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PERFORMANCE CHARACTERISTICS OF TALL FRAMED TUBE BUILDINGS IN SEISMIC ZONES

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ABSTRACT

Tall framed tube buildings are occasionally used in seismic zones because they perform well as moment-resisting space frames under lateral seismic loads due to their ductile three-dimensional behavior. This paper reviews the intricate performance characteristics of such buildings and presents an example of a "tube-in-tube" ultra high-rise building to illustrate the concepts.

KEYWORDS

Structural performance; ductility; dynamic analysis; lateral drift; fundamental period; modes of vibration; base shear; overturning moment; shear lag; optimum design.

INTRODUCTION

It is well known that the behavior of a building under seismic loads is essentially a random vibration problem. However, tall buildings respond differently under such loads from low-rise buildings due to their large slenderness ratios. Because of the greater flexibility and time periods of tall buildings, such buildings undergo "whiplash effects" which are represented by a series of progressively higher and more complex modes of vibration. Because of the presence of many parameters such as building mass and stiffness, dynamic characteristics of the building, intensity and nature of ground motion, soil-structure interaction, etc., the inertia forces generated in the building at different heights can hardly be accurately determined. Methods of dynamic analysis such as time-history analysis and response spectrum analysis only approximately estimate these forces but they have their own limitations. The response spectrum method is more popular because of its inherent simplicity of computation.

In seismic design, it is not sufficient to make a building or a member strong. It must also have sufficient ductility to dissipate or absorb energy imparted to the building by an earthquake. Thus, it is necessary to manipulate the structural design such that the building will provide adequate resistance to earthquake forces against collapse or excessive deformation that may damage architectural and non-structural components or cause death, injuries, discomfort, or panic for the occupant. For tall buildings, say over 30 stories, occurrence of collapse under seismic loads is rare. This is primarily because of longer periods of these buildings resulting in lower seismic forces and due to a higher degree of redundancy of the structure. Nevertheless, member stresses and deformations could be very large for such buildings under seismic loads.

Although the structural cost of a high-rise building is only about 20 to 25% of the total building cost depending upon the nature and complexity of the building project, yet substantial savings could be achieved by optimizing the design by following an iterative design process. In order to conduct such a design, an in-depth understanding of the behavioral parameters is of crucial importance for the designer.

SOME BEHAVIORAL PARAMETERS FOR TALL BUILDINGS

Framed structures may be either rigid frames or frame-shear wall type buildings. However, the presence of shear walls--although beneficial for increasing the building stiffness--reduces the overall energy-absorption capacity of the building. The tubular buildings allow for an economical solution for buildings about 40 stories or more in height.

An important parameter in optimizing the building frame is to make the lateral drift as close as possible to the maximum permissible drift. For the wind-load analysis, a maximum recommended interstory drift index of 1/500 is usually allowed in the design, which must be satisfied regardless of the seismic design criteria. For the seismic design, the drift limitation varies from code to code and depends on the type of construction. For equivalent static analysis, the allowable drift index, for example, may be taken as, say, from 1/250 to 1/200, while for dynamic analysis, the maximum drift index may be taken as 1/133 and 1/66 for the maximum probable (50-year return period) and maximum credible (100-year return period) earthquakes, respectively. Another significant parameter is the fundamental period of a building. The object of optimization is the maximization of building period through increasing the flexibility of the building without exceeding the permissible maximum drift value. Two other parameters are the base shear and base overturning moment. These parameters are, however, related to the stiffness and time period of the building in addition to the building mass. Another response parameter is the serviceability acceleration level of the structure. Other effects that should be considered for analysis are the P-Delta behavior and joint deformations of the tube frame (Charney, 1990).

SEISMIC BEHAVIOR OF FRAMED TUBE BUILDINGS

A tubular system is formulated by arranging the closely-spaced perimeter columns at a spacing of 15 feet (4.6m) or less and connecting them with deep spandrel beams at each floor. Since a good preliminary design results in less number of iterations during the final design process, the tubular structures should be designed as optimally as possible before the seismic load analysis of the structure is performed. The tubular behavior for a framed tube that results in axial stress in the column does not develop 100% efficiency (i.e., as for an ideal tube) due to a phenomenon called shear lag. The tube frame in a way resembles a thin-walled tube structurally that results in considerable shear lag effect which in turn gives rise to softening of the structure. An approximate method of dynamic analysis of tube frames using a continuum approach was developed by Chang and Foutch (1983). A measure of tubular efficiency of a building can be found by determining the shear wracking portion of the lateral deflection. If the shear wracking portion is less than 20 to 40% of the total deflection, a good tubular characteristic is indicated. Another measure is to compare the minimum axial stress in the interior columns and that in corner columns belonging to the flange frame (i.e., frame perpendicular to the direction of lateral load). The flexibility of the spandrels increases the axial stresses in the corner columns and, thereby, increases the shear lag effect. This can be demonstrated as in the following by considering the various parameters of tubular behavior of a building structure.

The bending stiffnesses K_c and K_b of columns and beams, respectively, are defined as

$$K_c = \frac{I_c}{H}; \quad K_b = \frac{I_b}{L} \tag{1}$$

where I_c and I_b are the moments of inertia of the columns and spandrel beams, respectively, H is the column height and L is the beam length.

The shear stiffness of the spandrel beams is defined as

$$S_b = \frac{12EI_b}{L^3} \tag{2}$$

and the axial stiffness of columns is defined as

$$S_c = \frac{A_cE}{H} \tag{3}$$

where A_c is the cross-sectional area of the columns and E is the modulus of elasticity of the material, and other terms are as previously defined. The parameters controlling the framed-tube behavior are (Khan and Amin, 1973),

$$\text{Stiffness Ratio, } S = \frac{K_c}{K_b} \tag{4}$$

$$\text{Stiffness Factor, } S_f = \frac{S_b}{S_c} \tag{5}$$

$$\text{From Eqs. (2), (3), and (5), } S_f = \left(\frac{12H}{L^3}\right)\left(\frac{I_b}{A_c}\right) \tag{6}$$

From the influence curves developed by Khan and Amin (1973), it is evident that as S_f increases, the axial stress in the corner column decreases. This will result in a decrease in the shear lag effect. Therefore, from Eq. (6), in order to increase S_f (i.e., to minimize shear lag) I_b must be increased and A_c should be reduced. Since A_c is usually influenced by vertical column force due to gravity loads and, hence, preselected on that basis, increase of I_b is the most effective means to increase S_f. Also, S_f may be increased by using 36 ksi (2.48 x 10^5 kN/m^2) steel for the beams (thereby increasing I_b) and 50 ksi (3.45 x 10^5 kN/m^2) steel for the columns (thereby reducing A_c). The shear lag behavior is usually predominant at the lower levels of a tall building for the following reasons:

1. At the upper levels, S_f is generally higher as compared to that at lower levels since I_b does not change as drastically as A_c towards the base of the building. This is because gravity loads affect the columns progressively whereas they affect the beams uniformly at the different floor levels, although higher beam stiffnesses at progressively lower levels required for controlling building drift will tend to negate this effect.

2. Since the columns are restrained axially at base, all column-shortening effects, i.e., effects due to shear lag, accumulate there. At higher levels, the columns and beams are more amenable to adjustment of deformations and redistribution of stresses, and hence undergo shear lag effects to a lesser degree.

The following observations are worth stating for the selection of locations where spandrel beams should be stiffened to get the optimum effect.

1. For rectangular buildings, as expected, the worst shear lag effect occurs when the lateral force is applied parallel to the narrow direction of the building. For framed tube structures, as the web frames deflect and rotate, the columns belonging to the web frames undergo axial deformation. This deformation is maximum in the corner region and is transmitted to the adjacent columns of the flange frames through the girders between them. This transmission of axial deformation of columns progressively decreases toward the centerline of the flange frames. To get an optimum effect, the spandrel beams in the web frame (i.e., frame parallel to wind load) must be stiffened by increasing the I_b values in order to minimize the transmission of axial column deformation to the flange frame.

2. The spandrels in the flange frame near the corner region should be stiffened to improve the shear flow in the flange frame to minimize shear lag effect as explained above. The length of the building at the corner zones where such stiffening is to be done may be taken as half the web depth or 10% of the building height, whichever is smaller (Khan and Amin, 1973). This is taken as the flange width of an equivalent channel for approximate analysis of a framed-tube structure.

3. When column spacing is different at different locations of the building, the size of the spandrel should be adjusted by taking the I/L of the spandrel beams in question as a basis of member proportioning. This will eliminate any abrupt change in frame stiffness along the building perimeter and thereby improve the tubular efficiency of the building.

A study of the shear lag phenomenon at various floor levels is in order for wind loads and/or static earthquake loads for the purpose of obtaining an efficient building skeleton. As a practical rule, a basic criterion of maintaining ΣK_c equal to ΣK_b (i.e., $S = 1$) at each joint at all floors within practical limits results in a reasonably optimum tubular structure.

A reasonably accurate preliminary design for steel tubular buildings may be obtained by taking into account the effect of shear deformations on the stiffness of the spandrel beams and columns, i.e., the so-called shear leak effect (Wong et al., 1981). It can be shown that if the ratio of the effective shear area of the beam, A_b^1, to the cross-sectional area of the beam, A_b, varies from 0.3 to 0.5, the shear leak effect is almost constant indicating an optimum range. A set of analysis and design charts which could be useful for preliminary member sizing is presented in Wong et al. (1981).

EXAMPLE

The non-rectangular office building shown in Fig. 1 (plan) was designed for the Los Angeles area. The material used is structural steel and the structural system utilizes the "tube-in-tube" concept. Details of this building design were presented earlier (Ali, 1986). A full 3D model comprising 19 lumped levels was adopted for the computer analysis. Member sizes were initially proportioned for the gravity and wind loads. Typical maximum spandrel beam depth is 42 in. (1070 mm) weighing 500 lb per ft (744 kg/m) at the lowest level. Typical maximum column section depth is 39 in. (990 mm) weighing 600 lb per ft (1042 kg/m) for the inner tube at the lowest level. All beams and columns are I-shaped built-up sections at the base and progressively decrease in weight and assume wide flange rolled sections towards the top of the building. The only exception is the corner box-shaped column along the inner tube having a maximum 30 in. x 30 in. (762 mm x 762 mm) size at lower levels.

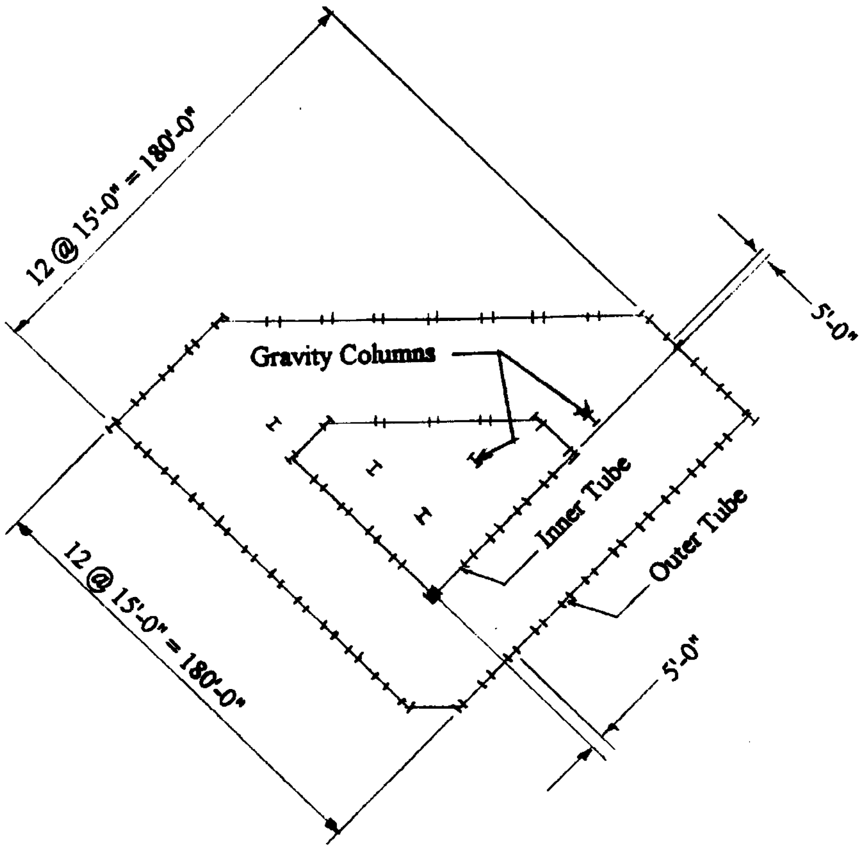

Fig. 1. Building Plan
(Note: 1 ft = 0.305 m)

The maximum wind-load deflection was noted to occur when the wind load was applied on the diagonal face of the building, i.e., in the north-south (N-S) direction. A static earthquake analysis was also performed. Shear lag and lateral drift plots were studied for both wind and static earthquake loads in order to optimize the member sizes. Also, the maximum moments in the spandrel beams were plotted at a few floor levels. The I_b values for the spandrel beams along the diagonal side were increased by 40% for both the exterior and interior tubes such that K_b is reasonably uniform in a typical floor. After a preliminary set of member sizes were obtained in this way, an approximate dynamic analysis (Ali, 1986) was performed on a "stick" model for the specified maximum probable design earthquake response spectra applied in the N-S direction. The period was found to be T = 7.04 seconds and the lateral deflection was found to be 11.58 in. (29.40 cm) considering four modes of vibration (Fig. 2). The base shear and base overturning moment were found to be 4149 kips (18463 kN) and 996100 kip-ft (1344135 kN.m), respectively. Building shears are shown in Fig. 3.

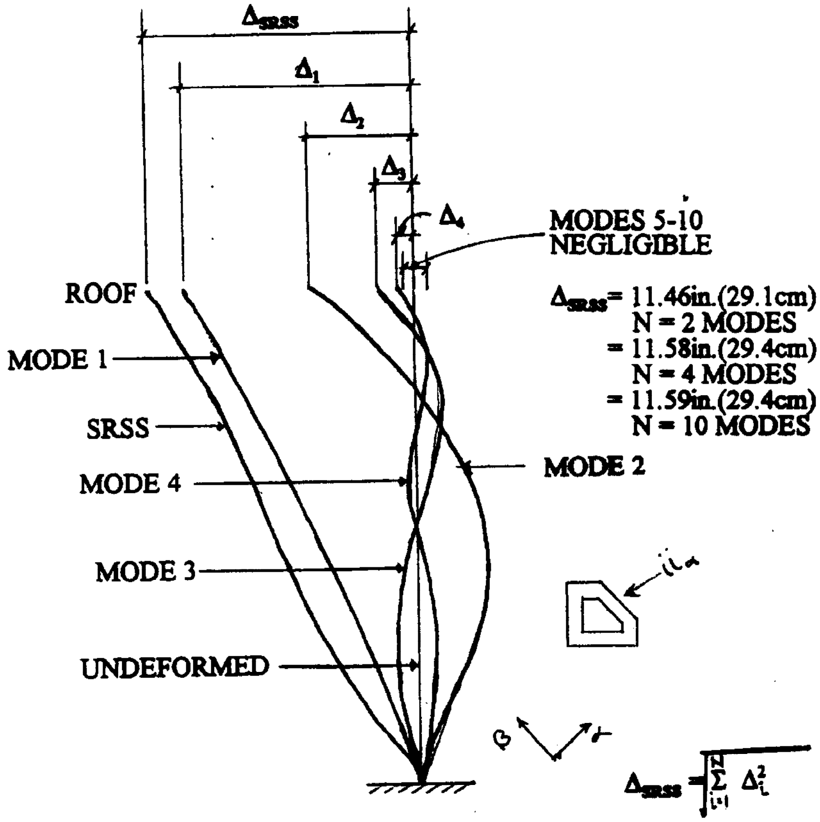

Fig. 2. SRSS deflection of "stick" model by approximate analysis.

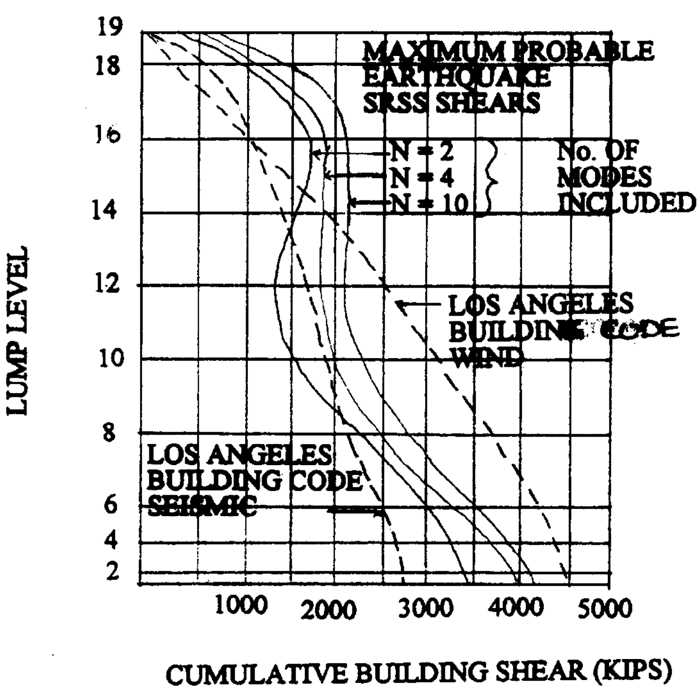

Fig. 3. Story shears for wind and earthquake loads based on approximate analysis.

After evaluating the structure on the basis of the results of the approximate analysis (i.e., as to whether any further adjustment of member sizes are required or not), a dynamic analysis was conducted on the full 3D model using a computer program. For this example, the structure designed for the wind load was found to be satisfactory by the final dynamic analysis. Since the building has a large fundamental period (T = 7.4 seconds for the 3D model) and the acceleration is low for such a long period of vibration, the building is not obviously excited as much as for a shorter building with a smaller period. For the same reason, the lateral deflection of the building for the maximum probable earthquake was found to be 10.50 in. (28.67 cm) for the 3D model. This example demonstrates that a framed tube building is generally suitable for seismic zones because of the inherent ductile moment-resisting nature of this structural system. Connections were designed following the ductility requirements of the Los Angeles Building Code.

CONCLUSION

The paper presents the parameters representing behavioral characteristics and some salient of tall framed tube buildings subjected to seismic loading. It is shown that there are some important parameters to be considered for the analysis and design of such buildings under seismic loading. With advances in the electronic computation techniques and development of new softwares in conjunction with a better understanding of the dynamic response of tall buildings, specific techniques of structural investigation for dynamic loads are expected to evolve in the near future.

The basic concepts presented in this paper are applicable to both steel and reinforced concrete buildings. While the methods of structural analysis for concrete buildings are similar to those for steel buildings, the seismic detailing of beam-column joints is naturally different for the two materials.

Some specific areas of research that influence the performance of tubular buildings and that need immediate attention are: optimization of building plan and elevation configurations under seismic loading, maximization of building-frame and connection ductility without loss of adequate strength and stiffness, building system and framing optimization, influence of different factors related to loading and performance criteria for a building on efficient seismic design, and investigations into the non-linear response of the building structure subjected to seismic excitation.

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