Design of Tall Buildings

Preliminary Design and Optimization

By

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Introduction

The design of tall buildings essentially involves a conceptual design, approximate analysis, preliminary design and optimization, to safely carry gravity and lateral loads. The design criteria are, strength, serviceability, stability and human comfort. The strength is satisfied by limit stresses, while serviceability is satisfied by drift limits in the range of H/500 to H/1000. Stability is satisfied by sufficient factor of safety against buckling and P-Delta effects. The factor of safety is around 1.67 to 1.92. The human comfort aspects are satisfied by accelerations in the range of 10 to 25 milli-g, where g=acceleration due to gravity, about 981cms/sec^2. The aim of the structural engineer is to arrive at suitable structural schemes, to satisfy these criteria, and assess their structural weights in weight/unit area in square feet or square meters. This initiates structural drawings and specifications to enable construction engineers to proceed with fabrication and erection operations. The weight of steel in lbs/sqft or in kg/sqm is often a parameter the architects and construction managers are looking for from the structural engineer. This includes the weights of floor system, girders, braces and columns. The premium for wind, is optimized to yield drifts in the range of H/500, where H is the height of the tall building. Herein, some aspects of the design of gravity system, and the lateral system, are explored. Preliminary design and optimization steps are illustrated with examples of actual tall buildings designed by CBM Engineers, Houston, Texas, with whom the author has been associated with during the past 3 decades. Dr.Joseph P.Colaco, its President, has been responsible for the tallest buildings in Los Angeles, Houston, St. Louis, Dallas, New Orleans, and Washington, D.C, and with the author in its design staff as a Senior Structural Engineer. Research in the development of approximate methods of analysis, and preliminary design and optimization, has been conducted at WPI, with several of the author's graduate students. These are also illustrated. Software systems to do approximate analysis of shear-wall frame, framed-tube, out rigger braced tall buildings are illustrated. Advanced Design courses in reinforced and pre-stressed concrete, as well as structural steel design at WPI, use these systems. Research herein, was supported by grants from NSF, Bethlehem Steel, and Army.

Subsystems and Components

The subsystems or components of the tall building structural systems are essentially the following.

- Floor systems
- Vertical Load Resisting Systems
- Lateral Load Resisting Systems
- Connections

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- Energy Dissipation Systems and Damping

The most commonly used structural systems have been classified by Khan, Iyengar and Colaco (1972, 74) These are illustrated in Figs.1.0 and 2.0. These are broadly defined as follows.

- Moment Resisting Frames
- Shear Wall-Frame Systems
- Shear Truss-Outrigger Braced Systems
- Framed-Tubes
- Tube-in-Tube Systems with interior columns
- Bundled Tubes
- Truss Tubes without interior columns
- Modular Tubes

The structural system should be able to carry different types of loads, such as gravity, lateral, temperature, blast and impact loads. The drift of the tower should be kept within limits, such as H/500.

Floor Systems

The floor system carries the gravity loads during and after construction. It should be able to accommodate the heating, ventilating and air conditioning systems, and have built in fire resistance properties. These could be classified as two-way systems, one-way systems and beam and slab systems. Two -way systems include flat plates supported by columns, flat slabs supported by columns with capitals or drop panels. Large shears and moments will be carried by the latter. Slabs of constant thickness are also used. Slabs with waffles are also used. Two-way joists are also used. One-way systems include following - slabs of constant thickness, with spans of 3m to 8m. Closely spaced joists could also be used. Beam and slab systems use beams spaced of 1m to 4m.Lattice floor joists and girders are useful to have ductwork inside of them. Floors of small joists are also used, in addition to integral floor slabs which house piping.
The IBM Mutual Benefit Life building, in Kansas City, MO illustrates the one way and two way joist systems. It also has shear walls for lateral resistance.

Concrete Floor Systems

In concrete floor systems, slabs of uniform thickness are often used with spans of 3m to 8m. One way or two way systems are used. Concrete joists or ribs are used in one way or two way systems, called pan joists are also used. One Shell Plaza, in Houston, TX uses this. Beam and slab system is used with beams spaced at 3m to 8m. Beam depths of L/15 to L/20 are used.

Steel Floor Systems

In steel floor systems, we use reinforced concrete slabs on steel beams. Thickness of slabs is in the range of L/30 to L/15 of the span. Pre-cast concrete slabs are also used with some shear connectors, grouted. Spans vary from 1.2m to 9m. Concrete slabs on metal decking are often used, with shear connection. For steel beams, wide flange shapes are used. Welded plate girders, latticed girders, and vierendeel girders are also used, which house ducts. Castellated beams and stub girders, developed by Colaco (1970), are also used, which allow mechanical ductwork to be placed between short stubs, welded on top of these girders. The stub lengths are 1.5m to 2m long. Stub girders are of composite construction.

Boatmen's Tower, St. Louis, and Mercantile Bank building, Kansas City, illustrate composite construction. These were designed by GCE Consultants, as a partner to CBM.

Vertical Framing Systems

Vertical framing elements are columns, bearing walls, hangers, transfer girders, and suspended systems such as cable suspended floors. Structural steel, reinforced concrete and composite columns are used. Bearing walls carry loads in compression, and sometimes, like staggered trusses between floors. Transfer girders are used to bridge large openings at lower levels of a tall building. Suspended systems use massive structure at top, with many floors suspended below by using cables. Lower floors are column free. Federal Reserve Bank in Minneapolis, MN is an example. Mercantile Bank building, Kansas City, has space truss as a transfer truss to carry loads to 5 columns at the first level.

Lateral Resisting Frame Systems

The essential role of the lateral resisting frame systems is to carry the wind and earthquake loads, as well as to resist P-Delta effects due to secondary moments in the columns. These systems could be classified into the following.

- Moment Resisting Frames
- Braced Frames
- Shear Walls

Moment Resisting Frames

Moment resisting frames are column and girder plane frames with fixed or semi-rigid connections. The strength and stiffness are proportional to the story height and column spacing. Concrete moment resisting frames, steel moment resisting frames and composite moment resisting frames are used. Composite beams and composite columns may be used. Concrete encased steel columns may be used. Steel beams encased in concrete and steel beams connected to slabs by shear connection are also used. Moment resisting frames could also be built with columns connected to flat plates, in concrete. Slab and walls could also be designed as moment resisting frames. Steel moment frames could be fabricated using 3 story panels of beam-column subassemblies. These are kept to 4m wide panels, with points of inflection at midpoints of columns and girders, field bolted. The transporting of panels is easy, when 4m width is used.

Braced Frames

Braced frames have single diagonal, x-braces and k-braces. Lattice and knee bracing are also used. Concrete braced frames are often not used, since shear walls are superior for construction and lateral resistance. Lattice bracing is used in pre-cast panel construction. Steel braced frames are used in interior cores, so connections could be easily made with wall panels. Composite braced frames may have steel bracings in concrete frames or concrete bracings in steel frames. Concrete encasement of columns and composite floor beams has also been used.

Shear Walls

Shear walls are plane elements made up of reinforced concrete thin walls having length and thickness providing lateral stiffness. The shear and overall flexural deformations are design constraints, along with the stress levels, axial and bending. Concrete shear walls may be cast in place or pre-cast. Pre-cast panel walls are also used within a concrete or steel frame to provide lateral resistance. The ductile shear walls used in earthquake resistant design have to be detailed carefully. Coupling beams should have diagonal reinforcement to develop shear resistance. Steel shear walls are also used sometimes, by connecting them to framework by welding or high strength bolts. Masonry shear walls are also used, with solid walls and grouted cavity masonry to carry shears and moments, with reinforcements encased.

Framed Tube Systems

Framed tubes are 3-dimensional space frameworks made by connecting intersecting plane frames at the corners by stiff corner columns. Framed tubes behave like giant flange frames and perpendicular web frames carrying axial loads and shear. The flange frames are normal to wind, while web frames are parallel to the wind. The axial forces in the columns in the flange frames are obtained by beam theory. However, due to flexibility of spandrel girders, and columns, there is a shear lag effect, in the box beam cantilever, with a hyperbolic type stress distribution in web frames. In the flange frames the column axial stresses are magnified also in a parabolic type stress distribution. Thus the corner columns may have almost 4 times the axial stress as in an ideal cantilever tube. Framed tubes have columns fairly closely spaced with variations from 1m to 3m. This allows stiff spandrel beams to be designed to enable lateral resistance. Shear lag effects are thus reduced. The overturning resistance of the overall tube is increased. Braced tubes are three dimensional diagonal braced or trussed system, acting like a giant space frame. The 100 – story John Hancock Center, designed by Fazlur R.Khan, Hal S.Iyengar, and Joseph P.Colaco, in Chicago, is the best example of a diagonal trussed tube. Its natural frequency is 0.125 hertz, giving a stiff system at about 30 psf steel for its structural weight. Shear wall tubes are made up of four shear walls connected at corners. Tube in tube system is designed by using interior core shear-walls combined with exterior framed tube. One Shell Plaza in Houston is one such example. Bundled tubes are made with multiple tubes sharing common interior side frames. Sears Tower in Chicago is an example of nine framed tubes to make a bundled tube, with belt and outrigger trusses at different levels. This is the tallest in the US, at 110 stories, and was designed by the same engineers as John Hancock. This has about 33psf steel and a frequency of 0.125 hertz. One Shell Plaza, Houston and Boatmen’s Tower, St. Louis, illustrate framed tubes designed by CBM and GCE Consultants. The structure weight is about 13 to 14 lbs/sft for a 32 story building, increasing to about 30 lbs/sft for a 90 story building. Tall Building Monographs (1978) have typical values, in the Systems and Concepts, Volume I.

New Structural Systems

New generation of extremely tall buildings may well go over 460m in height. Combinations of the previous systems are used to design new systems. Lateral resistance to drift and accelerations are overriding concerns. Damping is an important issue as the human comfort due to excessive acceleration beyond 25 milli-g, in the range of 35 to 50 milli-g, may have to be designed for. Tuned mass dampers and viscoelastic dampers are often used. Cable stiffened towers may also be designed for such tall buildings. The plan dimension of such towers is often limited to 60m for design. Height to width ratios of 7 to 1 are about the limit for such tall buildings. The twin towers of the world trade center had 20,000 visco-elastic dampers to absorb the dynamic sway. Their H/D ratio was 7.The Citicorp Tower, New York, has tuned mass dampers to absorb dynamic sway by increasing its damping to 3% of critical, from 1% in design. The 3 types of extremely tall buildings may be described as follows.

- Mega-structures
- Cellular Structures
- Bridged Structures

The 100 story John Hancock Center, Chicago, is a tapered trussed tube system which uses principles of mega-structures. Lower level has office and commercial space, while the upper levels have apartments.

This is a multiple use structure. This was designed by Khan, Iyengar and Colaco (1966). Cellular structures have increased overall building dimensions, by using a hollow, open center, and the framed tube designed on the periphery of this hollow mega tube. An exterior and interior wall tube may also be used. Bundled tube is an example, which is used in the 110 story Sears Tower, designed by Khan and Iyengar (1974).
The overturning resistance to wind can be increased by connecting two to four framed tube towers by bridges at different levels. This is termed bridged structure. The Petronas Towers, Kuala Lumpur, Malaysia, is an example of this. The width of the bridge should be equal to the size of framed tubes. The lateral forces are distributed to the towers in proportion to their stiffness. Tuned mass dampers are also used in mega-structures to enhance their damping. Flexible or sliding foundations can be used. Base isolation can also be used to enhance earthquake resistance.

Preliminary Design and Optimization

The structural design of a tall building involves conceptual design, approximate analysis, preliminary design and optimization, followed by detailed and final design. Codes and standards are used effectively to match limiting stresses, displacements and accelerations. Risk analysis with safety and reliability, is often included in arriving at suitable factors of safety in sliding and overturning. Tall narrow buildings develop uplift in the foundations, which should be designed for suitably. The initial selection of a structural system involves architectural, mechanical and electrical requirements. Different floor systems are studied, in combination with 3 to 4 lateral systems, with consequent structural schemes, almost 15 of them, for various combinations between gravity and lateral. Preliminary design and optimization of various schemes follows, in an iterative fashion by satisfying drift and acceleration limits. Often simple software systems are used in this stage, such as frame and shear-flexure cantilever beam, and cantilever box beam models. The first is for moment frames, while the second is for shear wall-frame buildings, and the third for framed tubes respectively. Methods developed by Fazlur Khan and Sbarounis (1964), Heidebrecht and Bryan Stafford Smith (1973) and Coull (1974) are used for shear wall-truss frame interaction, while the latter is used for framed tubes. Goldberg (1975) also has approximate methods of analysis for tall buildings composed of frames, shear wall-frames and framed tubes. Displacements and member forces are obtained, and corresponding components designed at different levels. The author and his students have developed some software systems based on these techniques. They are used to model frames, shear wall-frames, framed tubes and outrigger braced tall buildings. Herein, a review of these techniques is made. Sequence of design calculations is examined to assess procedures for preliminary design.

Optimum Structural Systems – Design Issues

The major quantity of interest in arriving at the cost of a structural system is its unit weight, in lbs/sft or in kg/sqm. In other words, the weight is directly associated with the overall efficiency of the system in carrying gravity and lateral loads. The stiffness of the system is associated with weight. An ideal structural system could be the one in which the steel required to carry the gravity loads alone, could carry the wind loads. Optimization could be such that the wind could be carried by keeping stresses within the difference between allowable stresses for gravity plus wind and stresses due to gravity alone, usually a one third increase. However, this is not always possible, as height to width ratios, may not allow this design to be achieved. Some premium for wind is often required. Buildings within about 13 to 14 stories tall, this is often possible. The one third increase allowed in the allowable stresses may be just sufficient to carry wind. Buildings in the 20 to 50 story range, this is not always possible. The structural engineer is required to use innovative schemes like shear wall-frame, shear truss-frame and framed tubes and outrigger braced systems. This premium for wind is often minimized by an optimum design of beams and columns and floor systems to match given stress limits and drift.

Height to Width Ratios

The efficiency of the structural system is often determined by its height to width ratio. The larger width for any height usually means larger stiffness. This implies larger bay widths, and larger lever arm for flange frames in framed tubes. The optimum height to width ratio should be between 5 and 7. Shear truss-frame buildings, the width of the truss should be less than about 12, relative to its height.

Span Dimension of Girders

The span length of girders often determines the steel quantity for the floor framing. Smaller spans for exterior frames, will lead to more efficient framed tube systems.

Member Sizes of Frame

The proportions of members of the frame play a leading role in efficiency, with deeper members being more effective in resisting drift. Deeper members also affect mechanical-architectural cost, and increased floor heights. The design optimization should include these costs. Larger column widths and deeper spandrel may lead to more efficient framed tubes. The orientation of the wider columns should be along the plane of the frame. Column spacing could be arranged in such a way, that all gravity steel can effectively carry wind, with very little increase in weight for girders. Floor framing should be so arranged that most beams frame directly into columns. Thus, gravity loads could be directly carried without extra girders.

Floor Framing Design

The floor framing is usually about 20% of the structure weight. It is useful to optimize this subsystem, before hand. Span to depth ratios, spacing of beams, slab thickness, composite design, and openings for mechanical ductwork, should be carefully considered in floor system design, for efficiency. Span to depth ratios for floor framing are usually good at 20 to 24. This is minimum depth for strength and stiffness. Open web trusses could be used for long spans. Composite action between trusses and slabs should be developed by shear connection. Two way grid systems are often avoided, as fabrication costs are higher. However, in concrete design, they are used if repeating formwork is used. Widest possible spacing of beams and largest spans for slabs should be used. The composite floor systems also have larger stiffness and diaphragm stiffness for the floors. This contributes to overall stability of tall buildings in resisting wind, blast and impact loads. Solid slabs are better than slabs with cellular openings. The diaphragm stiffness is increased.

Shear Lag Effects

This is an important consideration for framed tube system in extremely tall buildings. This effect should be minimized by using deep spandrels and wide columns and smaller spacing between columns. Transfer beams are used at lower levels to carry less number of openings. The stiffness between column and girder should be balanced. Sometimes, deeper built up I shaped beams are used to increase stiffness. Field welding should be minimized, by using 3 story sub-assemblies of column-girder trees, field bolted at points of inflection. These reduce erection costs. High strength steel is not often beneficial. Fabrication costs are high for these. Reduction in total number of pieces to be assembled will result in cost savings.

Comparison of Systems Efficiency

Plane frames (Type I), the important variables are span, bay lengths, and member depths. The spans vary from 6.1m to about 15.2m (20ft to 50ft). Shear trusses (Type II) improve the efficiency of plane frames considerably. Here, the distance between the chords and the number of trusses are important parameters. An optimum combination of trusses and frames yield efficient system. In concrete, it is an optimum combination of shear walls and frames. In framed tubes, the equivalent cantilever behavior of the tube dominates the efficiency. The overall length and width of the building determines its stiffness. The equivalent tube moment of inertia depends on column areas and chord distances of these columns from the centroid of the building. The systems with outrigger and belt trusses are more efficient than ones with shear truss only. The outrigger trusses increase the system efficiency by 20 to 25%. This is accomplished by engaging the exterior columns along with the core shear trusses. They develop overturning resistance. In system 5 and 7, the interior trusses interact with equivalent end cantilever channels. These are often termed partial tubes (Type III). Band trusses added to these will improve stiffness further. The full framed tube (Type IV) is more efficient. Bundled tube is used in Sears Tower, Chicago. Diagonal truss tube is used in the John Hancock Center, Chicago. Diagonal and tapered tubes, even though highly efficient, may have increased costs, of 15% or so, due to connections for diagonals and the tapered columns. Framed tubes with only perimeter frames are less efficient, due to shear lag effects. Tapered tubes have less shear lag. The tapered tube being designed in India, at Jabalpur, at 667m height and 334m width is highly efficient, with a ratio of only 2. Minoru Yamasaki and Associates are the architects, to be completed in 2008. This will be the tallest in the world. Fig.2 is an illustration of the various systems.Δ

Initial Selection of Structural System

Several different structural schemes are examined, for the initial selection of systems. Knowledge of behavior each structural system, rapid preliminary design methods, approximate analysis and optimization techniques are necessary to achieve this balance in design. Often 15 structural schemes are studied, with various combinations of gravity and lateral systems. Starting with a basic plan size, and height, each scheme is developed with a candidate structural system. In order to compare systems, different column spacing, member sizes, truss and other subsystem dimensions such as outriggers, and diagonal truss system should be carefully examined. Optimization can then be made with one or two story sub assemblies, at different heights of the building, in 2 to 3 iterative cycles, for given drift. Interpolation, often linear, could be made from these different level optimizations, for member sizes and moments of inertia, at intermediate levels. This is then used in an overall stress analysis, using large structural analysis software systems, such as Strudl, Sap4, Etabs and Drain2D. This will enable rapid final design and detailing. Otherwise, the initial sizes may not be very efficient and convergence to drift and acceleration limits will take many more iterative cycles. The optimum design of a tall building is an art and science, with the accumulated years of experience by the structural engineers, with techniques of stress analysis, structural design and detailing, put to judicious use at the right time and place. The detailed steps are as follows (Iyengar, 1972, Colaco, 1975).

Step1

Gravity loads are computed using live load reductions of all columns. This could be done at every 4 to 8 story level. The structural weight is assumed on average values, and variation could be assumed to vary on a linear variation from top to bottom, or a quadratic variation. For equivalent tube systems, this may not be valid, since these buildings distribute loads to other columns. An aggregate load, from groups of columns, for which the gravity loads are approximately the same, is computed and then the average load on each column in that group is obtained. These groups are divided into smaller groups at the top, as the tube action is more complete at bottom than at the top in distributing loads.

Step2

Column areas and moment of inertias are computed based on average axial stress. These should also be reduced for combined gravity and wind effects, in an approximate sense. The member efficiency, its location and fabrication economics and system efficiency should be included in this design. Wind effects may be included using portal or cantilever method for frames, while for framed tube, an equivalent cantilever model may be used. Agbayani and Jayachandran(1989) suggested a computer based method for column design.

Step3

The effects of wind are also included in the determination of equivalent girder sizes to match given drift limits. Usually we use H/500 as this limit. The shear racking component of drift is about 80 to 90% of total and column shortening effects are the remaining drift, for plane frames. Since points of inflection are at midpoints of columns and girders, the required moment of inertia of girders may be obtained by the following (Iyengar, 1972).

Equation 1

$$\sum(Ig) = \frac{VLH\sum(Ic/H)}{12E(\Delta/H)\sum(Ic/H) - VH}$$

In which L = girder span, H = story height, V = story wind shear at any level and ∑(Ic/H) and ∑ (Ig) are summations of column and girder stiffness, at any story level. The drift is Δ at any level, usually about H/500, normally 6mm to 8mm for any story. The girder sizes thus obtained now are checked also for the wind moments at that level using strength requirements. This expression is for plane frames only and was derived based on slope-deflection method. This could be used in frame part of shear truss-frame also.

Optimization of an equivalent one story subassembly could be made at this stage by a technique from Khan (1966). One story subassembly is modeled using points of inflection at midpoints of columns and girders, and for a drift limitation of H/500, a plot is made up of the variation of column stiffness versus structural steel weight. The region of minimum weight suggests optimum values to be used. Similar plots could be made for variation of girder stiffness also. Optimum sizes are then selected. This analysis could be made every 20 floors. Smaller intervals could be used for dramatic variations in wind loads, and frame configurations, which change rapidly. Computer software for plane frames could be used.

Similar models may be used for frame portion of shear truss-frame type buildings in group II. In addition to this, for shear wall-frame and shear truss-frame buildings, it would be advisable to further optimize the system, using methods by Khan (1966) and Heidebrecht and Smith (1973). This assumes that the tall building could be modeled as a shear-flexure cantilever beam, and its differential equation is solved for displacements and then moments and shears in the wall and frame separately. Then frame and wall could be proportioned using these respective moments and shears. Khan’s method is by equivalent 10-story models, while that by Heidebrecht is by solving the shear-flexure beam, in a closed form solution. The essential steps in this approach are outlined below.

The shear truss could be modeled as an equivalent cantilever beam by using an equivalent moment of inertia It as

Equation 2

$$It = Ef \sum Ac * d^2$$

Where Ac = area of one column, d = distance of column to centroid of truss, Ef = efficiency factor for truss, in the range of 0.8 to 0.9. For k-bracings the lower value is used while for x-bracing the higher value is used. For partial k-braces we use about 0.75. The interaction between trusses and frames could be obtained by using equivalent 10-story models developed by Khan and Sbarounis (1964), which give values of moments and shears carried by trusses and frames separately. The lateral displacements could be obtained as a proportion of the free cantilever modeled by the shear truss. Shear walls could be substituted for trusses in this approach. The weight of structural steel can then be obtained by plots of truss versus frame stiffness. This will enable optimum designs. The detailed structural analysis can then be made using these initial sizes.

Optimization of buildings with truss-frame stiffened with out-rigger trusses could also be made similarly. An effective increase in stiffness due to out-riggers is about 10 to 20% and about 15% average. An optimization of the stiffness and the location of out-riggers could then be made using equivalent models.

Framed tube buildings could be also modeled using an equivalent cantilever beam model. The shear racking component of drift is computed using the same approach as for moment resisting frames. The column shortening component is computed by using an equivalent moment of inertia for the tube, as follows.

Equation 3

$$Itube = Ef \sum Ac * d^2$$

Where Ac = area of one column, d = distance of column to centroid of tube Ef = Efficiency factor for the tube. The drift of the tube is made up of two parts, shear racking and column shortening effects.

Optimization of the tube systems can now be made by parametric variation. Different column spacing and depths of members could be used to bring down the shear racking part of deflection to be within 30 to 40% of total drift. The weight of steel may be computed in each cycle to realize the optimum values. If the windows design requirements limit the column depth to be 460mm, whereas if 3m column centers are used, then column depths could be as large as 0.9m to 1.2m, four times larger. In other words, the designer should also study beam stiffness also, to arrive at a balanced design. The shear racking component of deflection could be reduced further, if diagonal bracings are used in tube systems. This should be used to insure that the shear racking drift is only about 20% of total.

Optimization of Various Structural Systems

After the initial selection of certain types of structural systems, it would be now useful to do some detailed optimization studies to fine tune these systems further for drift and acceleration limits. The acceleration limits used are in the range of 0.5 to 1.5 milli-g, and frequencies computed using condensed stiffness of equivalent 10 story models. This refines the tall building design for strength, stability, serviceability and human comfort aspects. Some P-Delta analysis could be made for overall stability. This phase of design is mainly for verification of systems selected during the previous phase of preliminary design.

The plane frame buildings could be easily optimized because only the stiffness of two elements are required – beams and columns. An equivalent 10 story could be made using the following equations. If we lump n floors into an equivalent floor, then the stiffness of girder and column in the model can be written as

$$Kgm = n\ Kg \qquad Kcm = n\ Kc \qquad Acm = Ac \qquad \text{Equation 4}$$

where Kgm = Stiffness of girder in the model, Kcm = stiffness of column in the model and Acm = the area of column in the model. Equivalent diagonal brace areas can be determined to represent displacement characteristics of model and prototype truss. The outrigger braced buildings can also be modeled as shown in fig 5b. The equivalent frame-truss model is shown in fig.5a. Shear wall-frame buildings could be modeled using the same figure. In the outrigger braced tall buildings, the exterior columns which interact with the outriggers and interior shear truss, are to be simulated as shown in 5b.

Optimization of framed tube buildings needs to be studied further to minimize shear lag and best load distribution for gravity and lateral loads. Equivalent 10 story models of plane frames from the framed tube as shown in fig.5c, are subjected to an axial load at top, on one column. The rate and the manner of distribution of this load to other columns in the frame, will give some indication of the shear lag characteristics. Then one can study various combinations of column spacing and member depths to arrive at an optimum proportion. Obviously, introduction of diagonals in the framed tube will improve its efficiency and reduce shear lag. This leads to the diagonal truss tube.

Optimization of a diagonal truss tube is often done by performing a plane truss analysis of each of the perimeter frames. An equivalent 10 story model of a diagonal truss frame is shown in fig.5d. This gives a better column axial stress distribution, with lesser amount of shear lag. An axial load applied at the top, leads to a uniform stress distribution in lower columns, since the diagonals interconnect columns and spandrel girders. The aim is to have the columns carry the axial load in proportion to their axial stiffness and hence, areas. Effects of various diagonal areas, column, main ties, secondary ties and their areas, can now be studied. This leads to an efficient truss tube, with optimum member sizes. This tube will then be able to resist lateral loads in an efficient manner.

Overall optimization of the tall building frame is complex and time consuming. However, equivalent 10 story models as illustrated in the previous phase will lead to good designs. The overall design and optimization steps are shown in fig.6 for preliminary design. This can also be used for detailed design, with larger software systems, with several floors. The various subsystems, plane frames, shear truss-frames, outrigger braced truss –frames, framed and diagonal truss tubes can be studied in some depth, for member sizes, span length, stiffness and frequency, by the flow chart methodology. Often simple plane frame, plane truss and space truss and space frame analysis software could be used. The tall building design is simplified by subsystem design and optimization of various subsystems.

Summary and Conclusions

The design issues for preliminary design and optimization have been briefly summarized, and a rational methodology of design was shown. This enables optimization of initial structural systems for drift and stresses, based on gravity and lateral loads. Some insight into the design of many types of tall building structural systems and their subsystems was provided based on past experience in tall building design. The design issues are efficiency of systems, stiffness, member depths, balance between sizes of beam and column, bracings, as well as spacing of columns, and girders, and areas and inertias of members. Drift and accelerations should be kept within limits. Good preliminary design and optimization leads to better fabrication and erection costs, and better construction. The cost of systems depends on their structure weight. This depends on efficient initial design. Efficient structural design also leads to a better foundation design, even in difficult soil conditions. The structural steel weight is shown to be an important parameter for the architects, construction engineers and for fabrication and assembly. Optimization fine tunes this .

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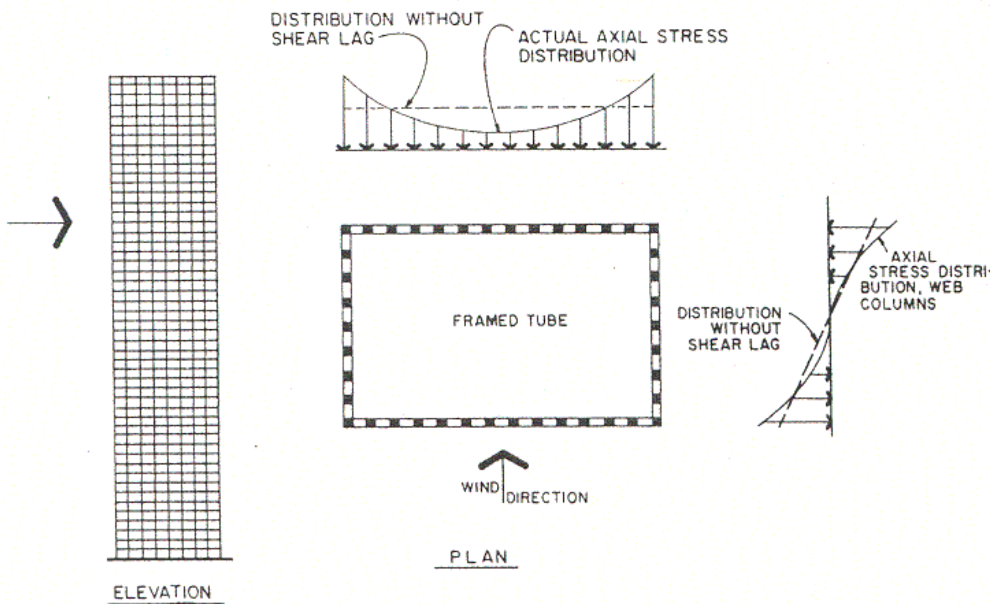

Figure 1 - Shear lag effects

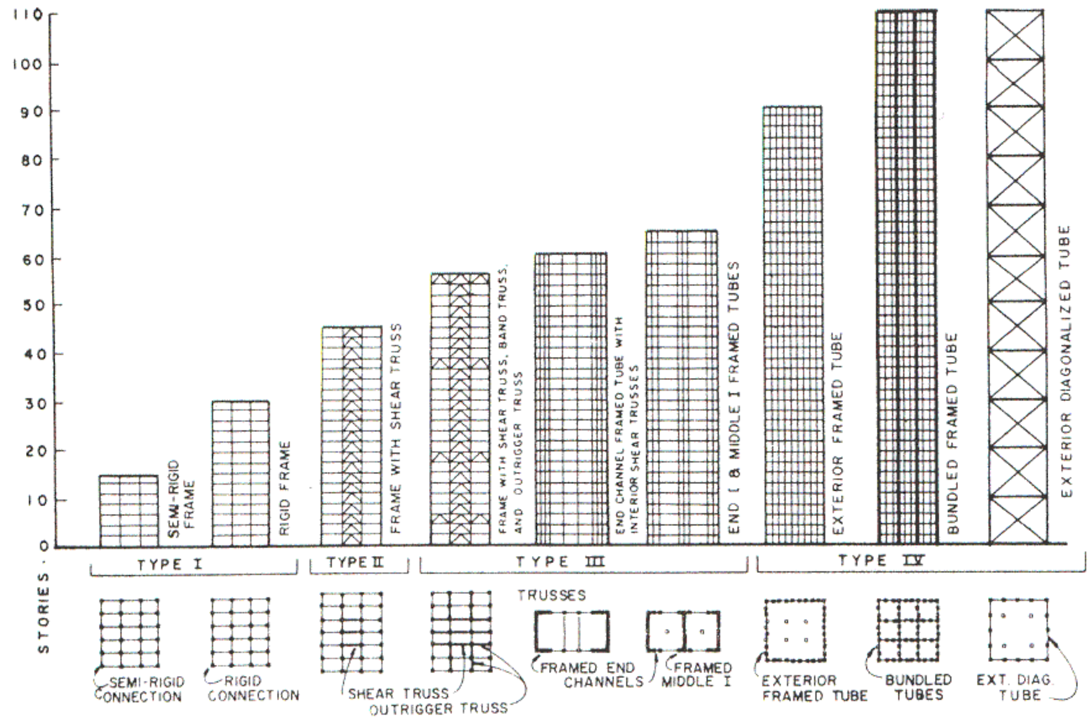

Figure 2 - Structural Systems

Credit : Dr.Hal S. Iyengar (1972)

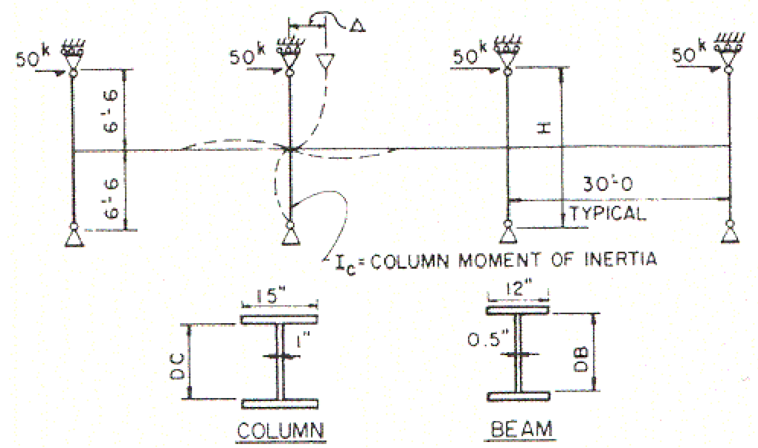

Figure 3 - One story sub-assembly

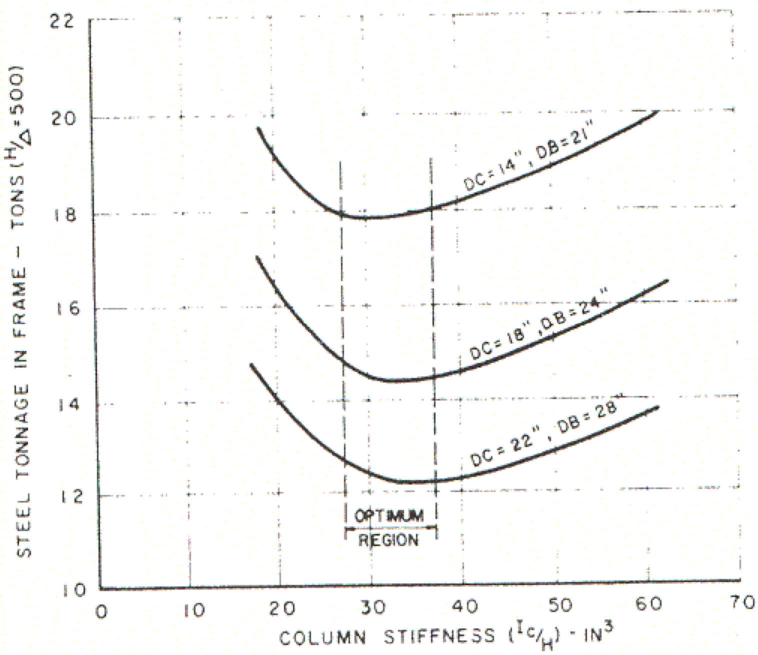

Figure 4 - Optimum beam and column stiffness

Credit : Dr.Hal S. Iyengar (1972).

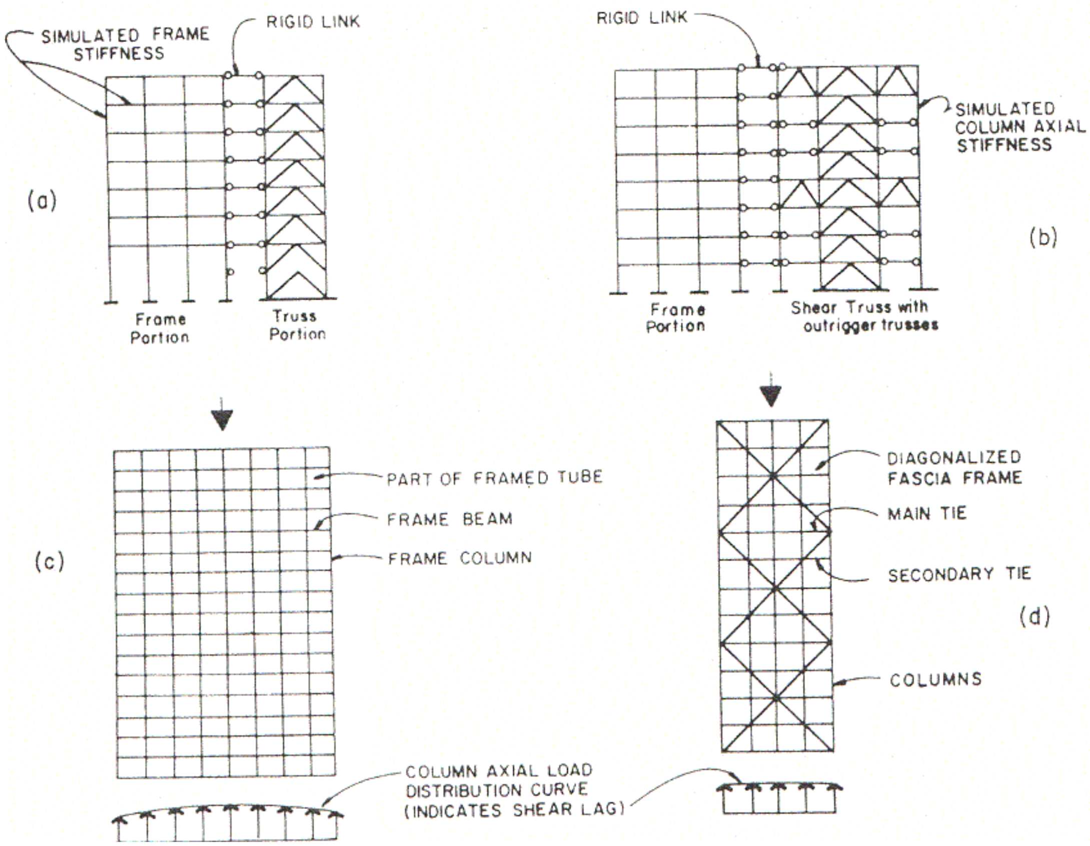

Figure 5 - Equivalent ten story models

Credit : Dr.Hal S.Iyengar (1972).

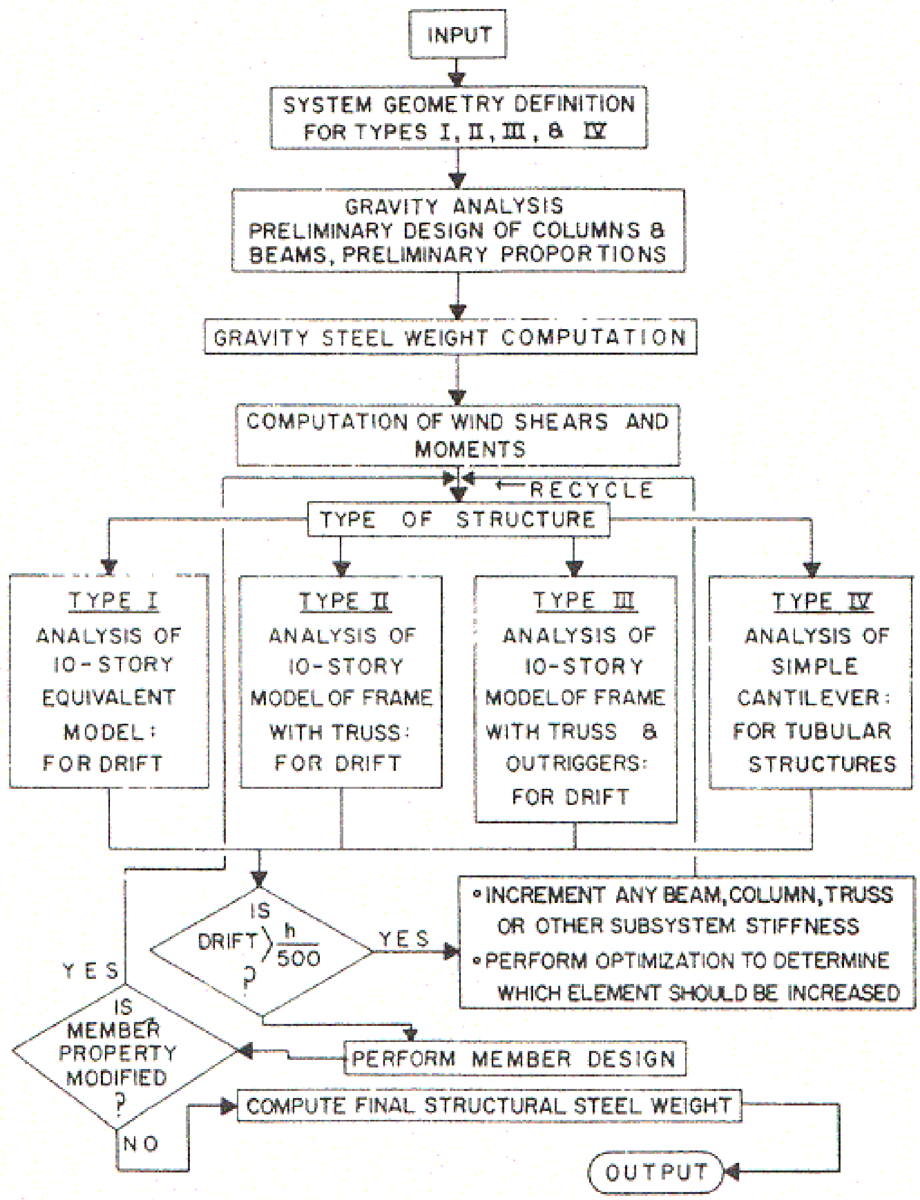

Figure 6 - Preliminary Design Flow Chart

Credit : Dr.Hal S. Iyengar (1972)

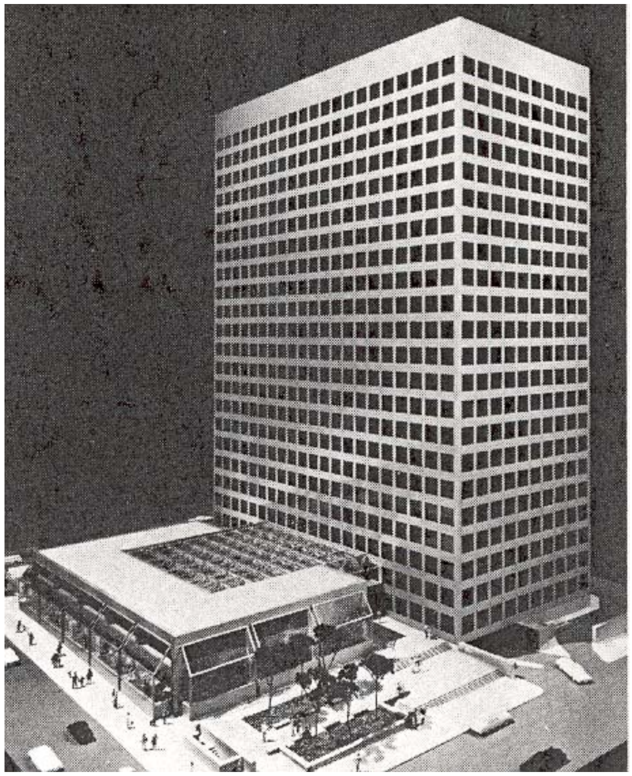

Figure 7 Boatmen's Tower, St. Louis, MO

Figure 8 Composite System, Houston, TX

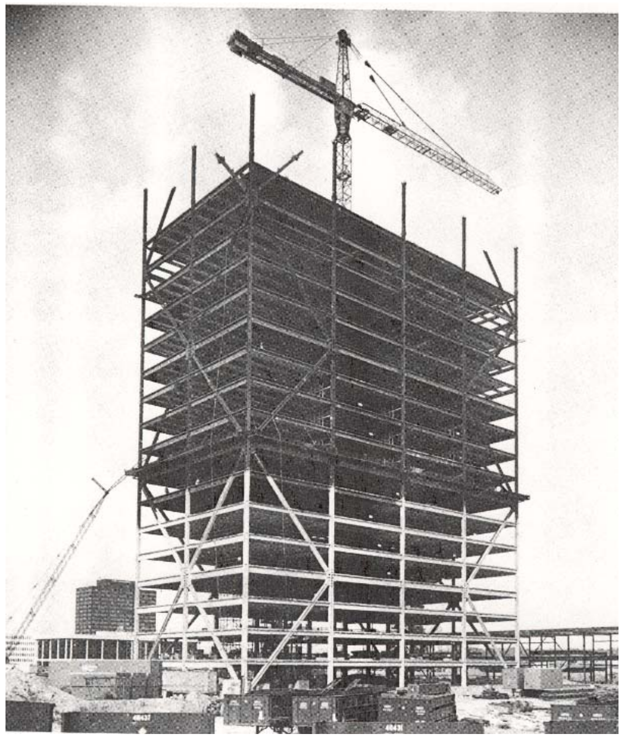

Figure 9 Partial Tube System, Southfield, MI

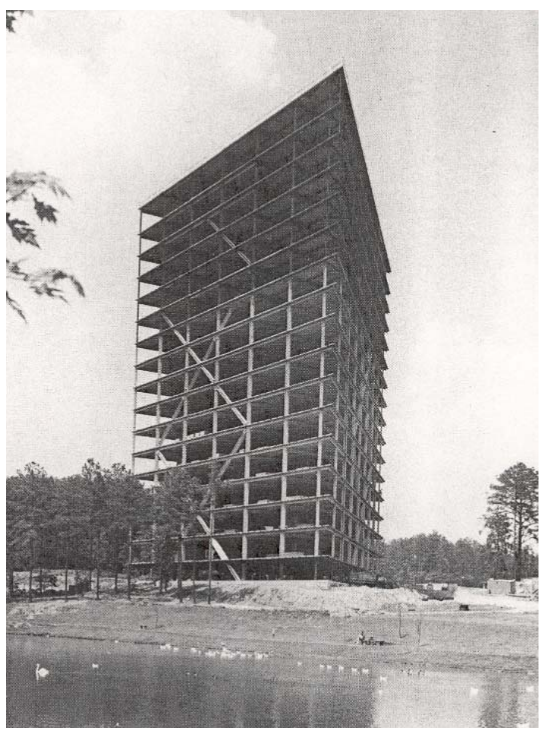

Figure 10 Partial-Tube, Athens, GA

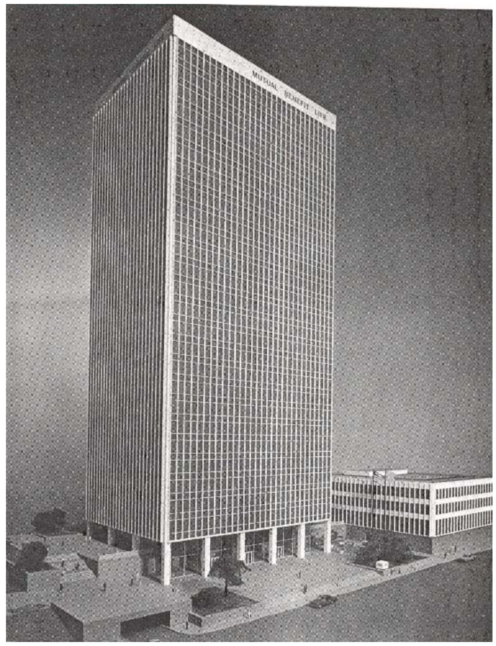

Figure 11 Shearwall-Frame, IBM Tower, Kansas City, MO

Figure 12 Mercantile Bank Tower, Kansas City, MO

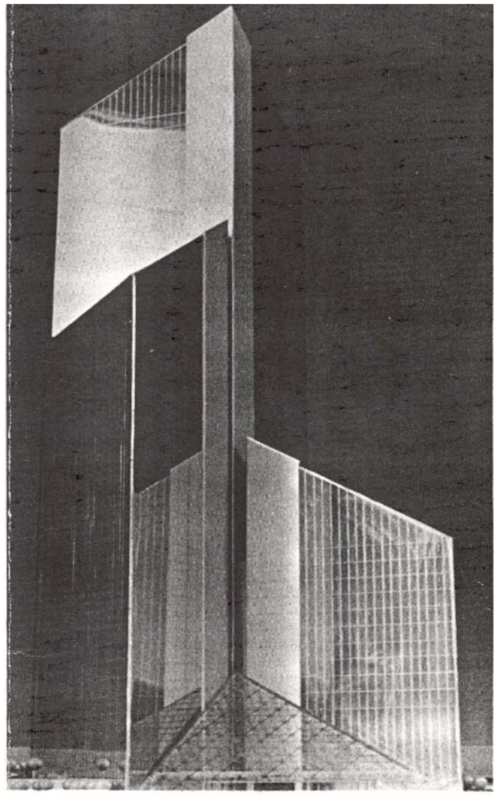

Figure 13 Torre Infinito, Caracas Venezuela