more involved problems.

Wind loads are closely related to wind velocities upon which much meteorological information has been accumulated. However, the possible shielding by nearby structures should be considered. Generally, wind forces have been treated as static loads covering the projected exposed area completely. Dynamic effects of gusts and of high-intensity small-area impacts are seldom individually studied; the over-all static force is assumed of sufficient intensity to include the dynamic effects. Obviously, an intensity of horizontal pressure that would be sufficient to insure frame stability of the structure as a whole would be a low value for designing the plate glass in a picture window of a penthouse apartment. Measurements now underway on some unusually high structures and including simultaneous observations of wind pressures will shed light upon many questions including: (1) how pressures on the face of a building relate to general wind velocities recorded in the area; (2) how well the lateral movement of a building and its cyclical characteristics are predicted by analysis; (3) whether these movements are tolerable by the structure and by its human occupants; (4) the approximate restraint offered by walls, partitions, and similar items often omitted in design analysis or accounted for by a reduction in the unit load.

Seismic forces are similarly under study, as well as the responses of structural frames to such exposures. Seismic forces are increasingly treated by dynamic analysis. Such factors as the energy absorption capacity and the ductility of structural frameworks then become important.

The level above which permanent distortions could be accepted must be considered. Great advances are being made both experimentally and analytically. Differences of opinion, of course, exist but a large body of knowledge is now available from information upon the forces set up by earthquakes, to the response of structural frameworks to them, and on to the levels that are tolerable by structures and their occupants.

In designing structures to resist these forces of dead and live loads, vibration, wind and earthquakes, analyses vary from the simplest to the most sophisticated and often combine many attacks on the problem. With electronic computers, it is practicable to solve frame matrices of tremendous complexity. It is also possible to develop a satisfactory structural frame by rather simple assumptions. As long as these simple assumptions are applied to structures similar to those where they have already produced satisfactory results, it is likely that they will give safe results and the major concerns are economy and the possible behavior under a combination of adverse circumstances, i.e., the magnitude of the overall factor of safety. Simple methods are a necessity in shaping up an initial skeleton to which more refined methods can be applied. The refined and computerized analyses can go so far as to account for the longitudinal deformation of members, in addition to flexural effects, and their consequent distortion of the quadrangular frames. Two words of caution are appropriate: (1) the work involved and the opportunities for error increase exponentially with the number of items considered—the computer, once properly programmed, can deal with great numbers of variables, but the analyst is not always similarly gifted; (2) there is a tendency to rely heavily upon the neatly typed columns of figures printed out by a computer; it is very difficult for the engineer who is not an expert at programming to see that each step and each item is properly accounted for, to learn which criterion determined the result, or what modification in design might greatly improve the result. Structural design is still almost as much of an art as a science; there is still no one best solution that a computer can automatically provide.

This summary, necessarily general, and free from applications and details, starts with the fact that all high rise structures have many areas in common, including architectural and economic considerations, methods of structural analysis, choice of loads, and human tolerances. Turn now to the specific considerations of high rise structures of reinforced concrete.

Floor systems can be of a variety of types: (1) slab, beam and girder; (2) concrete joist floor construction; (3) waffle slabs; (4) flat plate; (5) flat slab; (6) lift slab; and (7) others. Some factors that affect the choice between these include: (1) ceiling construction, (2) span, (3) load, (4) story height, (5) height of building.

The ceiling construction may have an important effect. If services are distributed in vertical shafts or ducts over corridor ceilings and do not require suspended ceilings in the rooms, a flat plate floor, with ceiling exposed and painted where acceptable or with acoustical tile or similar material appliqued where desired, is economical in itself, saves thickness in the floor system, and will accept the most irregular patterns of column spacings. If shear walls or braced bents are not provided, the transfer of moments between slab and columns requires structural analysis since slabs are thinner than columns and only a limited width of slab participates in this transfer of moments. Often the item that determines column periphery and slab thickness is the shear around the column. This very often has more of an effect on slab thickness than flexure.

Sometimes slab, beams and girder construction is left exposed and painted. The cost of formwork for this system is considerably greater than for a flat plate; the height of building, except for very long spans, is increased to accommodate the deeper beams, the appearance of the ceiling is cut up with beams, freely irregular column spacings are more difficult to achieve, and flat plates are a more accepted solution.

Concrete joist floor construction may be visualized as a solid slab of a thickness equal to the total depth, with all of the concrete that is above the neutral axis and so in compression under positive moment retained and with as much of the more or less inert concrete below the neutral axis removed as consistent with adequately resisting shear and covering the bars. This not only saves the cost of the displaced concrete but lightens the dead weight supported by the structural frame all the way down through the footings. The economy of this system may start with spans of as little as 4 or 5 meters and increases as the spans increase. Spans of 15 to 20 meters or more have been satisfactorily and economically used. The relatively close spacing and constant repetition of ribs is not very attractive. The substantial possible savings in cost may have to be reduced by the cost of a suspended ceiling. The ability of the joists to span considerable distances often results in beam spans of similar amount in the opposite direction. Then the working of these relatively deep beams into the architectural planning without sacrificing headroom may be a problem.

To digress slightly, it is tacitly assumed in what has been said that the cost of a high rise structure is dependent upon its contained cubage. This is roughly true. A higher building means more area of exterior enclosing walls, and of interior partitions and shafts, longer stairs and longer elevator travel, more length of riser pipes and ducts. Generally, the clear story height from floor to ceiling is determined by code. To this is added the thickness of the floor system from ceiling to finished floor to establish the floor-to-floor story height. Thus, a thin floor system saves not only in the amount of material it requires but in all the items just mentioned and other similar ones.

Waffle slab construction ("grid system") is to a two-way flat plate what a joist floor is to a one-way solid slab. It can be designed as a flat plate without supporting beams or girders. To some extent, columns need not be spaced in an exactly rectangular pattern, though the standard types of removable forms available severely limit very much irregularity. The grid-like pattern of the underside is often acceptable in itself as a finished ceiling. If a suspended ceiling is required under the slab, some economy and some headroom is lost.

Lift slabs are constructed by erecting and bracing the columns only to the full height of the structure, placing the concrete slab on the ground and superimposed directly on top of it, and on top of each other, all the floor slabs with appropriate bond-breaker and containing the built-in pipes and conduits. After the slabs are sufficiently hardened, they are raised up the columns already in place and supported at proper levels with collars or brackets. Thus the building of elaborate formwork is largely eliminated.

While flat plates are an almost standard feature in high rise apartments and hotels, the companion flat slab with a flaring capital, and possibly a drop panel, at the top of each column, thus taking substantial moments, is very seldom if ever used. It is considered more of a system for warehouses and factories where heavy loads induce large moments.

Columns, too, can be of all conceivable shapes. Square, rectangular, and circular shapes are perhaps the easiest to consider but ell and tee shapes fitted to corners in interior partitions and ducts often occupy less of the useable floor space. Spiralled reinforcement goes naturally with round columns. While spirals can be used in square columns, the new Code, ACI 318-63, does not appraise the ultimate carrying capacity high enough above that of a similar column with lateral ties to make the cost of the spiral pay out. Space-saving being of so high a dollar value, high strength concrete is usually specified in columns only. While the rest of the structural frame may use concrete of 250 kg/cm^2 to 275 kg/cm^2 (28-day, 15×30 cm cylinder tests), columns are often of 350, 400, or 450 kg/cm^2 quality. At around 450 to 475 kg/cm^2, coarse aggregates must be carefully selected; mixing and placing must be controlled; and soon economy vanishes. For precast and prestressed members, strengths approaching or surpassing 700 kg/cm^2 are in regular production, but not for cast-in-place concrete. Paper-tube forms or sectional sheet steel forms work extremely well for circular columns. They are coming into use for square columns. Ell and tee shapes are formed with plywood or boards. Small electrical conduits are regularly buried in columns, the small sizes without consideration in design, the larger ones considered as the displacement of that much bearing area.

Where architectural treatment exposes one face of an exterior column through the outside wall to the action of cold weather and freezing and at the same time exposes the interior portion of the column to the temperature of moderately highly heated rooms, problems of the temperature gradient through the mass of such a column arise. At first glance, a severe stress condition is suggested which is modified somewhat by further study and experience.

Foundations have already been mentioned. Foundation problems are about the same for structural steel frameworks and for reinforced concrete. While it has been claimed that the dead weight of the former is enough less to simplify design problems especially on soils of limited capacities, load determinations on several alternate studies did not find this to be the major item one would off-hand assume.

In lieu of columns, many recent high rise structures substitute bearing walls and partitions which may be of concrete cast in place, or of precast panels, or of masonry units laid up in mortar on the job. Some building codes that were not written with such bearing walls specifically in mind have rather empirical, safe but rule-of-thumb, methods for determining the dimensions of such bearing walls. With current usages, experiments and studies, the structural design of such walls or wall panels is gradually being put on a basis comparable with the structural design of other members.

An interesting variation is to carry up the cast-in-place wall system first with vertically moving slip-forms such as are used in the construction of grain storage bins and following behind with the floor system. Sometimes the appearance of such walls is satisfactory for exposed use in the finished building. Such electrical provisions as base plugs and switches then have to be incorporated as the forms move gradually upward. While pilasters, chases, and projections or incisions of this sort are readily incorporated into the forms while they are being built, and while pockets or boxes can be left to receive the floors, which must of necessity be built later, the same contours should, if at all possible, extend from foundation to roof. For bracing, floors should be installed not over two or three stories below where the sliding forms are in place.

So far, precast wall panels are much more used in Europe than in North America, largely on the basis of comparative economics, partly because of the interest, skill, and techniques of contractors.

The possibility of using lightweight aggregates to decrease the weight of the structural framework and so the size of bearing walls, columns, and footings has been mentioned. Lightweight aggregates are greatly used in various parts of the United States, somewhat less in areas that have good available natural stone, very much less in most other countries.

Part II

The purpose of Part II of this report is to present a survey of what these reporters consider the three most important problems, which they hope will provoke discussion and eventually serve as a basis for future researches.

1. The effect of wind loading on high rise building frames.

2. The effect of shrinkage, temperature, and creep on high rise building frames.

3. Design and performance of long span floor systems in high rise building frames, especially with reference to deflections and vibrations.

Each of these primary problems can be divided into several specific problems in which either little or no research has been done or in which present established methods of solution are probably no longer valid because the nature of the high rise building has changed. Brief comments on the change in the nature of high rise buildings is warranted here. The change we wish to stress is primarily the architectural change from heavy, stiff curtain wall and partition systems to lightweight systems which provide little or no extra stiffness to the building. The structural frame of the modern high rise structure and it alone must resist all lateral loads and it must not only be structurally safe against collapse or failure dangerous to life and limb, but also perform motion-wise in such manner as to be unobjectionable to the occupants and nondestructive of partition systems, glass and lightweight walls etc.

The trend toward large, column-free areas has led to longer spans and larger bay sizes in high rise buildings. Thus, more attention must be given to design for adequate performance of long spans in these modern buildings.

New exterior wall systems and architectural treatment of many high rise buildings, particularly concrete structures, now have the basic frame either partially or fully exposed to the effects of weather. These parts of the frame are subject to constant daily and seasonal changes in temperature while other connected parts are maintained at fairly constant temperature. It is thus evident that stresses and strains due to temperature effects must be given serious consideration by the designers of these types of modern high rise buildings and this consideration must extend beyond the level of providing safety from collapse or failure dangerous to life and limb, but also to performance.

The types of problems which will be discussed are not theoretical possibilities of unlikely difficulties, but are very real situations which have developed in some degree in the experience of the reporters and other engineers. These were situations that required some modification of completed structures and that could have been improved during the design stage. In researching each problem, information, data and experience were found to be quite inadequate for rigorous solutions of the problems.

The first problem, "The Effects of Wind Loading on High Rise Building Frames", involves problems ranging from realistic determination of wind velocities during the life of a structure at a specific location all the way to determination of the psychological and physiological effects of motion on occupants of the building. Subproblems under this heading can be listed as follows:

1. Meteorological research to determine wind velocities at ground level and above ground to heights of perhaps 600 meters in and around urban areas.

2. Analysis of existing meteorological data gathered over past years wherever available.

3. Instrumentation and gathering of meteorological data on existing high rise structures over a reasonable period of time together with instrumentation to determine pressure distribution and aerodynamic response of the structure, drift, period of vibration, etc.

4. Aerodynamic model analysis of an existing structure with its surrounding buildings and terrain which can be compared with actual data obtained from the investigations noted in Item 3.

5. Development of dynamic analysis methods for prediction of building drift under realistic wind conditions rather than conventional assumed static wind pressure.

6. Research on the psychological and physiological effects of actual building drifts as determined in Item 3.

7. Research in aerodynamic response of concrete structures with various types of framing systems and comparison with steel framing types.

8. Research on actual buildings, aerodynamic response and its effects on generation of noise and cracks in partition and floor systems.

9. Methods for design of partition and curtain wall systems which will perform satisfactorily when activated by aerodynamic response of the structural frame.

10. Under wind loading, it is possible for stress reversals to occur in certain members of a high rise building frame. Research toward accurate prediction of the number of stress reversals and their magnitude during the life of a structure seems to be warranted. The matter of fatigue stress in both steel shapes and reinforcing steel could then be more properly investigated. This research should include prediction of real live load studies as the combination of real live load and real wind load over the life of the structure will be the determining factors in computing the expected number and magnitude of stress reversals. Fatigue effects due to vibrations induced by both wind and other forces also merit consideration.

Our second category for study, "The Effect of Temperature, Shrinkage, and Creep on High Rise Building Frames", suggests many subproblems as follows:

1. Development of methods for computing thermal gradients in structural parts of a frame partially or fully exposed to temperature variation.

2. Research, including instrumentation, of existing structures to check the validity of the computation methods developed as noted in Item 1 above.

3. Development of methods for accurate computation of stresses and strains from the effects of shrinkage, temperature variation, and creep.

4. Research, including instrumentation, of existing structures to determine validity of computation methods noted in Item 3 above.

5. Research and development of curtain wall and partitioning systems to perform satisfactorily in structures with strain and movements due to shrinkage, temperature, and creep.

6. Development of structural frame details to assure adequate performance under conditions of varying temperature of exposed or partially exposed members.

Our third category of problems, "Design and Performance of Long Span Floor Systems in High Rise Buildings", suggest subproblems as follows:

1. Research on existing buildings with long span floor systems to determine:

a) Effects of deflections on partition systems and floor finishes.

b) Psychological and physiological effects of motion and vibration of floors induced from occupants, mechanical systems and wind forces.

c) Dampening effects of appurtenant items such as partitions, furnishings, window walls, etc.

2. Analysis of data obtained in Item 1 and development of adequate theory and methods for the prediction of possible motion problems and solution of these problems.

3. Establishment of criteria for adequate floor systems, not only which provide safety from collapse or failure dangerous to life and limb, but also which perform in such manner as to avoid objectionable motion and displacement.

4. Development of new floor systems specifically for high rise structures by intensive application of ingenuity and inventiveness.

We are of the opinion that many of the older high rise structures and some of the modern ones perform adequately, not because the design assumptions and methods of solution are precise, but more often because over-conservative horizontal and vertical static loading conditions were assumed and basic frames were stiffened by as much as 200% to 300% by wall and partition systems. In short, we habitually and fortunately built in enough error on the conservative side to offset the effects of failure to recognize and solve real design problems. Obviously this procedure worked for the type of buildings which were designed, but we should not continue such methods for design of the new and different structures we will be called upon to produce today and tomorrow. The state of the art must be upgraded. The problems must be clearly defined, data from instrumentation and observation of existing modern structures must be gathered and evaluated and new theory and design methods must be formulated. Codes must be constantly re-examined in the light of new experience and expanding knowledge.