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·特约专稿·

Vertical Seismic Action on Megastructure Systems of Tall Buildings

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Abstract To meet the needs of the multi - function and the multi - use of the modern tall buildings, the megastructure systems have been gradually emerged and used in tall buildings in many countries. In this paper, the analytical model and relative analysis method due to vertical seismic action of the megastructure are presented, including the spectrum and time - history analysis. The results of the calculation of an example show that the vertical seismic action on megastructure is remarkable. It reminds us that the vertical seismic action on megastructures can't be neglected in the design of this kind of structures. Furthermore, it is pointed out that the "story model" is not suitable to megastructures in dynamic analysis.

Keywords vertical seismic, megastructure, earthquake - resistant, response spectrum, time - history analysis

Tall building structural systems concepts have undergone a dramatic evolution in the later part of the 20th century. As a new kind of the structural systems, the megastructures have been adopted in recent years. The megastructure system is mainly composed of some mega - elements (including the mega - columns and mega - beams) so as to resist the vertical and lateral forces. Each mega - structural floor may support several thin conventional floors which can be referred to as the secondary frames. This kind of the structural system have many advantages, such as the big structural rigidity, high structural performance and good economy etc. Besides, it can bring about new style and new concept for architectural design. Now the research of the earthquake - resistant analysis method towards this kind of structure as well as the details measure towards the joints of the mega - structures has been an important problem which many engineers and researchers in structural engineering domain have focused on.

The earthquake macro - phenomena have demonstrated that the influences of the vertical seismic motion is obvious in high intensity area. Such as the earthquake record of the Gazli in 1976 and the Imperial Valley in 1979, the vertical acceleration of the ground is greater than the horizontal acceleration of the ground in these two records. The record of Kobe earthquake in Japan in 1995 has disclosed an important discovery, which the role of the vertical seismic action was more important than the hor-

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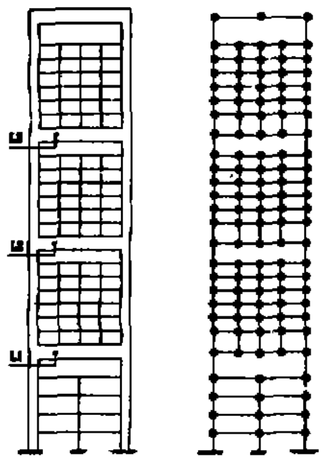
izontal seismic action to the failure of the buildings due to this disaster in the center zone of this earthquake. The Vertical seismic acceleration of the ground in the center zone of this earthquake was up to 500 Gal.

Compared to the present buildings earthquake – resistant design code of China (GBJ11 – 89), the vertical seismic action on the structures is still not emphasized enough in this code. On the other hand, the dynamic analytical model of tall buildings for the vertical seismic action are limited to "story model" in the code and many references. But this model can't reflect the vertical seismic action on the transfer girder of megastructure, it only reflects the action on the columns. So this model is not suitable to the megastructure. In this paper, the analytical model as well as the respective analysis method to vertical seismic action of the megastructure is presented, including the spectrum and time – history analysis.

1 ANALYTICAL MODEL

From the fifties, many scholars (E. Rosen – bluth, Qian Peifen, Liu Ji etc.) have made a lot of achievements in the research of the vertical seismic action of the structures. But these structures which they studied are only referred to as the high – rise structures (usually the chimneys), single – story buildings and ordinary tall buildings. So far, there is no report on the research of the vertical seismic action of the megastructures in the world according to author's investigation. In many references tall buildings are modeled as the shear buildings, that is "story model", while analyzing the response of the buildings due to the vertical seismic excitation. In few references tall buildings are modeled as "member model" and a concentrated mass is acted on the midspan of every beam of tall buildings. In the story model, the computational results can only reflect the change of the axial forces of the columns due to vertical seismic action, but it can't reflect the change of the internal forces due to vertical seismic action. Because the axial force ratios of columns are strictly limited in design of tall buildings in high intensity area. So it will bring about conceptual confusion here which the vertical seismic action on structure can be neglected if the story model is adopted in analyzing the structural response due to vertical seismic excitation. In the member model, although a concentrated mass is acted on the midspan of every beam, the effects on structure due to vertical seismic excitation are not so dramatic as in the condition of the horizontal seismic excitation because of the cause of the earthquake input. In the case of the megastructure, the transfer girders are very important for the whole structure in resisting the vertical loads and horizontal loads due to seismic excitation, and many columns can't be continuous in the height of the building. Besides, many huge concentrated masses acted on the girders



(1) (2)

Fig. 1 megastructure and vibration analysis and these masses will be the "source" of the vertical earthquake forces. So it is necessary to establish a new member model to analyze vertical seismic action on the megastructure. In this model, some concentrated masses act on girders. Such as in Fig. 1.

2 GOVERNING EQUATION OF THE STRUCTURAL VERTICAL VIBRATION

If the member model is adopted as in Fig. 1. (2) , then the governing equation of the mega-structural vertical vibration can be written as

$$[M]\{\ddot{z}\} + [C]_v\{\dot{z}\} + [K]_v\{z\} = -[M]\{\ddot{z}_g\} \tag{1}$$

In which, $\{Z\}$——the vertical relative column vector displacement of the structure;

$\{\ddot{z}_g\} = \{\ddot{z}_g(t)\}$ is the time - history curve of the vertical ground acceleration;

$[M]$——mass matrix of the structure, ;

$[K]_v$——vertical stiffness matrix which is assembled of the elements and condensed statically;

$[C]_v$——damping matrix of the vertical vibration of the structure. Here

$$[C]_v = [M][\Phi][E][\Phi]^T[M]^T \tag{2}$$

and, $[\Phi]$ is the vibration mode matrix, ζ is the damping ratio, generally $\zeta = 0.05$; ω_i is the ith - mode frequency. Besides

$$[E] = 2\zeta\begin{bmatrix} \omega_1/2\pi m_1 & & \\ & \omega_2/2\pi m_2 & 0 \\ & 0 & \omega_3/2\pi m_3 \end{bmatrix} \tag{3}$$

the vibration mode matrix and the ith - mode frequency can be obtained by following equations:

$$[M]\{\ddot{z}\} + [K]_v\{z\} = \{0\} \tag{4}$$

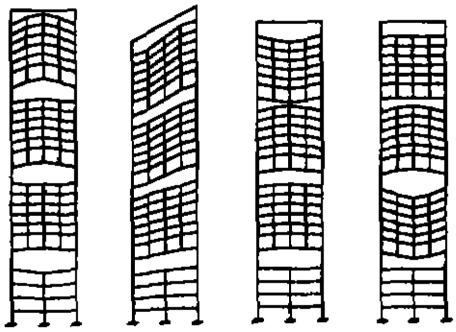
$$([K]_v - \omega^2[M])\{z\} = \{0\} \tag{5}$$

3 VIBRATION MODE SHAPE AND RESPONSE SPECTRUM ANALYSIS

As shown in Fig. 1(1), a uniformly distributed load 48kN/ m is acted on the each beam of the secondary frames of the megastructure, and a uniformly distributed load 100kN/ m actsd on each mega - beam. The cross sections of the mega - columns are 1.5m × 1.5m and those of the mega - beams are 0.65m × 3.0m; the cross sections of the columns of secondary frames are 0.5m × 0.5m and that of the beams are 0.3m × 0.5m for the 6 ~ 30 floors; the cross section of the columns of secondary frames are 0.6m × 0.6m and that of the beams are 0.4m × 0.9m for the 1 ~ 5 floors. The first four vibration mode shape under the vertical condition are shown in Fig. 2.

From the Fig. 2 it can be seen that all the components of mode 1 are positive, the left half components of mode 2 are negative and the right half components of mode 2 are positive. Other modes also have respective regulars. But each mega – beams as well as the secondary frames supported by them are interacted at any case of each mode. The period of each mode is shown in Table 1.

From Table 1 it can be drawn that the vertical vibration periods of the megastructure are very short and it is similar to high frequency vibration. Furthermore, another important characteristic is that every period (or frequency) is very close to each other except the first period. This is because that each transfer girder (mega – beam) as well as the secondary frame supported by itself is independent and can vibrate independently (see Fig. 2). This characteristic of the megastructures is quite different from ordinary tall buildings. So the combination approach of internal forces (axial forces, shear forces and bending moments) should adopt the CQC method. But for convenience, the SRSS method is still employed in this paper.



mode1 mode2 mode3 mode4

Fig. 2 the first four vibration modes

Table1 the first four period of the megastucture

Periond	T1	T2	T3	T4
Second	0.286 2	0.203 9	0.181 6	0.171 6

The type of soil in the general region where the megastructure located is supposed as II (corresponding to buildings earthquake – resistant code of China, GBJ11 – 89) and the earthquake intensity is eight. Here the vertical earthquake spectrum curve shape is the same as the case of horizontal and it's peak value of acceleration is decreased to 65% (proposed by GBJ11 – 89). If the axial force of mega – column due to vertical seismic action as well as static loads are denoted by N_v and N_g respectively. The ratio of N_N to N_g is denoted by μ, that is $\mu = N_v / N_g$. According to the spectrum analysis results, the value of μ varies with the change of the story number as shown in Fig. 3.

From Fig. 3 it is obvious that the value of μ is lowest at the bottom of the structure and gradually increased with the story number N up to 20, then tend to be stable. The maximum value of μ is 0.117. So the influence of the axial forces generated by vertical seismic action to mega – columns can be neglected in design of the megastructure if the axial force ratio is controlled strictly. The bending moment of the midspan of the mega – beam (L1, L2 and L3) due to vertical seismic action as well as static loads are denoted by M_v and M_g respectively.

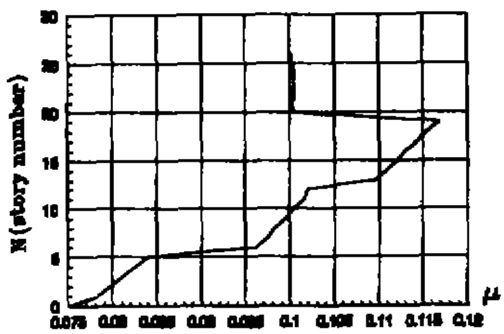


Fig. 3 the value of varying with the change of the story number

In Table 2 it is obvious that the value of M_v / M_g also reflects the tendency which the vertical seismic action increases with the number of story N. Besides, the value of M_v/M_g for mega – beam L3 has arrived to 15%.

Table 2 bending moments of mega-beams (kNm)

beam number	M_g (kNm)	M_v (kNm)	M_v/M_g
L1	12 910	860.5	0.067
L2	13 510	1 447	0.107
L3	14 050	2 076	0.143

4 TIME – HISTORY ANALYSIS

The elastic time – history analysis of the megastructure as shown in Fig. 1 is carried out by step – by – step integration method for eqn. (1). Here the El – centro, Taft and Parkfield earthquake wave are adopted. The peak value of the acceleration for the three waves is taken as 143Gal. According to the time – history analysis results, the maximum values of the bending moments and vertical displacements for midspan of mega – beams (L1, L2 and L3) are listed in the Table3 and Table4 respectively.

Table 3 bending moments of mega-beams (kNm)

beam nmber	El-ecntro	Taft	Parkfield
L1	1 107	1 362	1 175
L2	1 109	1 973	1 177
L3	1 360	2 492	1 516

We can see from the Table 3 that the difference of the values of bending moments of the same mega – beam due to different earthquake waves is remarkable. In which, the value of moment induced by Taft wave is the biggest. But there is a mutual tendency that the value of the bending moment of the mega – beam is relative to the height of story number N, just as the condition of the spectrum analysis.

Table 4 vertical displacements of mega-beams (mm)

beam number	El-centro	Taft	Parkfield
L3	2.513	4.545	3.196

The maximum value of the bending moments of the mega – beam L3 induced by Taft wave has reached up to 2 492 kNm and the relative value has reached up to 2 492/14 050 = 17.7%. The time – history curve of the bending moment for mega – beam L3 is shown in Fig. 4.

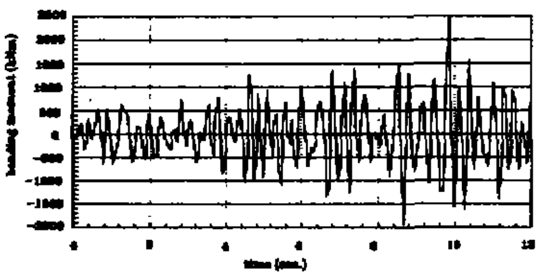


Fig. 4 time-history curve of the bending moment for mega-beam L3

5 CONCLUSIONS

According to the results of the spectrum analysis and time – history analysis, some conclusions for vertical seismic action on megastructure systems can be drawn:

1) the vertical vibration periods of the megastructure are very short and it is similar to high frequency vibration. Furthermore, another important characteristic is that every period (or frequency) is very close each other except for the first period. This is because that each transfer girder (mega – beam) as well as the secondary frame supported by it self is independent and can vibrate independently (see Fig. 2). This characteristic of the megastructures is quite different from ordinary tall buildings.

2) The above characteristic of the megastructure can also prove that the story model is not suitable to megastructures while carrying out the analysis of the vertical seismic action. So the combination

approach of internal forces (axial forces, shear forces and bending moments) should adopt the CQC method, according to the theory of random vibration.

3) According to the results of the spectrum analysis, Only the first N_m vibration mode are needed to be considerated in computation of the combined internal forces. Here the N_m is the number of the transfer girders.

4) There is a tendency that the effects of the internal forces due to vertical seismic action of the megastructures is relative to the height of story number N in which the member located basically. The higher the location of the member is, the more dramatic the effects of the internal forces will be. And vica versa.

5) It is possible that the internal forces of the mega – beam in the higher position of the megastructure due to vertical seismic action will exceed the relative values of the member due to static loads, as long as the peak value of the input acceleration reach up to a bigger value. So the vertical seismic effects on mega – beams can't be neglected in design of the megastructures.

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高层建筑巨型结构体系的竖向地震作用

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摘 要 为满足现代高层建筑的多功能和多用途需要，巨型结构体系在国内外高层和超高层建筑中已逐渐得到应用。本文建立了巨型框架结构体系在竖向地震作用下的分析模型及相应的分析方法，其中包括反应谱分析及时程分析。通过具体算例和分析表明，竖向地震对此类结构的作用是十分显著的，在巨型结构体系的分析和设计中，竖向地震力是不可忽视的。本文进一步地指出：在分析此类结构的地震作用时，“层模型”是不适用的。

关键词 竖向地震，巨型结构，抗震，反应谱，时程分析，高层建筑

中图法分类号 TU471.2

框架结构 地震作用