Wind-induced Vibration of High-rise Buildings and Its Countermeasures

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Abstract. This article analyzes the cause of the wind-induced vibration, points out its harm, and finally introduces some countermeasures of it nowadays. To commence, it introduces the phenomenon called Buffeting, Vortex-excited Vibration and Self-excited Vibration that leads to the vibration. Then, it concludes that the vibration will lead to structural damage and make its residents uncomfortable through analyses, indicating that the vibration can be controlled by structural optimizing, aerodynamic measuring and equipping energy dissipation systems. This article simply introduces their principle and application.

1. Introduction
Nowadays, more and more buildings that are over 100 meters are arising in our cities. However, at the same time, the frequency of extreme weather has increased rapidly in these 20 years including gale. As a result, the wind-induced vibration is of considerable threat to these high-rise buildings. For example, the Tacoma Narrows Bridge in Washington State collapsed just 4 months after it was first completed on July 1st 1940 due to wind-induced vibration.

Since then, plenty of researches on Structural Wind Engineering have been done, and solutions of wind-induced vibration also have come into being. The Sears Tower (442.3 meters high, completed in 1974) in Chicago uses bundle tube structure to reduce the amplitude of its vibration under wind [1,2]. The Taipei 101 building (508 meters high, completed in 2004) in Taipei equips the Tuned Mass Damper (TMD) and reduces its amplitude under wind and earthquake significantly [3,4]. The Burj Khalifa tower (828 meters high, completed in 2010) uses a complex outline to conquers the vortex-induced vibration effectively [5,6]. All the methods mentioned above have positive effects to protect high-rise buildings under extreme strong winds.

2. Cause of the wind-induced vibration
2.1. Buffeting
The structural wind load can be divided into two parts: the average wind and the pulsating wind. The average wind gives building a stable load, while the pulsating wind gives building a variational load and can cause a phenomenon named buffeting. Since the atmospheric boundary layer turbulence has random properties, the buffeting is a random vibration. Buffeting is a kind of wind-induced vibration that is the most common and can happen in any structure.

2.2. Vortex-excited vibration
When the steady incoming current under certain conditions bypasses tall buildings, the two sides of the building will periodically fall off and form regular double linear vortexes with the opposite direction of rotation. At first, these two lines of linear vortexes keep moving forward separately, then they interfere with each other and attract each other, and the interference becomes more and more serious (as shown in fig 1). This phenomenon is called the Karman Vortex Street [7].

![Figure 1 The Formation and Development of Karman Vortex Street](image)

Once the vortex street appears, the fluid exerts a periodic alternating transverse force on the building, which will lead to a transverse vibration. Similarly, since the building is very tall, the amplitude on the top floor will be considered obviously. Meanwhile, If the frequency of the vibration is close to the natural frequency of the building, it will cause resonance and the amplitude will be even bigger and may lead to Structural Damage.

2.3. Self-excited vibration
While the building is vibrating under wind load, its deformation and vibration can influence the aerodynamic force induced by the wind on the building, and result in an interaction between wing load and the vibration of the structure [8]. This phenomenon leads to a motion-induce force on the building. In some current situations, the direction of motion-induce force can be the same as the direction of building’s movement. Then, the vibration will absorb energy from the motion-induce force hour after hour, which will lead to the amplitude increase sequentially, and finally result in disaster.

3. Influence of the vibration
3.1. Structural damage
When the wind blows across a tall building, as shown in fig 2, the building will suffer from bending moment, which causes an uneven distribution of the direct stress in a vertical direction. If the wind strong enough, a side of the basement of building may even suffer from tensile stress.
As for concrete, its tensile strength is much less than its compressive strength. So, when a tall concrete building in face of a gale and its foundation subjected to tensile stress, the concrete may crack. As for steel, vibration means persistent alternating stress, which can lead to metal fatigue. The metal fatigue will create cracks inside the steel beam, pillar and fastenings, and reduce the load they can bear. Finally, both of these situations will lead to structural damage.

3.2. Comfort level
As for high-rise buildings, especially super-high steel frame structures, as their height increase, on the country, their lateral stiffness and damping ratio will reduce. Once in face of gale, the vibration of the building can lead to discomfort for its residents, especially for those who at top floors. There are various evaluation criteria on the comfort of tall steel buildings under wind-induced vibration. One of the most generally accepted criteria is the ISO 10137-2007, using the maximum of the acceleration of structure as criterion to evaluate the comfort level of a building [9]. And the acceleration of vibration is determined by both its amplitude and its frequency. Once these two factors satisfy certain conditions, it will cause discomfort for its residents. So, controlling the amplitude and frequency of the wind-induced vibration of a building is of vital significance.

4. The solution of the wind-induced vibration

4.1. Structural optimize

4.1.1. Composite Structure. As for concrete structure, its ability to bear the tension is low and may crack when in face of the gale. Meanwhile, as for steel frame structure, its rigidity is lower than concrete and easy to deformation under load and lead to a sharp vibration. It also more possibly for steel frames to fatigue and lost stability. But if combining these two kinds of structure together and developing a composite structure with a reinforced concrete core and steel frames around it, the reinforced concrete core can support structural load and approve rigidity for the whole building, while the steel frames can support the bending moment and avoid the tension stress on concrete core.

For example, the Shanghai Tower, a 632 meters high skyscraper located in Shanghai, is a high-rise building composed of mega frame-core-outrigger lateral resisting system (as shown in fig 3). There is a square reinforced concrete core at the center of the building, and there are 2 steel main columns on each side and 1 steel corner column each corner, 12 giant steel columns in total, surround it. There are also groups of trusses between the core and the columns to transmit load. The concrete core supports most longitudinal load due to gravity, while the giant steel columns can release the moment and lateral movement of the core under lateral wind load [10].

Figure 2 Variation of Foundation Stress Under Different Strength of Wind Load

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4.1.2. Bundle Tube Structure. Bundle tube structure is composed of a number of cylinders connected as a whole structure. When the building plane is large, in order to reduce the deformation of the external wall under the action of lateral force, the building plane is arranged according to the modular grid, so that the external frame type cylinder and the internal horizontal shear walls (or closely arranged columns) become the composite cylinder group. This greatly increases the building's stiffness and ability to resist lateral forces. Moreover, the bundled tube structure can be composed of any architectural shape, and can adapt to the needs of different height of the body combination, enrich the appearance of the building. For example, the Sears Tower (442.3 meters high, completed in 1974) in Chicago. The shape of the tower is gradually collected. The first to the 50th floors are 9 square tubes with a width of 23.86 meters, 51-66 layers cut off a pair of square cylinder units, 67-90 layers cut off the other pair of diagonal square cylinder units to form a cross shape, and the 91-110 layers are raised from two square cylinder units to the top (as shown in fig 4). In this way, the wind pressure can be reduced and the effect of external modeling can be obtained [1,2,11].

Figure 3 The Shanghai Tower and its Structure [10]
4.2. Aerodynamic measure

The aerodynamic measure is to improve the aerodynamic characteristics of the building structure by changing the shape of the building, such as chamfering, adding convex corners, setting up additional pneumatic devices, or designing taper or sudden shrinkage of section, to interfere with the local flow field, control the boundary layer separation and vortex shedding, so as to reduce the wind load and wind-induced vibration [12]. The long-term engineering application shows that aerodynamic control is an economical and effective means to reduce the wind-induced vibration of buildings and improve their wind resistance performance [13].

Figure 4 The Sears Tower and its Bundle Tube Structure [11]

Figure 5 The Burj Khalifa Tower and its Outline [5]
For example, the Burj Khalifa tower in Dubai not only uses a sudden shrinkage of section, but also has an unpredictable outline combined by many arcs (as shown in fig 5). This complex outline can give guidance to the wind, change the direction of the airflow, and break big vortexes form behind it into small ones around it. As a result, the power of wind and vortex was dispersed [5,6].

4.3. Energy dissipation systems

Energy dissipation and vibration reduction measures are to set damping devices in some parts of the structure to dissipate or absorb the vibration energy of the structure and reduce the dynamic response of the structure. The specific principles include friction, bending, shear, torsion or elastic-plastic deformation of damping device, installation of substructure damping system, and active application of a group of control forces.

One of the most widely used Energy Dissipation Systems is the Tuned Mass Damper (TMD). It is composed of mass, spring and damping system. When the structure was pushed by wind load and has an acceleration, the mass will be static instantaneously and the spring will give the structure a counter-force. Meanwhile, the damping systems can expend the energy of movement and transfer them into heat, which can reduce the amplitude effectively. By adjusting the vibration frequency to the frequency of the main structure and changing the resonance characteristics of the structure, the damping effect can be achieved [14]. Some other dampers use liquid (such as water) as mass and are called Tuned Liquid Damper (TLD). Meanwhile, active control is also widely used to control vibration [15].

For example, The Taipei 101 building (508 meters high, completed in 2004) in Taipei equips the heaviest TMD all over the world at its top floor (as shown in fig 6), which is approximately 5.5 meters in diameter, consists of 41 layers of 12.5 cm solid steel plating welded into a gold sphere mass, weighing 660 metric tons. This system reduces its amplitude under wind and earthquake significantly [3,4].

Figure 6 The Taipei 101 building and its TMD [16]

5. Conclusion

Wind-induced vibration is caused by the variety of wind, the vortex and the Aeroelastic effect, and brings very serious problems. But the vibration can be controlled by structural optimizing, aerodynamic measuring and equipping energy dissipation systems. Nowadays, high-rise buildings often make a comprehensive application of these methods and rich the best cost-effectiveness ratio.

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