Numerical Analysis and Application on the Whipping Effect of Buildings

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Abstract

Through the review of the literature, it summarizes the research progress of the whiplash effect of the roof tower at home and abroad at this stage and different views of scholars. Moreover, it summarizes the reasons and dynamic characteristics of the whiplash effect of tower. In addition, it gives the dynamic equation of the whiplash effect under earthquake. The paper verifies whiplash effect on earthquake resistance and shock absorption by the numerical simulations. From the side, if the differences which are the stiffness and the quality between the main structure and the roof tower are very large, it can ignore the impact of towers on the main structure. If the differences are not very large, it is equivalent to a shock absorber system installed on the roof of the main structure and the influence to the structure of the main body can not be ignored, and even can be used. Finally, it makes a summary of the full text and points out the shortcomings of the model and whiplash effect of the tower in future are discussed.

Keywords

Whipping effect; seismic performance; seismic reduction; finite element analysis.

1. Introduction

It was found in many previous earthquake disaster investigations that prominent structure on buildings, for example the elevator room of the roof, is seriously damaged in the earthquake and this phenomenon is caused by the whiplash effect. In engineering, the whiplash effect could cause the damage of prominent structure of buildings. But the whiplash effect has a damping effect on the main structure in certain circumstances. The structure which is increased on the top of the dam does not affect the structure safety of the dam, for example a sightseeing tower, and it has not only the landscape effects but also the whiplash effect which can make full use of prominent structure in the earthquake. The whiplash effect of prominent structure has large displacement to effectively absorb and dissipate seismic energy transmitted to the dam[1].

In foreign countries, the application of steel structure towers which are mainly used for communication in high rise buildings is very common in Japan. In China, the phenomenon of the towers of high-rise buildings are very common such as staircases, communication facilities and lightning rod structure. And this makes the structural stiffness of the construction change suddenly. Zhao Xi'an et al.[2] carried out a shaking table model test of a high-rise building with a tower and suggested a simplified calculation method for the seismic effect of the tower.

This paper mainly analyzes the research results, the causes and conditions of the whiplash effect at the present stage. Through the numerical simulation, This article discusses the damping effect of the whiplash effect for frame structure and provides some references for the seismic design and research of frame structure.

2. Research contents of the towers at the top of buildings

At present domestic and international research articles are mostly about the seismic response of the top tower. The main contents are the following categories[3]:

The first class is just simple qualitative discussion on the change of seismic performance of structures after towers built on the top of high-rise structures, including the influence of the tower on the main structure mode, the change of lateral displacement, axial force of ground floor and interlayer shear force.

The second is to discuss the causes of structural whiplash effect. Starting from the vibration equation, it deduces the simplified method of various calculation of the whiplash effect. Moreover it simplifies the main building and the towers of the roof into a two degree of freedom structural system. Besides, it is a qualitative analysis of the causes of the whiplash effect. Then, it is analyzed qualitatively that the resonance is most likely to occur when the main frequency is close to the ground. Finally, the earthquake action of the tower could be calculated.

The third kind is the simplified calculation method of the earthquake action of the tower. Theoretical analysis method is so complicated that it is not convenient for engineering calculation. In order to adapt to the need of engineering design, engineers generally use enhancement coefficient of the seismic function to simplify the earthquake action of the tower.

The fourth category is the impact of the tower of whiplash effect on the main structure. Usually, the main structure and the roof of the tower stiffness and quality is very rich and the poor, it can ignore the influence of the main structure of the tower.

3. The dynamic characteristics of the whiplash effect of the tower on the roof

3.1 Generation of whiplash effect

The whiplash effect of the tower at the top of high-rise building[4] is that the tower is resulted in secondary vibration by vibration excitation of the main structure layer when the main structure generates vibrations in the earthquake. The vibration of the roof towers has been magnified two times. The first magnification is the vibration generated by the main body structure under the ground motion excitation; the second enlargement is the vibration of the roof tower under the excitation of the main roof vibration. Generally, when The first natural period of a certain order of the top tower is equal or close to the one of the lower main body structure, the tower will have the highest acceleration and whiplash effect of strong due to resonance. Therefore, it can make the difference to increase between the tower vibration period and the main structure vibration period and it can reduce the influence of the whiplash effect.

Some scholars[5,6] put forward different views. They think that the whiplash effect is mainly due to the self interference frequency equal to tower vibration frequency and the ground motion or similar. When the tower of the first order vibration frequency is equal to the whole structure of the self vibration frequency and similar to ground scrambling, the whiplash effect of the tower is strongest. But when the order of self vibration frequency of the main structure is close to the ground disturbance frequency, it can make the main structure resonance and the tower is generally not occurrence of whiplash effect.

The consensus reached at present is that the whiplash effect of the tower depends mainly on the relationship between tower vibration periods, vibration periods of the main structure and predominant period of ground motion. But the reason for the whiplash effect of the tower is still not a consensus.

3.2 The dynamic equation of the whiplash effect under earthquake[4,7,8]

Usually, the natural vibration period of the site soil varies from 0.2 to 0.6, and the building usually has a natural period of vibration in the range. So the dynamic equation can be written as:

$$\begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} \begin{Bmatrix} \ddot{X}_1 \\ \ddot{X}_2 \end{Bmatrix} + \begin{bmatrix} K_1 + K_2 & -K_2 \\ -K_2 & K_2 \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix} = A\omega^2 \begin{Bmatrix} M_1 \\ M_2 \end{Bmatrix} \sin\omega t \tag{3-1}$$

Among them, ω is the natural frequency of the building.

Hypothesis $\begin{Bmatrix} X_1 \\ X_2 \end{Bmatrix} = \begin{Bmatrix} B_1 \\ B_2 \end{Bmatrix} \sin\omega t$, Solution:

$$-\omega^2 \begin{bmatrix} M_1 & 0 \\ 0 & M_2 \end{bmatrix} \begin{Bmatrix} B_1 \\ B_2 \end{Bmatrix} + \begin{bmatrix} K_1 + K_2 & -K_2 \\ -K_2 & K_2 \end{bmatrix} \begin{Bmatrix} B_1 \\ B_2 \end{Bmatrix} = A\omega^2 \begin{Bmatrix} M_1 \\ M_2 \end{Bmatrix} \tag{3-2}$$

When ${}^{K_1}/_{M_1} = {}^{K_2}/_{M_2}$ and $\left|{}^{K_1}/_{K_2}\right| \geq 1$, it gets $|B_2| \geq |B_1|$. Then it produces the whipping effect.

In the seismic design of the tower, we need to pay attention to the following points:

The natural vibration period of the main structure should avoid the predominant period of ground motion.

When the ground movement predominant period is less than that of the main structure, the natural period of the tower should avoid that of the main structure. But at this time, the seismic shear force coefficient of the tower will be very large.

When the ground motion predominant period is larger than that of the main body structure, the dynamic parameters of the tower should be selected to avoid the predominant period of the ground motion. When the quality of the tower is smaller, the self vibration period of the tower should avoid the predominant period of the ground movement.

4. Numerical analysis of tower whiplash effect

4.1 Engineering survey

The project is the four storey concrete frame structure. And it will be a shopping mall in future. There is a tower on the top of the building. It's a stair passage to the top of the building. The construction area is 135m^2, 15m length, 9m width, height 4m, bottom floor building plan as shown in Figure 1. The size of building components is shown in Table 1. The load information is shown in Table 2. The strength grade information of concrete is shown in Table 3.

Tab.1 The size of building components

Catego ry	Column (mm)	Main beam (mm)	Secondary beam (mm)	Floor thickness (mm)	Floor thickness of toilet (mm)
Size	500 × 500	250 × 600	250 × 500	120	100

Tab.2 The load information

Cate gory	Floor dead load(kN/m2)	Floor live load(kN/m2)	Roof dead load(kN/m2)	Roof live load(kN/m2)	Beam to beam load(kN/m)	Basic wind pressure (kN/m2)
Size	4.5	2.5	3.5	2	17.28	0.55

Tab.3 The strength grade of concrete

Category	Concrete of beam and column	Concrete of floor	Steel bar of beam and column	Stirrup of beam and column
Strength grade	C30	C25	HPB400	HPB300

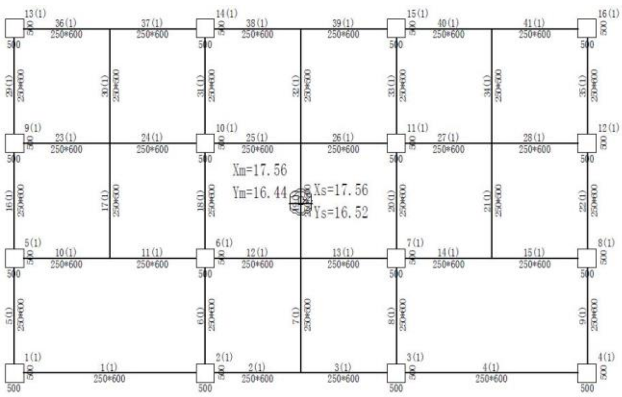

Fig.1 Bottom floor plan and beam column size

4.2 The establishment of numerical model

This article uses the software PKPM2010, SATWE2010_V2.2 that carries on the modelling of this frame structure. The 3D model is established as shown in Figure 2 and Figure 3.

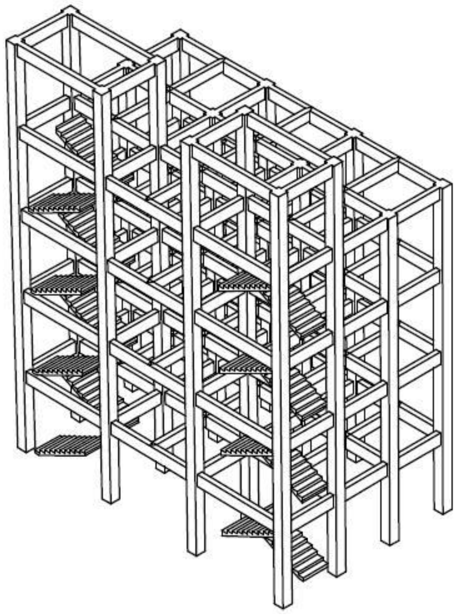

Fig.2 The 3D solid model

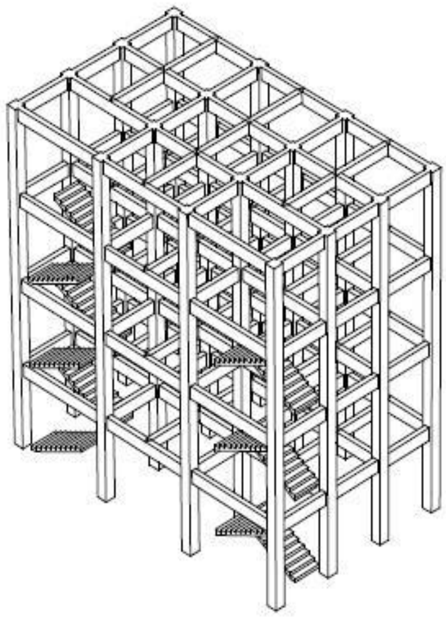

Fig.3 The comparison model

4.3 The calculation results of numerical model

The internal forces and displacements of the frame structure and the non tower frame structure (contrast) are calculated by using the PKPM software. The calculation results of numerical models are shown in Table 4.

Tab.4 The calculation results of numerical models

variable	Earthquake force (kN)		shear force (kN)		bending moment (kN.m)		displacement (mm)		Inter layer drift angle	
	X	Y	X	Y	X	Y	X	Y	X	Y
Original model	102.2	124.7	359	435.5	4653.4	5589.3	5.9	5.7	1/1833	1/2229
Comparison model	146.9	159.4	403.8	442	4506.7	4913.1	5.6	5.1	1/1965	1/2298

4.4 Result analysis

Through the comparison of the calculated results of the two models, it is known that there is a certain effect on the structure of the tower under earthquake. With the structure of the tower under earthquake, the force of the structure is less than the force of the non-tower structure (except for bending moment). That is to say the existence of the tower has a certain effect on reducing the internal force of the structure.

According to the results of numerical analysis, the author thinks that although the building of the tower would make some floor displacement increase, the building with the tower has a certain protective effect on the lower building under the premise of reasonable design.

5. Conclusion and Prospect

Model results indicate that the tower of buildings belongs to the mutant of the stiffness of the structure. It will have whiplash effect at the time of the earthquake and the site is relatively easy to damage in the earthquake. But the damage of the tower can absorb the earthquake energy, protects the lower building and it is beneficial to the structure. To the safety of the building, we should not blindly increase stiffness of prominence, but the tower should be used to ensure the safety of the buildings in the case of earthquake and let it absorb the earthquake energy as much as possible to protect the lower buildings.

Model has some flaws. One of them is that whiplash effect of the model is not significant, the reason may be: 1) The number of model floors is small and the stiffness of the model is lager; 2) The quality between the tower and the main structure has great disparity. So the tower has little effect on the main structure of the model and it leads that the whiplash effect is not very obvious.

At the present stage, there are many researches on whiplash effect on earthquake resistance. They believe that the damage of the tower caused by whipping effect in the earthquake is beneficial to the seismic resistance of the lower building. Because the tower of destruction can absorb earthquake energy. The author thinks that the designer should prevent the Domino effect caused by the destruction of the tower in the earthquake if we want to use the favorable side of the tower in the earthquake, making the continuous damage of the lower structure.

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