The Grappling of High Rise Buildings Subjected to Lateral Loads

Abstract

The task of structural engineer is to arrive at suitable structural systems, to resist gravity, lateral, fire and blast loadings. The architects and owners often require the weight of a structural system in N/sq. m. of the weight of structural steel. The design of tall buildings involves the following design criteria,

- Strength – stresses within permissible limits.
- Serviceability – displacements within specified limits.
- Human Comfort – accelerations within specified limits.
- Stability – sufficient safety against buckling and P-Delta effects.
- Ductility – sufficient safety against yielding under extreme events.

This paper presents the structural behavior of high-rise buildings with different structural system caused due to wind and seismic effects. The grappling for the realization of salient aspects of the structural design methodology deployed for the tall buildings are covered in this paper. The grappling of structural engineer about structural system, which is indispensable for the realization of optimum structural system for tall buildings subjected to wind and seismic forces are discussed in this paper in view of tall structures such as 1) Mega-structures, 2) Cellular Structures and 3) Bridged Structures.

Keywords: High rise buildings; Grappling; Structural systems; Lateral loads; Optimization.

1. Introduction

Practically, the design of high-rise building requires special consideration of dynamic behavior in case of the wind and seismic loads. The study demonstrates the process of dynamic response analysis of high-rise building and emphasizes the importance of long-period ground motion effects.

The essential role of the lateral resisting frame systems is to carry wind and earthquake loads, as well as to resist P-Delta effects due to secondary moments in columns. Evidence of seismic activity in world demonstrates the need for earthquake protection in certain regions. Geographic location determines the wind gust pressure and the seismic factor. The considerable influences that location has on the design forces are discussed and the same structure is analyzed for two different areas, one with high wind loads and the other with a high earthquake factor. Shear and moment are plotted against building height, and it was found that although the shapes of the curves remain the same, the relations between those for wind and those for earthquake vary considerably from one region to the other. The higher the building, the more probable it is that wind effects will exceed earthquake effects. Earthquake effects, on the other hand, exceed those due to wind for all buildings below a certain height.

2. Lateral Loads

Most lateral loads are live loads whose main component is horizontal force acting on the structure. Typical lateral loads would be a wind load against a façade, an earthquake, the earth pressure against a beach front, retaining wall or the earth pressure against the basement wall. Most lateral loads vary in intensity depending on the buildings geographic location, structural materials, height and shape. The dynamic effects of wind and earthquake loads are usually analyzed as an equivalent static load in most small and moderate sized buildings. Others must utilize the iterative potential of the computer. The design wind and earthquake loads on a building are substantially more complex which will be evident in this paper.

2.1 Wind Loads

Buildings and their components are to be designed to withstand the code specified wind loads. Calculating wind loads is important in design of the wind force-resisting system, including structural members, components, and cladding against shear, sliding, overturning and uplift actions.

The most common lateral load is a wind load. The Eiffel Tower is one of the examples of a building which has a structure that was designed to resist a high wind load. Wind against a building builds up a positive pressure on the windward side and a negative pressure (or suction) on the leeward side. Depending upon the shape of the structure it may also cause a negative pressure on the side walls or even on the roof. The pressure on the walls and roof is not uniform, but varies across the surface. Winds can apply loads to structures from unexpected directions. Thus, a designer must be well aware of the dangers implied by this lateral load. The magnitude of the pressure that acts upon the surfaces is proportional to the square of the wind speed.

Wind loads vary around the world. Meteorological data collected by national weather services are one of the most reliable sources of wind data. Factors that affect the wind load includes the geographic location, elevation, degree of exposure, relationship to nearby structures, building height and size, direction of prevailing winds, velocity of prevailing winds and positive or negative pressures due to architectural design features (atriums, entrances or other openings). All of these factors are taken into account when the lateral loads on the facades are calculated. It is often necessary to examine more than one wind load case.

For this paper, it is assumed that wind loads as well as the pressure they develop upon wall and roof elements, are static and uniform. They actually not only pound a structure with a constantly oscillating force, but also increase as a building increases in height. The loading of a tower can be very roughly approximated by and evenly distributed load. It is a vertical cantilever. The applet below allows us to investigate the variables which influence the structural behavior of a tall, thin tower. It does not represent actual methods of calculating the total wind force on a tall building. It is intended to demonstrate the interaction between the variables of the equations which governs the structural behavior.

2.2 Earthquake Loads

Earthquake loads are another lateral live load. They are very complex, uncertain and potentially more damaging than the wind loads. It is quite fortunate that they do not occur frequently. The earthquake creates ground movements that can be categorized as a shake, rattle and a roll. Every structure in an earthquake zone must be able to withstand all three of these loadings of different intensities. Although the ground under a structure may shift in any direction, only the horizontal components of this movement are usually considered critical in a structural analysis. It is assumed that a load-bearing structure which supports properly calculated design loads for vertical dead and live loads are adequate for the vertical component of the earthquake. The static equivalent load method is used to design most small and moderate-sized buildings.

The lateral load resisting systems for earthquake loads are similar to those for wind loads. Both are designed as if they are horizontally applied to the structural system. The wind load is an external force, the magnitude of which depends upon the height of the building, the velocity of the wind and the amount of surface area that the wind attacks. The magnitude earthquake load depends upon the mass of the structure, the stiffness of the structural system and the acceleration of the surface of the earth. It can be seen that the application of these two types of loads is very different.

3. Lateral Resisting Frame System

The essential role of 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

3.1 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. 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.

4. 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 use. 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 10 are about the limit for such tall buildings. The twin towers of the world trade centre had 20,000 visco-elastic dampers to absorb the dynamic sway. Their H/D ratio was 7. The three types of extremely tall buildings may be described as follows.

- Mega-structures
- Cellular Structures
- Bridged Structures

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.

5. Seismic Effects on Curtain Wall System

A curtain wall system consists of multiple facing panels, panel supporting frames, and frame connection system secured to the edge of the floor slab or the spandrel beam. Weather sealing methods against air and water infiltrations are provided along the joints between two adjacent facing panels. The thermal load and wind load are the direct loads on the curtain wall system. The direct loads can relatively easily be designed with adequate safety factors. For example, the curtain wall system is normally designed with adequate safety factor for a wind load caused by the maximum wind speed with 50-year recurrence intervals. In the event of seismic activity, however, the curtain wall system cannot be simply designed for a specific earthquake magnitude with 50-year recurrence intervals.

A seismic event causes the building frame to undergo various displacements producing relative inter-floor deflection (vertical component of seismic motion) and inter-floor story drift (horizontal component of seismic motion). Since the mass of the building frames and floor slabs are extremely large compared to the mass of the curtain wall system, it is impractical to design the curtain wall system to resist the inertia forces inherent in the relative inter-floor deflection or inter-floor story drift. Therefore, the curtain wall system must be designed to tolerate the seismic-induced building frame displacements which are functions not only of the seismic zone rating but also of the building frame stiffness. In case of seismic induced story drift, the curtain wall supporting mullions are forced to tilt to one side which in turn will create the tendency to force the curtain wall panel to change shape. However, the in plane stiffness of the curtain wall panel is normally very high against changing shape, therefore absorption of the amount of lateral distortion caused by the story drift produces a significant amount of shear strain along the sealant lines. This type of shear strain along the sealant line is the primary failure in the seismically active regions. The recent trend of allowing a higher degree of story drift in the building frame design makes the sealing integrity design even more problematic.

6. 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 suitability. 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. 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.

6.1 Height to Width Ratios

The efficiency of 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 farmed 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.

6.2 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 columns and girder should be balanced. Sometimes, deeper built-up I shaped beams are used to increase the stiffness. Field welding should be minimized, by using 3 story sub-assemblies of column-girder trees, field bolted at points of infection. 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.

7. Concluding Remarks

Several different structural schemes are need to be examined for the initial selection of systems. Knowledge of behavior of each structural system, rapid preliminary design methods, approximate analysis and optimization is necessary to achieve this balance in design. 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 overall stress analysis using large structural analysis software systems such as STRUDS, SAP or ETABS. 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.

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