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Wind-Induced Responses and Reinforcement Measures of Integral Steel Platform System for Super High-Rise Building's Construction

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ABSTRACT

As a new type of construction tool, Integral steel platform system has been widely used in construction of many super high-rise buildings in China. Consisting of steel skeleton and flexible external suspended scaffold, steel platform bears large wind load in the air, so it is necessary to obtain the wind-induced responses of steel platform to evaluate safety. Based on the steel platform of Shanghai Tower, a finite element model is established. The analysis result shows that the natural frequency of structure is 0.693 Hz and the first mode shape is torsional mode. The mid-span position of external hanging staging has the maximum displacement under wind load. When wind speed is larger than 20 m/s, there will be collision of external hanging staging and core tube, leading to a huge acceleration at bottom of external hanging staging. External hanging staging will be tied to the formwork of core tube under heavy wind. The first mode of steel platform become translational mode after the reinforcement and wind-induced responses are greatly decreased. So it is suggested that external hanging staging should be tied to formwork under heavy wind.

1. INTRODUCTION

In recent years, many high-rise buildings have been constructed in China and integral steel platform system (steel platform) has been developed for the construction of concrete tube of super high-rise buildings since 1992. Steel platform has distinct advantages on cost-saving and shortening the construction period for super high-rise buildings while it is not so suitable for ordinary high-rise buildings. As shown in Fig. 1, steel platform, mainly consisting of steel skeleton and flexible suspending scaffold, stands on the concrete tube by steel corbels. Steel platform can move upward by the alternate motion of upper and lower supports, just like the hands and legs of human beings. Reference [1] introduced the detail working principle of steel platform.

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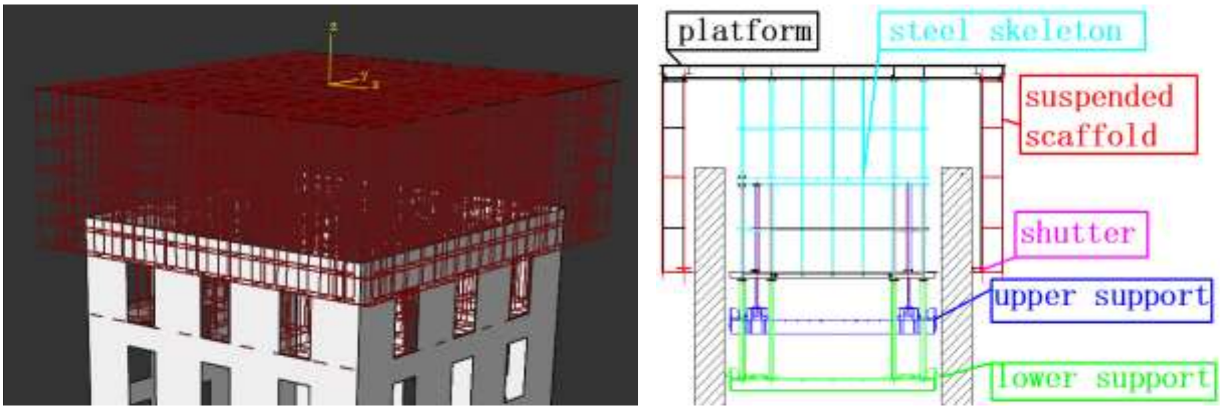


(a) Appearance of steel platform (b) Side view of steel platform

Fig. 1 Sketch map of steel platform

Steel platform is a kind of special construction tool, so there is only a few studies on it. Yanbin Luo (2006) carried out modal and time history analysis on the steel platform of Shanghai World Financial Center [2-3]. Zhao (2015) proposed reinforcement measures of steel platform by modal analysis but wind load were not involved [4]. Yue Feng (2004) carried out a force measurement in wind tunnel to get the shape coefficient and wind vibration coefficient of attached self-lifting scaffold [5-7]. In addition, H.Irtaza (2012) and Feng Wang (2013) both tested the wind loads on scaffold and gave recommended wind force coefficient [8-9].

Steel platform bears large wind load in the air and the flexible external suspended scaffold is the weak point of steel platform. Part of the external suspended scaffold of Shanghai Tower tore during Typhoon Haikui in 2012. The steel platform stayed 300 m from the ground at that time and fortunately the scaffold didn't fall down. So it is significant to get wind-induced responses of steel platform so that reinforcement measures can be developed. A finite element model was established to obtain the wind-induced responses and several reinforcement measures are evaluated here.

2. FINITE ELEMENT MODEL AND WIND LOAD

It was demonstrated in reference [10] that the wind load on steel platform decreased when the stiffness of concrete tube was taken into consideration, so the concrete tube was not included in the finite element model. As all the components of steel platform were connected by bolts and welding, all the joints here were set to be rigid joints and all the components were beam elements. Separated from other parts during working condition, the upper support was ignored in the model. The shutter, located at the bottom of suspended scaffold to prevent object from falling out, are designed to be closed and contact the concrete tube. But in practical construction, the shutter cannot contacts the tube, so the nonlinear springs were used here to simulate the shutter. There is a width of about 50 mm between the shutter and tube, so the displacement of shutter towards tube cannot exceed 50 mm. The nonlinear springs may be unstable under compressive load, so the tube and springs were placed out of the scaffold. The stiffness of springs were set to be nearly zero when the displacement of shutter was less than 50 mm and the stiffness would increase sharply when the displacement reached 50 mm.

The wind loads were created by Davenport wind spectrum and linear filter method. The wind loads lasted 60 s and the turbulence intensity was 0.18. The wind force coefficient of scaffold, based on reference [5], was set to be 0.3717.

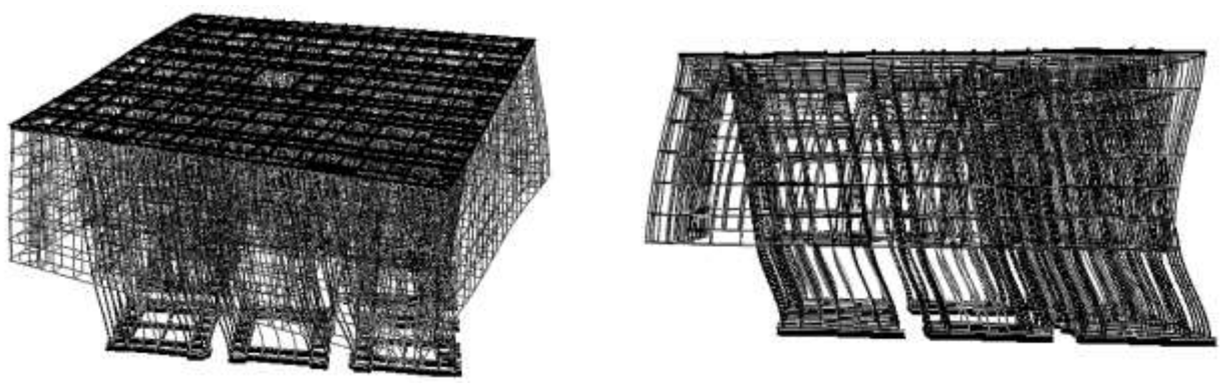
3. ANALYSIS OF THE PROTOTYPE MODEL

The external suspended scaffold is a cantilever beam in the initial state and become simply supported beam when the shutter on windward side is pushed on the tube by wind. So the natural frequency of steel platform will change as the wind velocity and boundary condition changes. The external suspended scaffold can be cantilever or simply supported and results of modal analysis of these two conditions are listed in Tab. 1. The mode shapes of steel platform under two different boundary conditions are the same. The 1st mode is torsional mode and the next two modes are translational mode, as shown in Fig. 2.

Time history analysis of steel platform under various wind loads was then carried out. The shutter will not be pressed on the tube all the time even if the wind velocity was very large because of the turbulence of wind. It can be seen from Fig. 3 that the shutters are nearly pressed on the tube when wind velocity is larger than 22.5 m/s as the root mean square (RMS) value is approximately 50 mm. Fig. 4 shows the different frequency components of displacement of the point in the middle of scaffold under wind speeds of 15 and 30 m/s. The external suspended scaffold is cantilever when wind speed is 15 m/s and become simply supported when wind speed is 30 m/s. It can also be implied from the power spectrum of displacement that when the wind speed is larger than 22.5 m/s, the boundary condition of the external suspended scaffold is considered to be simply supported.

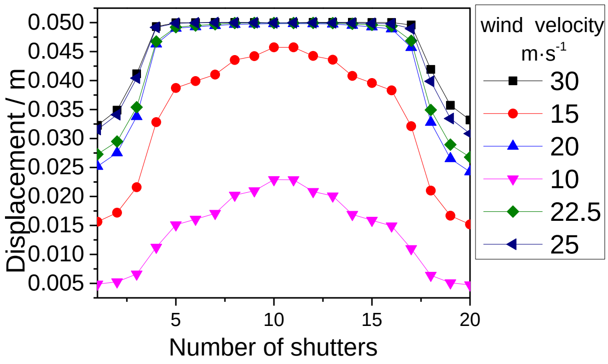
Tab. 1 Frequencies of steel platform under two different boundary conditions

Boundary condition	Cantilever			Simply supported		
Modal order	First	Second	Third	First	Second	Third
Frequency (Hz)	0.692	0.776	0.786	0.719	0.776	0.821



(a) Torsional mode (b) Translational mode

Fig. 2 Mode shape of steel platform



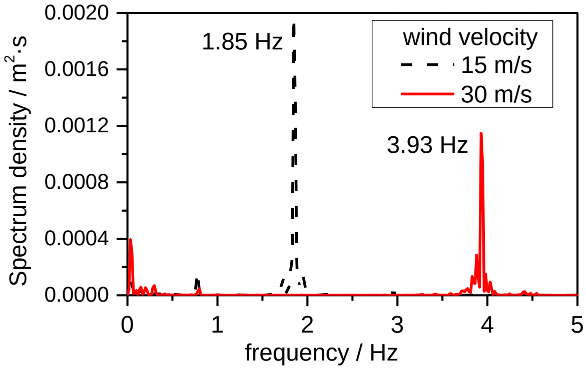
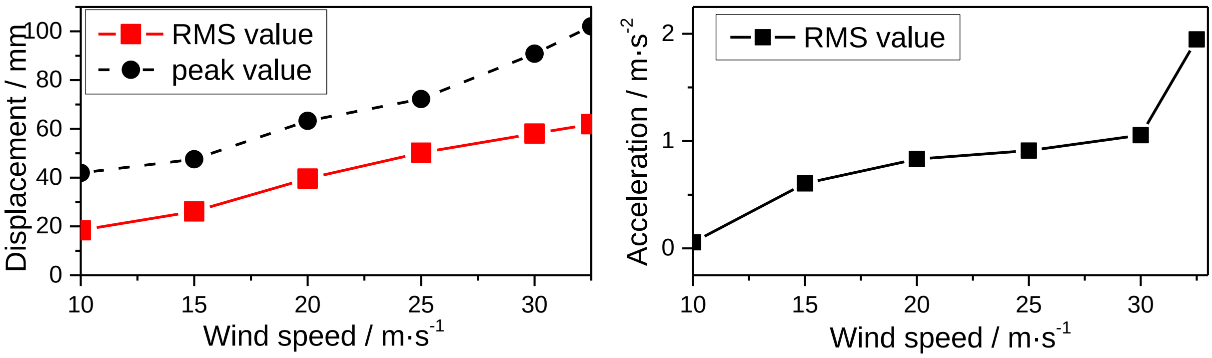


Fig. 3 RMS values of shutters under different wind velocities

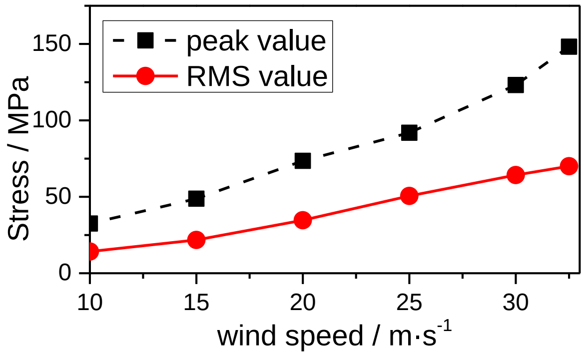
Fig. 4 Power spectrum of displacement of the point in the middle of scaffold

Fig. 5 shows the displacement, acceleration and stress responses of steel platform under wind speed of 10, 15, 20, 25, 30 and 32.5 m/s. According to reference [1], all the work on steel platform will be stopped when the wind speed is larger than 20 m/s and extra reinforcement measures will be taken when the wind speed is larger than 30 m/s. The displacement of scaffold relates to the safety of components of scaffold. The maximum displacement in the middle of scaffold is less than 100 mm when the wind speed is smaller than 30 m/s. The RMS value of acceleration response on the platform is larger than 0.5 $m \cdot s^{-1}$ when the wind speed reaches 15 m/s. all the workers still work on the steel platform when the wind speed is smaller than 20 m/s and the acceleration of 0.5 $m \cdot s^{-1}$ may cause human uncomfortable. The point of the maximum stress of the steel platform locates at the joint of the suspended scaffold and the platform. Different from ordinary scaffold, the safety of the external suspended scaffold relates to the strength rather than buckling of components because the scaffold is suspended on the platform. The peak value of stress can be 148 MPa when the wind speed is 32.5 m/s. Although the stress is smaller than the strength of steel, the bolt of the connection may broke under large load.



(a) Displacement at the mid-span of scaffold

(b) Acceleration on the platform



(c) Stress of the joint of the suspended scaffold and the platform

Fig. 5 Responses of steel platform under various wind speeds

3. REINFORCEMENT MEASURES

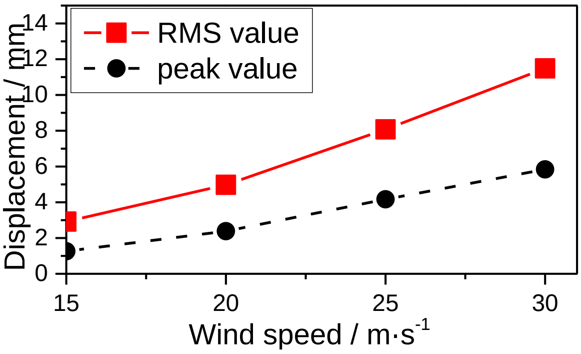
The gap at the bottom of scaffold causes collision between the shutter and the concrete tube, leading to large acceleration responses and possible damage to the scaffold. And the displacement of shutter causes extra stress at the joint of the scaffold and the platform. So the gap should be eliminated at the construction field as the technical regulation specified.

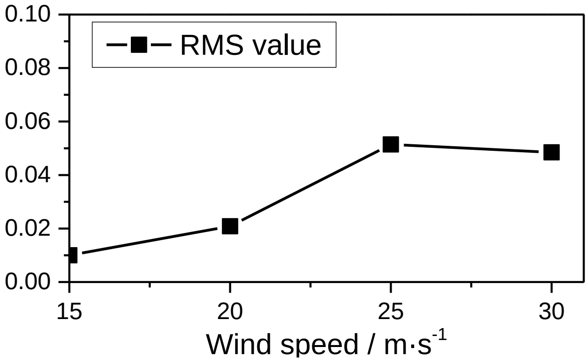
As enlargement of the cross sections of the components of scaffold is not economic, adding lateral supports at the mid-span of scaffold is a more feasible way to increase stiffness of the scaffold. There are large frameworks at the top of the concrete tube and they can provide lateral support for the scaffold. According to the technical regulation, the scaffold should be tied to the framework when the wind speed reaches 30 m/s.

To evaluate the effect of the two reinforcement measures above, the reinforced model was established. Compared with prototype model, the model 2 adds lateral supports at the mid-span of scaffold as well as the gap between the shutter and tube is eliminated. Tab. 2 shows frequency of the reinforced model. The first two modes of reinforced model become translational mode and the stiffness significantly increases compared with prototype model.

Tab. 2 Frequencies of reinforced steel platform

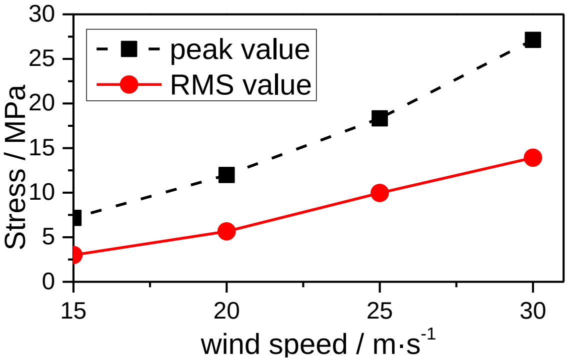
Model	Reinforced model		
Modal order	First	Second	Third
Frequency (Hz)	0.898	0.908	0.909





(a) Displacement of the maximum deformation point of the scaffold

(b) Acceleration on the platform



(c) Stress of the joint of the suspended scaffold and the platform

Fig. 6 Responses of reinforced model under various wind speeds

Fig. 6 shows the result of time history analysis of the two reinforced models under wind speeds of 15, 20, 25 and 30 m/s. The displacement response of scaffold of reinforced model is significantly smaller than the prototype model because there are lateral supports at the mid-span. The acceleration responses on the platform also reduces and the value is less than 0.02 m·s^{-2} when the wind speed is smaller than 20 m/s. The stress of the joint of the suspended scaffold and the platform is also much smaller in reinforced model. The bolt used for the joint should be checked regularly in case of loosening.

4. CONCLUSION

Modal analysis of the steel platform shows that the natural frequency of the steel platform is 0.692 Hz and the first mode is torsional mode, which indicates that the stiffness of external suspended scaffold is too small.

The wind load can cause large displacement at the mid-span of scaffold and large stress at the joint of the scaffold and the platform when the wind speed is large. The acceleration response of the steel platform can reaches 0.5 m·s^{-2} under operating condition, which can lead to human uncomfortable.

Adding lateral supports at the mid-span of the scaffold and eliminating the gap between the shutter and the concrete tube can efficiently reduce the responses of the steel platform. So it is suggested that external hanging staging should be tied to formwork under heavy wind.

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