TIME DEPENDING SERVICE LOAD INFLUENCE ON STEEL TOWER VIBRATIONS

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ABSTRACT

Usually typical steel towers are mainly subject to wind loads. In the case of sightseeing towers with lattice steel structure core and low natural frequency of the structure human and structure interaction could play a role in the tower design. This paper analyses the response of the tower structure to excitation caused by a human movement to assure safe exploitation and acceptable human comfort levels during the exploitation. There are adopted different levels of the structure and human behavior synchronization and its effect on the structure. This phenomenon (synchronization) should be taken into account because people respond naturally to a structure oscillation when the structure has a frequency close to people natural movement frequency. In this paper there are possible mode shapes of the existing 34m high steel core sightseeing tower structure analyzed. The paper gives recommendations of the maximum number of people allowed on the existing structure to ensure safe tower exploitation. The dynamic performance is established through finite element modeling of the tower structure.

Key words: *frequency, mode shapes, sightseeing tower, steel tower, synchronization*

INTRODUCTION

Lattice steel structures are remarkably flexible, low in damping and light in weight. Traditionally for such type of structures dynamic analyses are performed and dynamic parameters such as fundamental frequencies, mode shapes and damping ratios are found to evaluate wind induced vibrations and effects on the structure. Even most advanced and comprehensive codes concentrate mainly on these issues, including the Eurocodes.
In case of the steel lattice sightseeing towers with low natural frequency of the structure human and structure interaction could play a role in the tower design. Human walking induces dynamic and time varying forces. These forces have components in vertical, lateral and longitudinal directions. The lateral forces are a consequence of the sideway oscillation of the gravity centre of a human’s body while stepping alternatively with the right or left foot forwards (Franck, 2009).
The published data on dynamics loads quote that pedestrian vertical and longitudinal walking on stationary pavements fundamental frequency is 2.0 Hz for normal walk, 1.7 Hz for slow walk and 2.3 for fast walk. Horizontal fundamental frequency is 1.0 Hz for normal walk, 0.85 Hz for slow walk and 1.15 for fast walk (Bachman, 1987). In a case of the tower structure there is an interest in the horizontal and longitudinal component of the pacing frequency. Recently, there has been a growing tendency to construct light weight foot bridges. Due to the experienced problems in some of these structures with lateral vibrations there have been performed studies about phenomenon of synchronous lateral excitation.
It is noted that humans are much more sensitive to lateral vibration than vertical one. Even if horizontal vibration is only 2-3 millimeters lateral motion affects balance and pedestrians tend to walk with their feet further apart which increases the lateral force imparted by individuals. In order to maintain balance, pedestrians tend to synchronize their footsteps with the motion of the structure. This instinctive behavior ensures that dynamic forces are applied at the resonant frequency of the structure and increase the motion even more. As the motion increases also the synchronization between pedestrians increases. It will not go infinitely but reaches a steady state by people stopping when motion becomes too uncomfortable (Fujino et al. 1993). It is presumed that the same processes will take place on sightseeing towers. Wind forces will promote initiation of the lateral motion and because of adaptive nature of the human beings the lateral vibration will have a self exited nature until some point.
Expected lattice sightseeing tower vibrations require limitation to meet the human comfort criteria. The limit values for acceleration in the international codes are directly linked to pedestrian comfort. International standards and sources in literature propose different acceleration limit values for different reasons but most of these values coincide within a certain bandwidth.
Guideline (Heinemeyer, 2009) recommended bandwidths for different comfort levels are presented in Table 1.

Table 1

Acceleration limits

Degree of comfort	Lateral acceleration limit a_{limit}
Maximum	<0.1 m/s^2
Medium	0.1-0.3 m/s^2
Minimum	0.3-0.8 m/s^2
Unacceptable discomfort	>0.8 m/s^2

MATERIALS AND METHODS

The present study focuses on the identification whether the particular structure - sightseeing steel lattice tower is at the risk of the harmonic human induced excitation in resonance with natural frequency of the structure. The study looks at the allowable static live load bandwidth to meet the acceleration limits and takes into account possible human and structure synchronization. There are possible mode shapes and corresponding fundamental frequencies of the existing steel core sightseeing tower analyzed. The studied steel core sightseeing tower is located in Dzintari, Jurmala city, Latvia. It is open for public since the 15th of May 2010. The total height of the tower is 36.48m. All elements – the inner and outer core, platforms, and stairs are made of steel except the wooden cladding on the facades of the steel cores. The structural configuration of the tower and its picture is provided in Figure 1. and Figure 2.

The structure consists of a braced inner core with dimensions 1500x1500mm made of tubes with the cross section 200x200x8 and the outer core with dimensions 4240x4240mm made of tubes with the cross section 140x140x5. The outer core does not have any vertical bracing as this was requested by the architectural concept. The inner and outer cores are connected only with steel stairs.

Since the tower was opened for public there have been complaints about tower excessive vibration. The human perception of vibration is very sensitive and the reaction is substantially psychological. Therefore it should be analyzed whether these vibrations are realistic or just perceived by the human visual stimuli. The literature (Heinemeyer, 2009) provides a recommendation whenever fundamental frequencies are close to a critical range (from the point of view of the pedestrian excitation) to use a more precise numerical model, because hand formulas and simplified methods are not enough for assessment of fundamental frequencies. The finite element software is widely spread and accepted as a more precise numerical model. To evaluate the degree of vibration there were fundamental frequencies and critical mode shapes of the existing tower established using three dimensional finite element models created by structural analysis software STRAP 12.5.

Figure 1. Sightseeing tower in Dzintari.

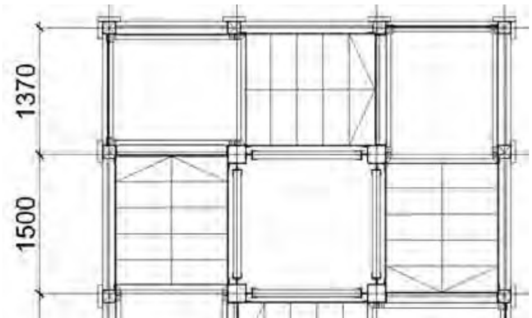

Figure 2. Plan of the sightseeing tower in Dzintari

The fundamental frequency and mode shapes of the structural system can be determined by solving undamped free vibration equation (1) (MacLeod I., 2005):

$$K\,\phi = M\,\phi\,\Omega^2 \quad (1)$$

where K – stiffness matrix;
M – mass matrix;
Φ – corresponding eigenvector matrix;
Ω – eigenvalue matrix.

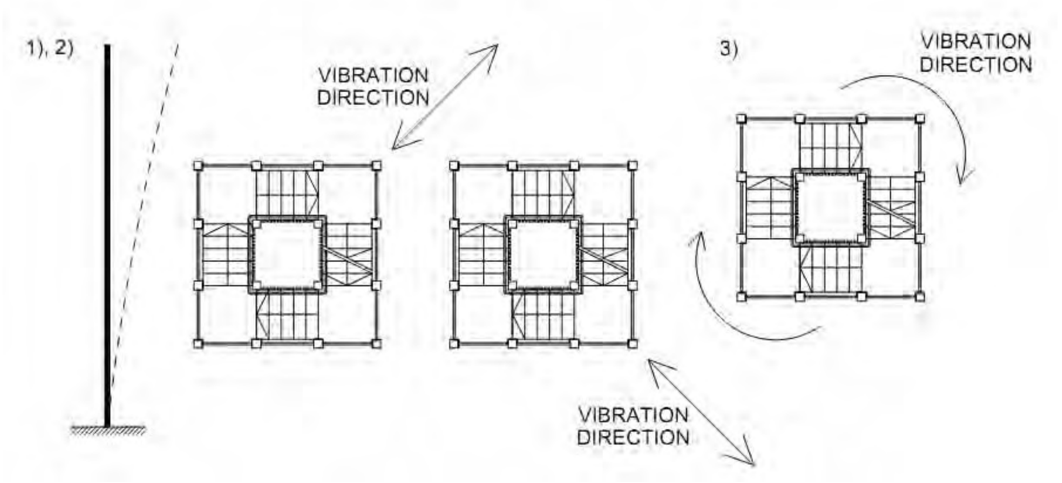

Figure 4. Mode shapes,
where 1), 2) first and second mode shape and vibration directions accordingly;
3) third mode shape vibration direction.

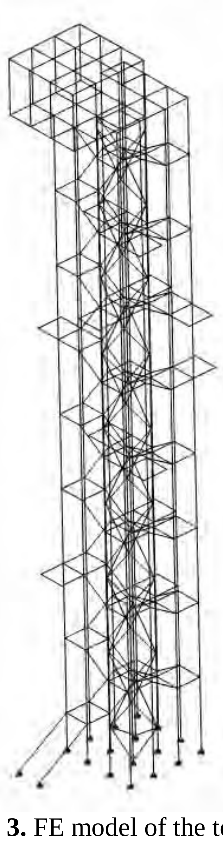

Figure 3. FE model of the tower.

For extraction of eigenvalues the structural analysis software uses the subspace iteration technique. The created finite element (FE) model is presented in Figure 3. and the first three critical mode shapes for the structure are presented in Figure 4.

There is a necessity to evaluate the influence of the static sightseers' mass on the tower natural frequency because natural frequencies of the structure decrease due to a live load and could shift into the critical frequency range or could leave it.

In literature (Heinemeyer, 2009) it can be found that the critical interval of 0,5Hz≤f_i≤1,2Hz for the lateral vibrations and critical range for longitudinal ones is 0,5Hz≤f_i≤1,2Hz, where f_i is natural frequency of the structure.In the tower case the longitudinal component corresponds to the tower torsional mode. The critical range of natural frequencies is based on empirical pedestrians on the flat surface. In this paper it is assumed that similar range will be present for the pedestrian movement on the stairs. But more careful investigation is required as this matter has not been found in literature.

To evaluate acceleration of the tower there is adapted a recommended method in literature (Heinemeyer, 2009) and adjusted to suite the tower case. If harmonic load ($F_o \sin(2\pi f_o t)$) is applied to a damped single degree of freedom system, the response of the system would be:

$$x(t) = \frac{F_0 / 4\pi^2 M}{\sqrt{(f^2 - f_0^2)^2 + 4\xi^2 f^2 f_0^2}} \sin(2\pi f_0 t - \varphi) \qquad (1)$$

where F_0 – amplitude of the lateral load, N;
M – system mass, kg;
f – system natural frequency, Hz;
f_0 – load frequency, Hz;
ξ – structural damping ratio;

$$\varphi = \arctan\left(\frac{2\xi f f_0}{f^2 - f_0^2}\right).$$

From the results obtained by Arup Partnership in the experiment with a shaking table (Newland, 2003) and given by Dallard, 2001 and Fitzpatrick, 2001 amplitude of the lateral load is taken as percentage of the vertical live load and depending on the lateral amplitude of the tower vibration (3). It is observed that the fundamental component of the lateral force increases with the platform amplitude but remains insensitive to the lateral frequency of the structure:

$$H_0 = 0{,}2A + 4 \quad (3)$$

where H_0 – lateral force/vertical force, %;
A – tower vibration amplitude, mm.

Let us model a lattice tower as a cantilever with one degree of freedom and apply amplitude of the horizontal load at the cantilever tip. The equivalent mass applied at the cantilever tip from the tower mass and pedestrian live load uniformly distributed over the height of tower can be obtained by taking approximately one fourth of the total mass of the beam at the free end (Thompson, 2007). Then by approximate methods such as the Rayleigh's method or the Dunkerley's formula approximate equivalent mass of cantilever is found applying formula:

$$m = \frac{33m_b}{140} \quad (4)$$

where m_b – uniformly distributed mass, kg.

To analyze the effect on the structure from the pedestrian synchronization there is considered the first translational mode shape. There is analyzed one of the critical directions of the tower vibration. Applied horizontal live load component is taken as a half of the total equivalent horizontal force taking into account the degree of the synchronization effect. In this paper it is assumed that the sightseers' stream is up and down the same. There is considered only lateral force component influence on the tower vibration.
The loading created by pedestrians' is much more complex in the sightseeing towers than in the case of the bridges. Not only transverse loading should be considered but also longitudinal loading. Horizontal and vertical load component value should be determined as well for pedestrian movement on stairs. This issue will be addressed in a separate study, but for now the Eurocode approach is used for the tower vibration calculations.
During the synchronization process pedestrians adopt the same pacing frequency as natural frequency of the tower. The response of the system (1) becomes:

$$x(t) = \frac{F_0}{8\pi^2 M\xi f^2}\sin(2\pi ft - \frac{\pi}{2}) \quad (5)$$

where F_0 – amplitude of the lateral load, N;
M – system mass, kg;
f – system natural frequency, Hz;
ξ – structural damping ratio.

According to the recommendations of the Eurocode (Eurocode, 2005) the damping ratio ξ for the steel lattice tower with ordinary bolts is 0.05.
Displacement of the tower tip can be found from equation (5):

$$y(t) = x(t)\Phi \quad (6)$$

where y(t) –vector of the movement of concentrated mass;
x(t) – response of the system;
Φ – vector of modal displacement at the tip of the cantilever.

Then human comfort criteria – acceleration at the tip of the tower for the first translational mode shape can be found from equation (7):

$$y^{''}(t) = -\frac{F_0}{2M\xi}\sin(2\pi ft - \frac{\pi}{2}) \quad (7)$$

where F_0 – amplitude of the lateral load, N;
M – system mass, kg;
f – system natural frequency, Hz;
ξ – structural damping ratio.

RESULTS AND DISCUSSION

The determined natural frequencies of the sightseeing tower for the first two mode shapes were just outside the critical frequency range of $0.5\text{Hz} \le f_i \le 1.2\text{Hz}$ and equal to 1.26Hz and 1.3Hz for translational mode shapes.
For the torsional mode shape the tower is already in the critical range of $1.25\text{Hz} \le f_i \le 2.3\text{Hz}$. This means that the sightseers' live load should be taken into account for the tower natural frequency determination. In Figure 5 the natural frequency dependence on the additional sightseers' live load is presented.

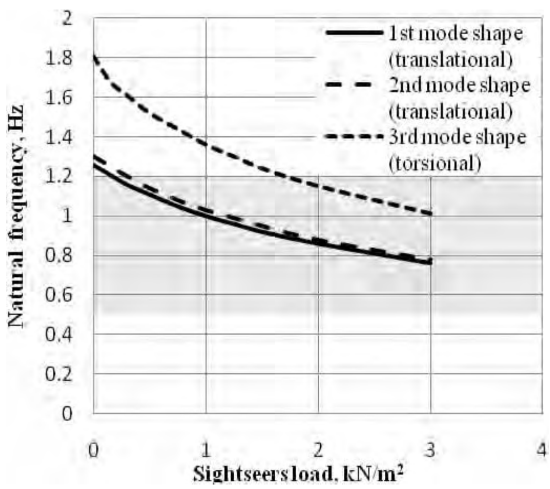

Figure 5. Calculated natural frequencies of the tower as a function of the applied live load.

The chart shows that the visitors' movement up and down the tower may induce vibration combined in torsional and translational directions. When the live load increases torsional vibration gets less frequent and leaves critical range when the live load is around 1.7Hz, which is a significant amount of people on the tower.

It should be mentioned that the accidental situation - intentional tower swaying was not analysed.

"Fujino et al. (1993) estimated from the video recordings of crowd movement that some 20% or more of pedestrians on the bridge were walking in synchronism with the bridge's lateral vibration which had a frequency of about 0.9Hz and amplitude of 10mm" (Newland, 2003).

A similar process of tower sightseers' synchronization is assumed to happen, because it is natural for humans to compensate additional lateral movement of their centre of gravity by swaying with the structure displacement. The initial amplitude of 10mm is 1/3350 of the sightseeing tower deflection and can be easily initiated by wind forces.

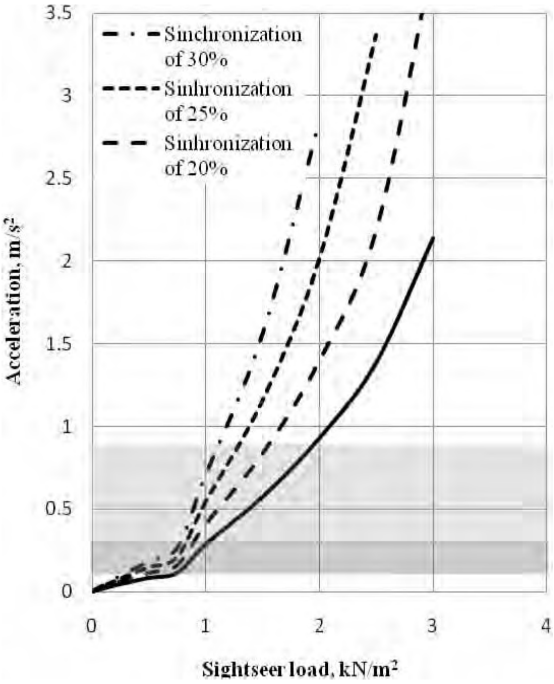

Figure 6. Maximum resonance acceleration.

In this study the range of sightseers' synchronisation has be taken from 15% to 30%. Initiated acceleration from this phenomenon is presented in Figure 6.

During sightseers' synchronization with the structure their step frequency matches to the tower natural frequency. The calculated resonance maximum acceleration is presented in Figure 6. and shows that the medium comfort level for tower visitors is when the sightseers' stream does not exceed 0.75kN/m^2. It corresponds to 180 sightseers with mean weight of 75kg.

When higher live load and degree of synchronization is presented the acceleration increases to unacceptable level. If 15% of synchronization occurs the allowable live load will be almost 2kN/m^2 till unacceptable level is reached in comparison with synchronization level of 30% when unacceptable level will be reached with 1,2kN/m^2 live load.

CONCLUSIONS

According to analytical calculations of the existing 34m high steel lattice sightseeing tower dynamic performance is susceptible to the human induced vibrations. It is concluded that for steel lattice tower type structures with natural frequencies close to the lateral pacing frequency it is important to take into account the potential live load in the tower modal mass calculations. The existing sightseeing tower in Dzintari has critical natural frequency for the torsional mode shape. Therefore, even a relatively light live load induces tower vibrations created by the sightseers' pacing force longitudinal component. More increase of live load adds transversional vibrations created by the sightseers' pacing force horizontal component and depends on the degree of sightseers' synchronization. There is a necessity for further research to evaluate the degree of human synchronization effect during the tower type structure exploitation. The recommended maximum allowable live load to meet medium degree of the comfort level for the tower visitors is 135kN in respect to tower transversional vibrations. In this study there have not the resonance accelerations for the torsional vibration mode been calculated which could further limit the maximum live load.

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