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Column-Free Box-Type Framing with and without Core

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Introduction

The development of cast iron and later on steel in the late 19^{th} Century made it possible to build multi-story buildings without the use of the traditional masonry bearing walls. The Chicago School in the early 1900's provided added momentum to steel construction by refining the beam-column type frame construction which has since been used in almost all steel multi-story buildings. For more than 50 years since then, the architects and engineers used various interesting refinements in terms of connections or proportions of the beam-column rigid frame. It seems that during this period, frame-type construction was considered the only possible way to build multi-story buildings. The frame construction method reached its limit in height in the 102-story Empire State Building and its limit in span (87 feet) in the 30-story Chicago Civic Center Building.

During early 20^{th} Century the basic design criterion was the wind load capacity of a frame. The lateral rigidity of a frame was considerably augmented by the use of the traditional block partition walls as well as masonry or stone exterior facings. It was therefore possible to design most of these buildings only for strength without considering the effects of lateral sway. After World War II the building construction materials drastically changed the architectural approach to developing the non-structural elements, such as partitions and exterior facing. The solid block interior partitions were replaced by light demountable metal and glass partitions, and the masonry exterior facing was replaced by exposed structures for concrete buildings and light metal claddings in the steel buildings. As a result, the actual stiffness of the finished building became closer to the theoretical stiffness of the structural frame. This made the lateral stiffness of the structural frame probably the most significant factor affecting the design of a multi-story building.

From the structural point of view a multi-story frame is different from a one or two story frame in that the design of the main structural members in a multi-story frame is affected by the stiffness and strength consideration of these members subjected to lateral loads, whereas in a one or two story frame, the lateral load is seldom a controlling factor. Ideally, the most efficient way to build a building is therefore to use a total structural system such that all members in the structure are affected only by gravity load considerations and not by the lateral load considerations.

For example, if a three-bay multi-story frame with average spans is designed only for the gravity loads—that is, dead load and live load—a curve could be plotted showing the quantity of steel per sq.ft. of average floor area for varying height expressed in number of stories. If, however, the normal wind load is brought into the design of these frames, a new curve can be plotted showing the required quantity of steel per sq.ft. of floor area for increasing number of stories. If these two curves are qualitatively plotted together as shown in Fig. 1, it would become immediately apparent that the premium in structural material for increase in height of building is indeed substantial enough to influence the entire economic feasibility of any building.

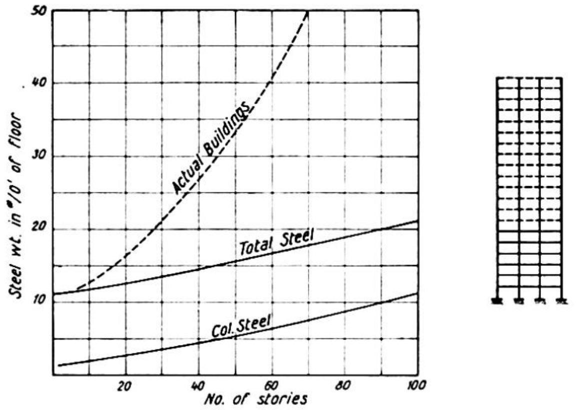

Fig. 1. Qualitative Steel Quantity Curves for Gravity Versus Wind Load Condition

It is therefore not surprising that during the last few years new structural systems for high-rise construction have been developed with the main objective of avoiding the traditional premium for height. From fundamental theory of structures it can be proved that for a given series of columns in a building the most efficient behavior both in strength and in stiffness can be obtained only by tying the exterior columns in a way that they act together like a rigid box or a tube cantilevering out of the ground. Obviously all the new systems proposed during the last few years do fully or partially achieve this behavior.

In principle these rigid box or tube type structural systems are typically composed of an exterior "tube" consisting of the exterior columns and a central core consisting of rigid or simply connected columns and beams. The floor beams span from the exterior wall to the central core enclosing the service area (i.e. elevators, stairs, etc.). A typical floor plan is shown in Fig. 2. Be-

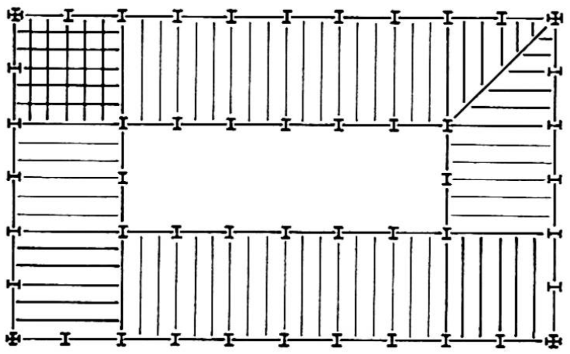

Fig. 2. Typical Plan Showing Various Possible Corner Framings

cause the floor beams in such systems do not participate in resisting the lateral load on the building they can be relatively shallow at every floor. For this same reason longer spans can be used between the exterior walls and the interior core.

Although there is no basic difference in elastic behavior between a concrete structure and a steel structure, having the same total system, the discussion in this report will be limited to only steel structures. However, where necessary, relevant references to concrete structures will be made only to make certain points.

Framed Tube

The easiest way to simulate the rigid box or tube action in a rectilinear building is to arrange very closely spaced exterior columns and connect them together at each floor with deep perimeter spandrel beams. This has the advantage of keeping the traditional rectangular windows which are often created by directly attaching the glass to the closely spaced structural columns. The general concept was probably first used by Skidmore, Owings & Merrill in 1961 in the 43-story DeWitt Apartment buildings in Chicago where the exterior columns were spaced at 5′–6″ centers all around the perimeter of the building and were designed to resist the entire wind load. This was, however, a concrete building. Since then at least one more concrete building (500 North Michigan Building in Chicago) has been designed by the same firm using the same concept. A number of tall buildings using this concept are now in the planning stage, the most significant of which is the 110-story twin towers for the World Trade Center in New York.

The system of closely spaced exterior columns and rigid spandrels may be called the "framed tube" system of construction. While the first impression of this system is its tube-like configuration, further investigation will indicate that the overall behavior of such systems is more similar to a rigid frame than to a true cantilever. Under lateral loads acting on such a structure as shown in Fig. 3 two distinctly separate behaviors take place. First the entire structure

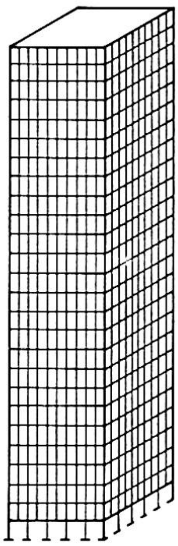

Fig. 3 Typical Framed Tube

acts like a tube causing only compression and tension in all the exterior columns and deflecting similar to a true cantilever. Second, the two faces of the structure parallel to the direction of wind act as independent rigid frames subjected to the full wind load and undergo wracking movements at each story as would be expected in any frame structure.

Even the tube action causing direct stresses in the columns does not develop 100% efficiency. The flexibility of the spandrels invariably causes shear lag which in turn increases the actual stresses in the corner columns and reduces the actual stresses in the other columns as shown in Fig. 4. From the study of this combined behavior, it is evident that in order to increase the efficiency of this system, the spandrel stiffness must be increased to a very high level (to reduce the shear lag), and the columns should be oriented along the face of the building (to reduce the wracking at each floor). In practice the framed tube system result in considerably greater lateral sway than an ideal equivalent solid tube. Furthermore, the bending stresses in the columns in the two faces parallel to the direction of wind may eventually govern the design for taller buildings.

The greatest advantage of the "framed tube" system is that it conforms to the traditional architectural arrangement of the windows and its use may be economically and aesthetically justified for a wind range of number of stories.

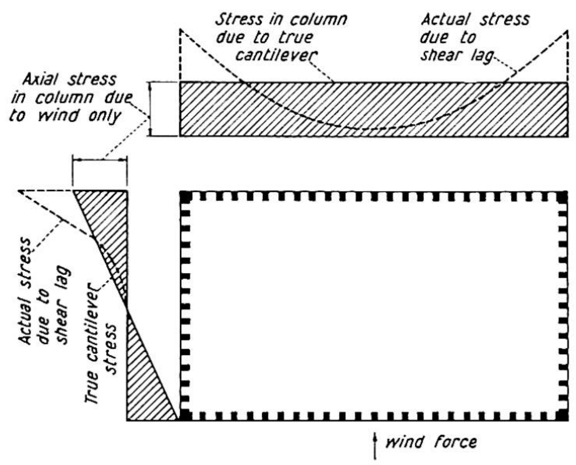

Fig. 4. Shear Lag in Framed Tube

On the other hand, its economic use may be somewhat limited because of the following possible reasons:

1. Increased number of exterior columns invariably means increased number of jointing details. Where labor is an important factor in the total economy it would mean that some form of prefabrication has to be adopted to make this system effective.

2. Increased number of exterior columns in steel construction means increased amount of fire proofing and cladding details which may override the economy achieved by use of this system. Standardized details and multi-bay fabrication for cladding may therefore be necessary to reduce this cost.

3. The shear lag as shown in Fig. 4 may result in sufficient warping of the floors to cause distress in partitions and window details.

4. Because the lateral sway caused by bending in the columns (rigid frame behavior) may be as high as three times the true cantilever sway the considerations for partition distortion and perception of motion may control the design which would mean relative increase in cost.

Diagonaled Truss Tube

Another way of achieving the tube effect is to eliminate the use of vertical columns altogether and substitute with closely spaced diagonals in either direction as shown in Fig. 5, the "diagonaled truss tube" if used without large discontinuities is obviously an extremely efficient system as far as the tube action is concerned. The effects of shear lag and floor wracking, if any, would be insignificant and the entire perimeter system will be effective in resisting the over-turning moment caused by wind load. Architecturally, however, this means arranging the perimeter supply system in a more complicated way. The successful use of this system in the 13-story I.B.M. Building in Pittsburgh points to its future possibilities.

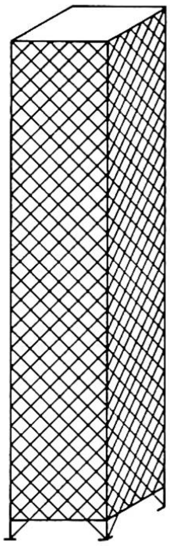

Fig. 5. Diagonaled Truss Tube

While theoretically this system is extremely efficient, from the practical design and construction point of view it seems to have three major problems:

1. The diagonals, being closely spaced, are generally small in size. This tends to reduce the efficiency of these members.
2. Number of joints in the exterior wall is considerably higher than that in a traditional rigid frame building. This may increase the cost of fabrication and erection.
3. The secondary stresses due to construction tolerance may be unusually high and therefore provision for special field adjustments is necessary. For this same reason any sharp change in temperature during construction is liable to cause high local stresses.

Column-Diagonal Truss Tube

Some of the disadvantages of the "framed tube" and the "diagonaled truss tube" can be eliminated by the use of an optimum combination of diagonals, columns and spandrels to create an effective rigid box or tube. Exterior columns with normal spacing from 20 feet to about 60 feet can be made to act together as a tube simply by connecting them with widely spaced diagonals at about 45°. Except at levels where diagonals from both faces meet at the corner, the spandrel normally designed for floor loads are sufficient to resist the internal force distribution between the diagonals and the columns. However, at the levels where the diagonals from both faces intersect at the corner, it is necessary to provide a large tie spandrel first to limit the horizontal spread out of the floor at this level, and second to make the diagonals function more efficiently as inclined columns as well as the primary load redistribution member. The 100-story

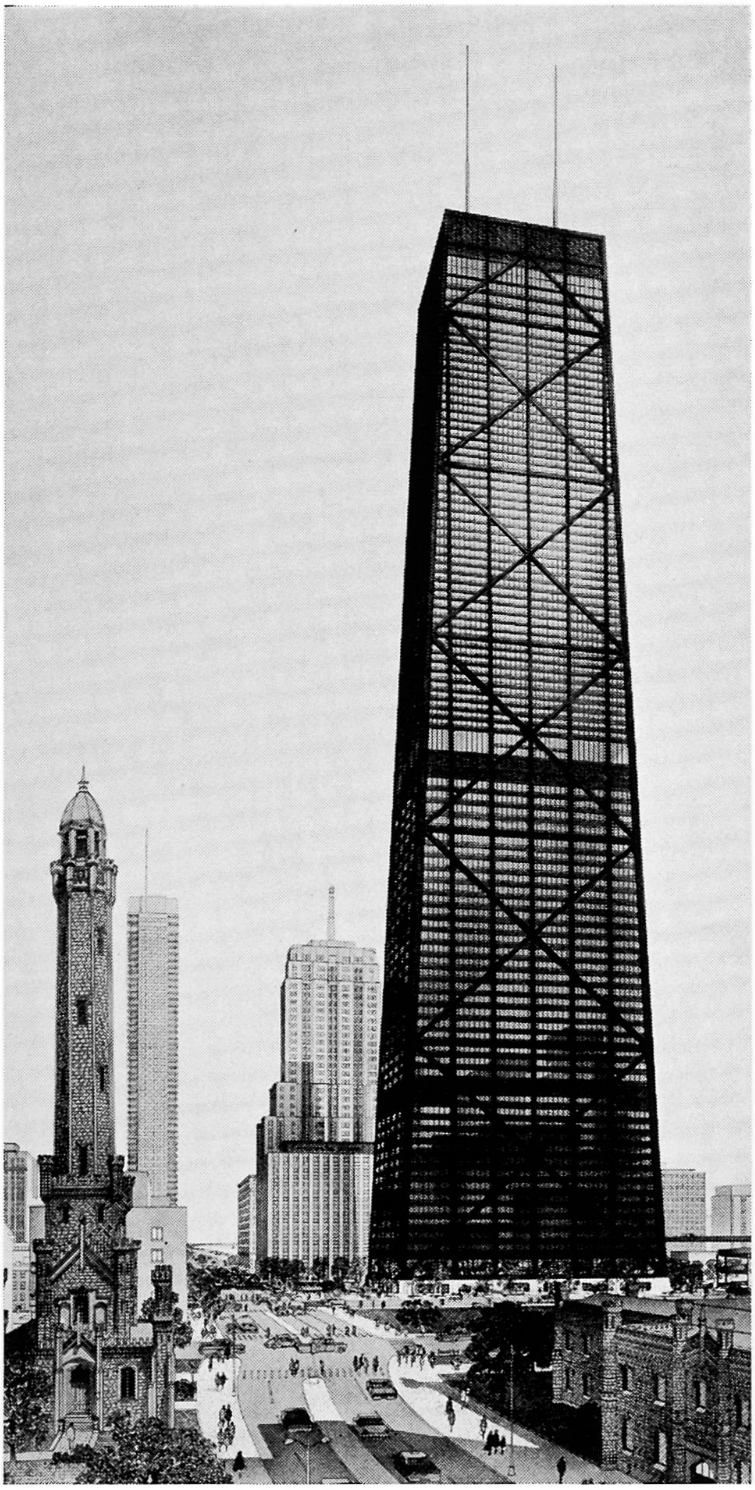

Fig. 6. View of John Hancock Center

John Hancock Center shown in Fig. 6 is an ideal example of the optimum truss tube system described above.

One of the special advantages of this system is that the diagonals redistribute the vertical loads among the columns so that in spite of different tributary areas for each of these columns, all columns can actually be made of same size at any floor. In terms of fabrication, this means standardization of columns and their details. Furthermore, the diagonals acting as inclined columns seldom develop tension even under extreme wind load. As a result, the splicing of the diagonals can be quite similar to that of the column and should add to the overall economy in construction.

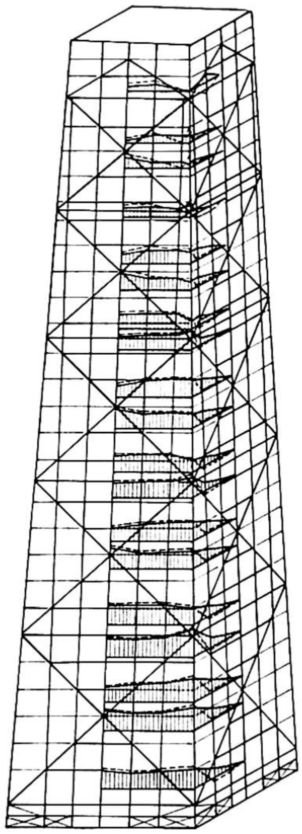

Fig. 7. Stress Distribution in John Hancock Center

The optimum truss tube shows remarkably insignificant shear lag under wind loads as shown by the analysis of the John Hancock Center, Fig. 7. However, the relative sizes of the diagonals, spandrels and the main ties affect the overall economy and efficiency and studies indicate that increasing the size of the diagonals or the ties beyond a certain limit does not increase the overall efficiency significantly. In view of the large number of variables involved in establishing the optimum relationship among these members it seems considerable research is needed for future design of similar buildings.

Structural Connections

The success of a steel structure, and particularly a high-rise structure, depends largely on the joint details. While the analysis is not substantially affected by variations in types of joints, the fabrication and erection cost can be greatly affected by the type of joints used. In a rigid box structural system where the entire lateral load is resisted by the exterior columns, beams or diagonals, the most important practical consideration must be given to the development of efficient and simple joints.

In countries like the United States one has to remember that total use of field welding will result in a more expensive and slower construction. Therefore, every effort must be made to avoid field welding. In the framed tube type of structures, the rigidity of the joints being the primary factor for the efficiency of the entire system, it is extremely difficult to avoid welding of these joints. However, the total construction cost can be considerably reduced by developing details that will limit most of the welding to shop fabrication and achieve field connections by the use of bolts. This means that the engineer must consider the possibility of prefabricating segments of the exterior wall in the shop and connecting these assemblages in the field by high-strength bolts. This is schematically shown in Fig. 8.

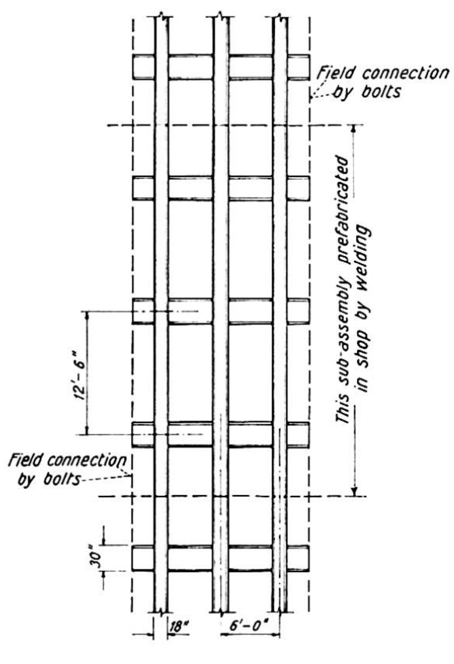

Fig. 8. Prefabricated Units for Framed Tube Type Structures

In the column-diagonal truss type structures, such as the John Hancock Center, the rigidity of the joints at the intersection of the primary members is no longer an important consideration. Furthermore, the number of primary joints is relatively few compared to the framed tube type structures. For example in John Hancock Center the large joints occur at approximately every 20 floors. The cost of a complicated joint therefore is relatively low when spread out to the total floor area of the entire building. Even then, every effort must be made to limit the welding to shop fabrication and use bolting for field connections. This was achieved in John Hancock Center at all the major joints. The joints themselves were prefabricated in the shop and full penetration welds

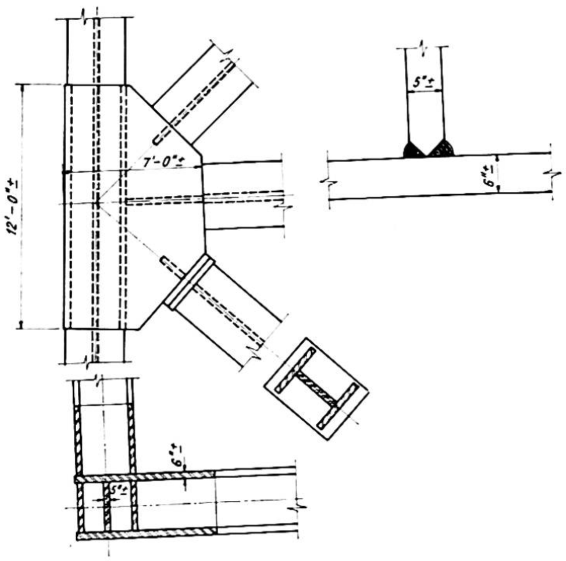

Fig. 9. Schematic Joint Detail for Optimum Truss Type Structures

were used. After thorough testing of all the welds in each joint by ultrasonic method, the entire joint was stress-relieved in a furnace. The field connection of the major diagonals coming into the joint were achieved by bolting. This is schematically shown in Fig. 9.

In a gusset plated joint such as shown in Fig. 9 an important consideration is the proportioning of the columns, the diagonals and ties in a way that they do not present any problem at the points of intersection. If the columns, diagonals or ties are box shaped, the connections may become extremely cumbersome which would lead to considerable increase in the total cost of the structure. This was solved in John Hancock Center by making all exterior columns, diagonals and ties in the form of *H*-sections such that the flanges or all the main members intersected in one plane as shown in Fig. 10.

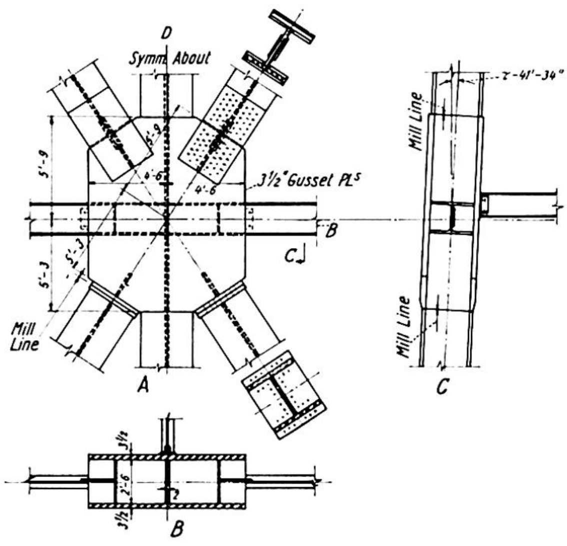

Fig. 10. Difficult Joint Detail for John Hancock Center

Effect of Temperature Variation

For all structures using a central structural core, the relative difference in temperature between the exterior column and the interior core column must be considered while developing the window wall and column jacket detail. Although the entire exterior column system does not have to be enclosed within a curtain wall, it is necessary to limit the exposure of the exterior column in a manner that the maximum differential movement between the exterior wall and the interior core will not exceed an allowable value. In terms of architectural detailing of the partitions, doors, etc., it is the author's experience that ¾ of an inch in differential movement should be considered as a realistic maximum limit. To stay within this limit the exterior wall structure may have to be insulated. Exterior columns may be exposed considerably more if artificial heating system is designed for all these columns. However, the experience of the writer indicates that artificial heating of exterior columns tend to verge on gadgetry and may lead to unreliable performance. Temperature controls requiring mechanical heating or cooling should therefore be avoided if possible.

Analysis Versus Understanding

The development of the computer technology in the last few years has given the structural engineer an almost unlimited scope in analysing any given structure no matter how complicated it seems to be. Generalized analysis programs such as *stress* and *fran* have already made the frame analysis a routine operation. Simplified methods of analysis are no longer considered adequate for final design of a structure. While in the past engineers used to take great pride analysing complicated structures, the development of these programs and the easy availability of the computers have naturally changed the role of the structural engineers more to the understanding and creation of systems rather than analysis of such systems. Research on all of these systems should, therefore, be directed not at the analysis as such, but at developing parameters for greater understanding of the systems. The effect of various variables need to be understood in order to make better engineering judgements in proposing these systems for any building. In each of the three rigid box or tube type structures discussed above, the following specific research is greatly needed.

Research in Framed Tube

1. Develop relationship between the properties of the spandrel and the column which may be used to make efficient preliminary design.
2. Develop non-dimensional parameters which will provide informations regarding shear lag in the exterior system subjected to wind loads.

3. Develop non-dimensional parameters which will improve understanding of the vertical load redistribution between all the columns in any face of the building.

4. Develop various fabrication and erection details and relate them in terms of fabrication and erection of costs. It would be interesting to see the effect of fabrication techniques on economy in different countries.

Research in Diagonaled Truss Tube

1. Since the diagonaled truss tube almost invariably will require special supports discontinuities at the base of the building, there is an immediate need for research in developing simple parameters to establish flow of load due to gravity as well as wind into these support points.

2. Economic studies with various joint details and floor slab construction.

3. Effect of temperature variation and erection tolerance of the exterior tolerance of the exterior wall on the internal stresses of the diagonal members.

Research on Optimum Truss Tube

1. Develop non-dimensional parameters relating properties of columns, diagonals, spandrels and main ties in order to establish pattern of vertical load redistribution.

2. Develop non-dimensional parameters relating the member properties to the effective tube action of the entire system.

3. Develop simple curves to establish redistribution of column loads due to settlement of any column.

Project Reports

In view of the increased building construction activity, it is expected that a large number of buildings using some of these systems are being built, or have been built. Reports on fabrication and erection details which have contributed to the success of these projects should be welcome for the conference. A short report on complete design and analysis for each of these projects should be selected for presentation at the conference.

Interaction Between Core and Exterior Tube

While the rigid box systems generally do not require added lateral stiffness from the interior core it may be necessary to make the interior core also rigid so that the floor distorsions under lateral load will be reduced to tolerable limits. An interaction study of this nature with particular reference to partition distortion will be interesting to the participants.

Conclusion

A general survey of the state of art for the rigid box systems developed within the last few years has been presented together with examples on each of these systems. For each of these systems the relative advantages and disadvantages are also discussed.

In view of the available generalized computer programs, it is pointed out that studies in methods of analysis are no longer as important as they used to be. However, studies and research which will contribute to better understanding of the overall behavior of each system are needed to help make preliminary design.

A list of research items for each of the rigid box systems has been incorporated in this report. It is expected that papers on these subjects will be forthcoming for presentation at the Eighth Congress in New York.