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VIBRATION PROBLEMS OF AN EXAMPLE OF TEMPORARY STEEL GRANDSTAND UNDER HUMAN-INDUCED EXCITATION

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Abstract

Lighter and slender structural members of a typical grandstand leads to a significant reduction in the frequencies, that is why such structures are more easily induced to vibrations. The aim of the present paper is to show the results of the experimental tests and the numerical analyses focused on the behaviour of a part of a typical temporary steel grandstand under dynamic loads. The peak values of accelerations of a steel scaffolding grandstand under human-induced excitation have been determined and compared with the limit values concerning the perception of vibrations by people. The results of the study indicate that the human-induced excitation may induce structural vibrations which substantially exceed the allowable limits.

Keywords: steel grandstands, dynamic loads, human-induced vibrations

1. INTRODUCTION

In the past, grandstands were mainly used during sporting events. Nowadays, due to a number of advantages (economic and aesthetic), these types of structures are commonly used for unsporting events, such as concerts, exhibitions or festivals that involve the presence of loud music beats [10]. It is really a common situation that these types of structures are erected using scaffolding system. The system allows the temporary steel grandstands to be

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quickly and efficiently placed on uneven ground. The size of the structure is not a problem for grandstands erected using scaffolding system. It is possible to build up the structure that can fit just a few spectators or large number of people.

The use of lighter and more slender structural members of a typical grandstand may lead to a significant reduction in the values of natural frequencies and that is why such structures are more easily induced to vibrations [3]. Moreover, previous numerical studies have confirmed that the crowd of spectators significantly decreases the values of natural frequencies (see [6, 8] for example).

A large number of accidents (more than 90), involving the collapse of temporary grandstands, were observed between the years 1889 - 2008, where more than 60 persons were killed and around 6000 were injured [1]. Different types of supports and connections between elements as well as inappropriate bracing systems were mentioned as major causes of disasters. The main problems were related to unexpected excessive loads (23%), where more than 60% of disasters involved dynamic loads as the result of behaviour of spectators, mostly jumping. Possible causes of collapses are presented in Fig. 1 (see [1]). Moreover, structural vibrations have also a significant influence on human perceptions during vibrations [2, 9].

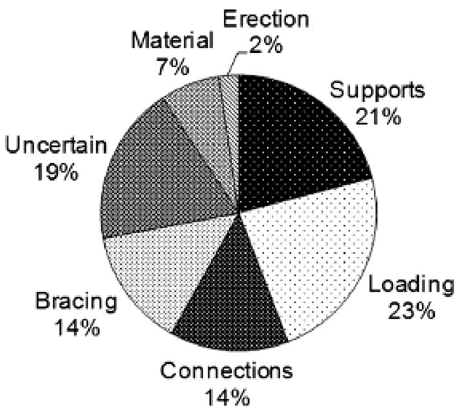

Fig. 1. Possible causes of collapses of temporary grandstands [1]

Temporary steel grandstands are erected using different approaches that should be accurate and appropriate to the considered situation. Different configurations of structural members, types of connections and even weather conditions may have a big influence on changes in dynamic parameters of a structure [2]. Temporary steel grandstands should be designed so as to withstand the effects of unexpected dynamic loads [3].

The aim of the present paper is to show the results of the experimental tests and the numerical analyses focused on the behaviour of a part of steel grandstand under human-induced dynamic loads. The peak values of accelerations of a temporary steel scaffolding grandstand have been determined and compared with the limit values concerning the perception of vibrations by people.

2. TESTS OF FREE VIBRATIONS OF A PART OF A STEEL GRANDSTAND

An example of a part of a temporary steel grandstand, erected using a typical in Poland scaffolding system, has been considered in the study. The structure has a total length of 2.1 m, width of 1.8 m and height of 2.42 m. It consists of tubular members, steel platforms and wooden benches that provide seats for people. The front and back view of the temporary steel grandstand considered in the study is presented in Fig. 2 and Fig. 3, respectively.

Fig. 2. Front view of temporary steel grandstand considered in the study

During the experimental investigation, the steel grandstand has been excited to free vibrations by applying an initial drift at the top of vertical tubular members, so as to determine modes of free vibrations and the corresponding natural frequencies. The measurements have been conducted using four accelerometers mounted at vertical elements. The results of the tests in the form of the acceleration time history, as well as the Fourier spectrum, for the case of left-to-right swaying vibrations, are presented in Fig. 4 and Fig. 5, respectively. It can be seen from Fig. 5 that the spectrum is dominated by one well separated peak representing the fundamental frequency of 4.62 Hz, which has been determined for the direction considered.

Fig. 3. Back view of temporary steel grandstand considered in the study

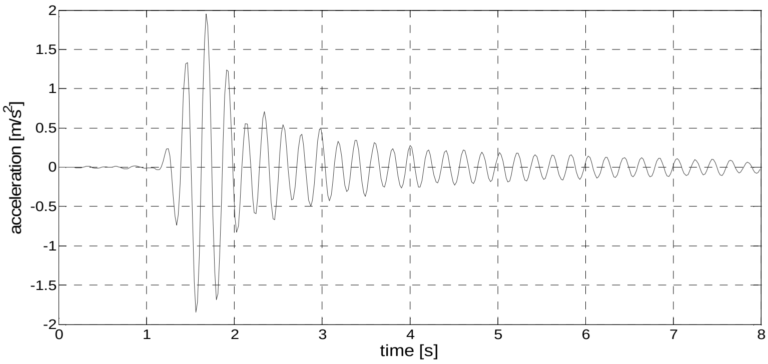

Fig. 4. Acceleration time history for steel grandstand for left-to-right vibrations

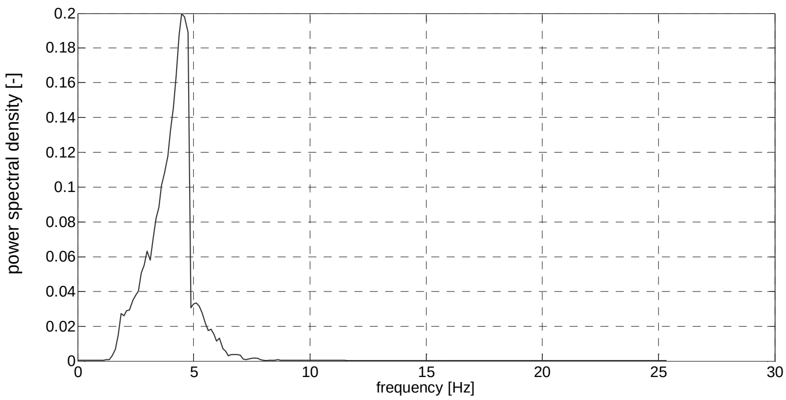

Fig. 5. Fourier spectrum for steel grandstand for left-to-right vibrations

3. NUMERICAL ANALYSES

3.1. Modal analysis

In the next stage of the study, finite element mesh has been generated in the commercial program MSC Marc (see Fig. 6) using two-node beam-column elements (in the case of tubular members) and four-node shell elements (in the case of benches and steel platforms).

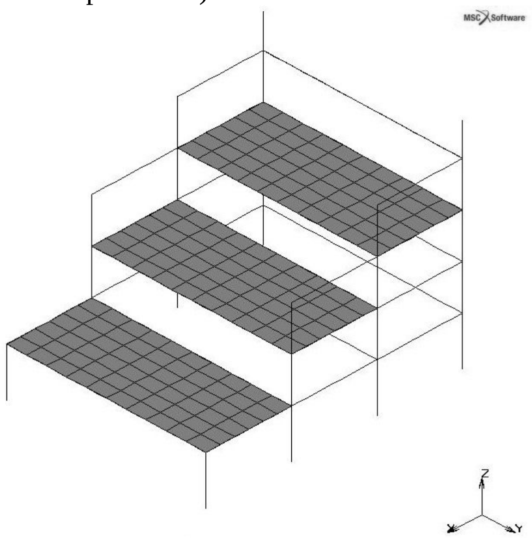

Fig. 6. Finite element mesh of steel grandstand

It is worth mentioning that, due to the system of connections, benches and platforms do not really change the stiffness of the whole structure. Actually, only their masses are important parameters of the model.

The following values of material properties (steel) have been used in the numerical analysis: Young's modulus E=210 GPa, Poisson's ratio ν=0.3 and mass density ρ=7850 kg/m^3. The supports of the model have been considered to be fixed for displacements.

A modal analysis has been firstly conducted so as to verify the accuracy of the finite element mesh generated. A large number of modes of free vibrations and the corresponding natural frequencies have been estimated. The first mode (left-to-right swaying vibrations) of the structure is presented in Fig. 7. According to the British Standards (see [3]) this mode of vibrations is crucial during the design of temporary and retractable grandstands.

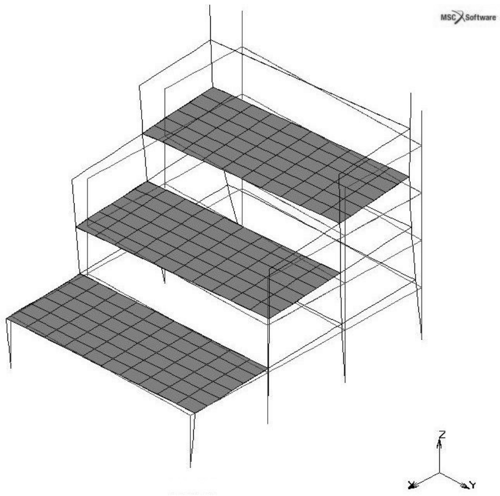

Fig. 7. The mode of free left-to-right vibrations for steel grandstand

The natural frequency for the mode of free left-to-right vibrations has been determined from the modal analysis as equal to 4.6 Hz. Comparison between this value and the natural frequency obtained from the experiments shows good agreement between the results.

3.2. Dynamic response due to a human-induced excitation

The second stage of the numerical study has been devoted to the dynamic transient analysis. The analysis has been focused on determination the peak values of accelerations of the grandstand under human-induced excitation due to jumping with swaying effect.

In the analysis, the dynamic load has been assumed to be consisted of synchronous repetitive impacts, as expressed by Fourier series according to the formula [3]:

$$F_s(t) = G_s\left[1 + \sum_{n=1}^{\infty} r_n \sin\left(\frac{2n\pi}{T_p}t + \varphi_n\right)\right] \tag{3.1}$$

where $F_s(t)$ is dynamic load,
G_s is weight,
r_n is Fourier coefficient (or dynamic load factor) of the n-th term,
n is the number of Fourier terms,
T_p is the period of the jumping load,
φ_n is the phase lag of the n-th term.

The example of the force time history for the two load cycles at 2 Hz is presented in Fig. 8 [3]. In order to account for jumping with swaying effect, the load in the vertical direction, $F_V(t)=F_s(t)$, has been applied together with the additional load in the horizontal direction (left-to-right vibrations), which has been calculated as equal to: $F_H(t)=0.1F_s(t)$ (see [3] for details).

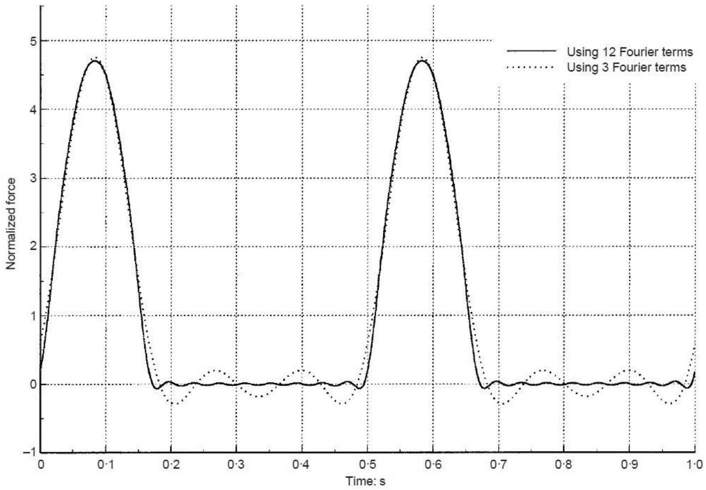

Fig. 8. Load time history for jumping at 2 Hz [3]

The total time of dynamic transient analysis has been assumed to be equal to 2 s and the time step of 0.005 s has been applied in the dynamic analysis. It has been assumed during the analysis that twelve people, with mass of 100 kg each, induce vibrations of the structure. This assumption may seem to be a bit difficult to be satisfied in the reality, since the average mass of a spectator in a typical situation is about 80 kg, but allows us to analyse the worst-case scenario which is actually possible. In the case considered, the mass of the jumping audience is eight times larger than the total mass of the structure itself.

An example of structural response in the form of the acceleration time history (left-to-right vibrations) estimated numerically at the highest level of the grandstand under jumping with swaying effect for the frequency of 2 Hz is shown in Fig. 9. The peak value of acceleration equal to 1.73 m/s^2, as observed from Fig. 9, has been compared to the limit values from the point of view of human perceptions that have been presented in Table 1 (see [3] for details). The comparison indicates that the structural vibrations due to human-induced excitation are much above the acceptable limit for human perceptions that can be classified as disturbing for spectators.

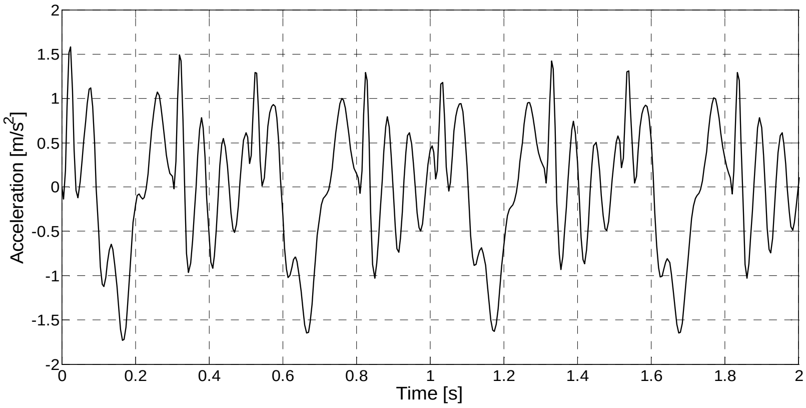

Fig. 9. Acceleration time history for steel grandstand under jumping with frequency of 2 Hz (left-to-right vibrations)

Table 1. Reaction of people on grandstands to various peak acceleration levels [3]

Vibration level	Reaction
<5%g	reasonable limit for passive person
<18%g	disturbing
<35%g	unacceptable
>35%g	probably causing panic

4. FINAL REMARKS

In this paper, the results of the experimental tests and the numerical analyses focused on the behaviour of an example of a temporary steel grandstand under human-induced excitation, have been presented. Comparison between the natural frequencies obtained from the experiments and the numerical analysis confirms the accuracy of the finite element mesh generated. The peak values of acceleration, determined from the dynamic transient analysis, indicate that the human-induced dynamic excitation may induce vibrations which have significant influence on human perceptions exceeding the allowable limits.

Further detailed experimental studies and numerical analyses are planned to be conducted so as to propose a method of reducing human-induced vibrations of different types of steel grandstands by the application of dampers made of flexible polymer (see [4,5,7]).

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PROBLEMY DRGAŃ PRZYKŁADOWEJ TYMCZASOWEJ TRYBUNY STALOWEJ PODDANEJ ODDZIAŁYWANIOM DYNAMICZNYM WYWOŁANYM PRZEZ LUDZI

S t r e s z c z e n i e

Coraz bardziej powszechne staje się stosowanie trybun stalowych podczas różnego rodzaju koncertów i imprez sportowych, podczas których konstrukcje te są narażone na oddziaływania dynamiczne wywołane przez przebywających na nich ludzi. Lekkie i smukłe elementy, z jakich wykonane są trybuny stalowe przyczyniają się do niskich wartości częstotliwości drgań własnych konstrukcji, przez co łatwiej wzbudzić je do drgań. W niniejszym artykule przedstawiono wyniki badań eksperymentalnych i analiz numerycznych dotyczące zachowania się przykładowej tymczasowej trybuny stalowej poddanej oddziaływaniom dynamicznym wywołanym przez ludzi. Podczas eksperymentalnych badań polowych, analizowany fragment konstrukcji wzbudzano do drgań poprzez poziome wychylenie górnej części konstrukcji celem wyznaczenia wartości dominującej częstotliwości drgań własnych. Z kolei, przeprowadzone analizy numeryczne obejmowały analizę modalną oraz analizę dynamiczną trybuny stalowej obciążonej tłumem skaczących widzów. Maksymalne wartości przyspieszeń konstrukcji poddanej dynamicznym oddziaływaniom ludzi porównano z wartościami granicznymi określonymi w literaturze. Na tej podstawie przeanalizowano wpływ drgań konstrukcji na komfort oraz samopoczucie widzów. Uzyskane wyniki wskazują, iż generowane podczas drgań wartości przyspieszeń znacznie przekraczają wartości dopuszczalne.

Słowa kluczowe: trybuny stalowe, obciązenia dynamiczne, wibracje wzbudzane przez ludzi

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