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Cite as: AIP Conference Proceedings **2309**, 020038 (2020); https://doi.org/10.1063/5.0033950
Published Online: 30 November 2020

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Dynamic Analysis of Temporary Steel Grandstand Subjected to Human-induced Excitations due to Jumping

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Abstract. Steel grandstands are structures that are frequently used during sport games and many other non-sporting events, such as festivals, music concerts, or even politicians rallies, with participation of a large number of attendees. Unfortunately, the presence of unexpected excessive dynamic loads due to unpredictable behaviour of spectators (e.g. synchronized harmonic jumping or swaying) may lead to serious structural damage or even total collapse of a structure, and such cases were observed in the past. Given that, steel grandstands should be designed so as to withstand the unexpected dynamic loads leading to damage and, therefore, ensure maximum safety for all participants. Building codes, however, apply different approaches. According to the Polish Standard, an additional horizontal load equal to 6% of the total vertical load acting on a grandstand has to be considered at the design stage. The British Standard, on the other hand, specifies a higher value of horizontal load, i.e. 10% of the total vertical load that should be taken into account. Therefore, the aim of the present paper is to conduct a dynamic numerical investigation focused on the response of a steel temporary grandstand subjected to human-induced vibrations due to jumping with two different values of horizontal load (6% and 10% of the total vertical load) as well as for two different bracing elements (typical tubular member and polymer damper). The results of the study clearly show that the response of a temporary steel scaffolding grandstand equipped with two different bracing elements taking into account two different approaches is substantially different.

INTRODUCTION

Steel grandstands are structures that are frequently used during sport games and many other non-sporting events, including festivals, music concerts, or even politicians rallies, where large number of attendees is observed [1]. Nowadays, temporary structures are more often used, as compared to the permanent ones, due to their quick and easy assembly. It is possible to build up within hours a temporary grandstand that can fit large number of spectators and place it on uneven terrain. Each modular grandstand has to be designed for a particular location and application, while all components can be assembled and disassembled several times. A single structure is therefore erected for a particular event and removed when the event is finished [2].

Temporary steel grandstands are regularly subjected to dynamic loads due to unpredictable behaviour of spectators (e.g. synchronized harmonic jumping or swaying). Moreover, such types of structures are often erected using scaffolding system where very light and slender structural members are more easily induced to vibrations [3]. Unfortunately, the presence of unexpected excessive dynamic loads may lead to structural damage or even total collapse of a structure, which was already observed in the past [4]. Moreover, human-induced vibrations should be controlled not only to prevent structural damage or failure but also to ensure human comfort [2]. That's why full dynamic analysis is often recommended to be conducted so as to properly design such structures [5,6]. Peak values of acceleration are estimated and compared with the limit values so as to verify if temporary steel grandstand is safe and ensures comfort for spectators [7].

Fracture and Damage Mechanics
AIP Conf. Proc. 2309, 020038-1–020038-7; https://doi.org/10.1063/5.0033950
Published by AIP Publishing. 978-0-7354-4045-6/$30.00

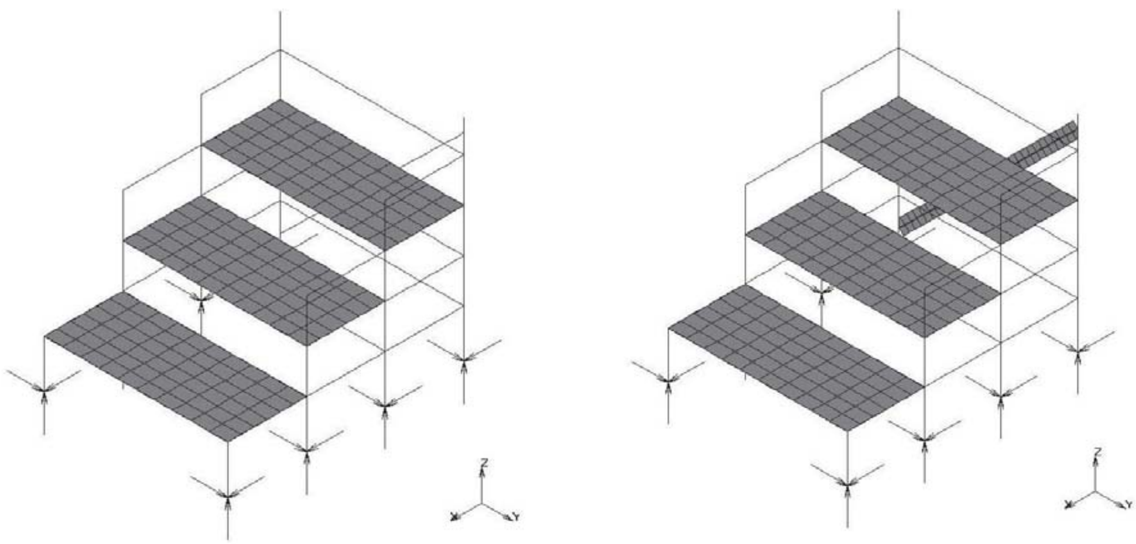
One of the best known methods preventing damage of temporary steel grandstands is the application of specially arranged bracing system. It is individual for each structure and it is used so as to increase the structural stiffness [8, 9].

The Institute of Structural Engineers (IStructE) published in 1999 (see [10]) a guidance collecting rules and directions necessary to design temporary grandstands. Despite the vertical load that is taken into account at the design level, they introduce an idea of applying additional horizontal load as the result of spectator action and geometrical imperfections of frames (e.g. the lack of alignment of vertical members). A percentage of the imposed vertical load has to be applied in horizontal direction. Building codes, however, apply different approaches. According to the British Standard BS 6399-1: 1996 [11], an additional horizontal load equal to 10% of the total vertical load acting on a grandstand has to be considered at the design stage. On the other hand, the Polish Standard PN-EN 13200 [12], specifies a slightly lower value of horizontal load (i.e. 6% of the total vertical load) that should be taken into account.

Therefore, the aim of the present paper is to conduct a dynamic numerical investigation focused on the response of a steel temporary grandstand subjected to human-induced vibrations due to jumping with two different values of horizontal load (6% and 10% of the total vertical load). Moreover, two numerical models of a temporary structure are considered in the study. One of them is equipped with typical tubular bracing element. The second one assumes the installation of a polymer damper instead. It has already been confirmed that structural elements with polymer adhesive of high damping properties can be effective in reduction of structural vibrations (see [13-16] for example).

NUMERICAL MODELS

Two numerical models of a part of temporary steel grandstand erected using scaffolding system have been generated using computer programme MSC Marc. The first of them presents the structure with diagonal bracing member of tubular cross-section (Model A - see Fig. 1a). The second one describes the same temporary grandstand but polymer damper has been applied instead of tubular bracing element (Model B - see Fig. 1b).



(a) (b)

FIGURE 1. FE model of temporary steel grandstand equipped with: (a) tubular bracing member, (b) polymer damper

Tubular structural members creating scaffolding structure have been modelled by standard two-node beam-column elements, while platforms and benches have been generated as standard four-node shell elements available in the program. Polymer element consists of two L-shape steel members (50×50×5 mm) bonded with polymer mass of thickness 5 mm (see also [9]). Standard eight-node (six degrees of freedom for each node) solid elements have been used to model the behaviour of polymer mass, described using Mooney-Rivlin material, that is the most frequently adopted method for modelling complex mechanical behaviour of elastomers and rubber-like solids. The following material constants for the five-parameter Mooney-Rivlin model have been applied: C_{10}=889.490 kPa, C_{01}=-245.840

kPa, C_{20}=-155.310 kPa, C_{11}=93.786 kPa, C_{30}=11.148 kPa [17]. The bulk modulus has been set to be equal to 2.5 GPa, as commonly used for elastomers and rubber-like materials.

DYNAMIC ANALYSIS

Dynamic transient analysis has been focused on the response of a steel temporary grandstand (Model A and B) subjected to human-induced vibrations due to jumping. In the analysis, the dynamic load has been assumed to be consisted of synchronous repetitive impacts, as expressed by Fourier series [7]:

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

where F_s(t) = dynamic load; G_s = weight; r_n = the Fourier coefficient (or dynamic load factor) of the n-th term; n = the number of Fourier terms; T_p = the period of the jumping load; and φ_n = the phase lag of the n-th term. Additionally, two different cases of horizontal loads have been analysed. The first of them, described in the British Standard [11], where 10% of the total vertical load has been considered (Load Case 1). The second approach (Load Case 2), assuming 6% of the total vertical load, has been applied in horizontal direction following the recommendations of the Polish Standard [12].

Dynamic transient analysis has been conducted so as to determine peak values of accelerations and dis-placements for two numerical models under two different values of horizontal load (6% and 10% of the total vertical load). Acceleration time histories (Y direction) for both models determined at the highest steel platform for two load cases are presented in Fig. 2-5. The displacement time histories (Y direction) for temporary steel grandstand equipped with different bracing elements assuming two load cases (Load Case 1 and Load Case 2), as measured at the same location, are also shown in Fig. 6-9. Additionally, the peak values of accelerations and displacements (Y direction) of the temporary steel grandstand with typical tubular member (Model A) and with polymer damper (Model B) under two load cases are summarized in Table 1 and Table 2, respectively.

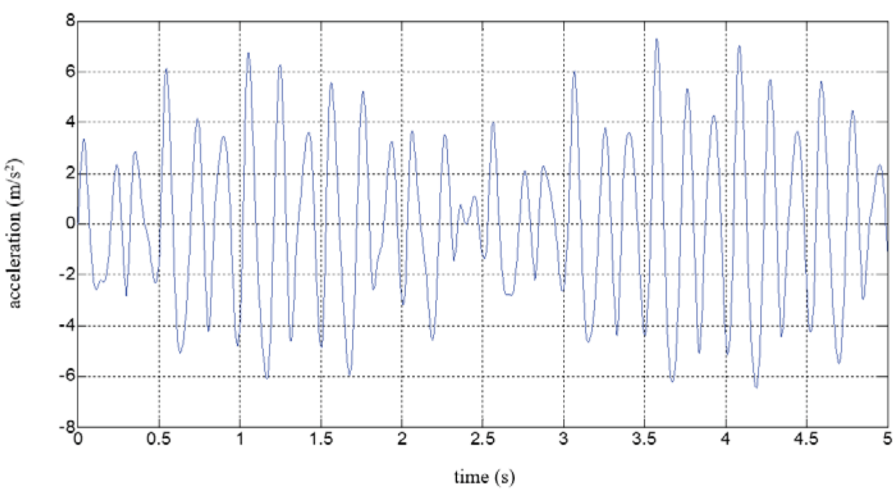


FIGURE 2. Acceleration time history for Model A under Load Case 1 (Y direction)

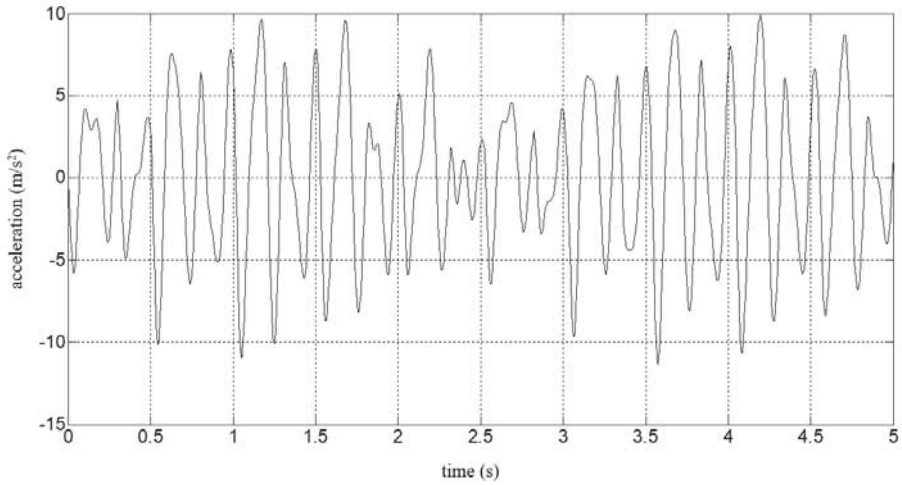


FIGURE 3. Acceleration time history for Model A under Load Case 2 (Y direction)

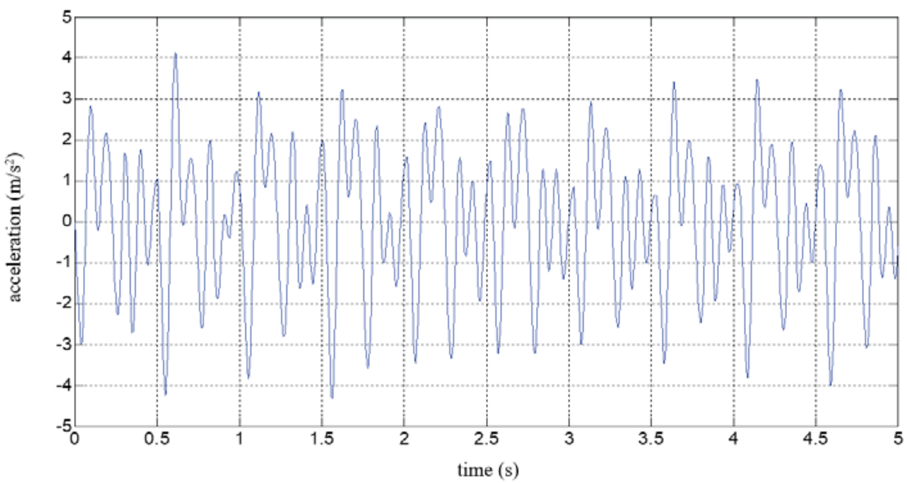


FIGURE 4. Acceleration time history for Model B under Load Case 1 (Y direction)

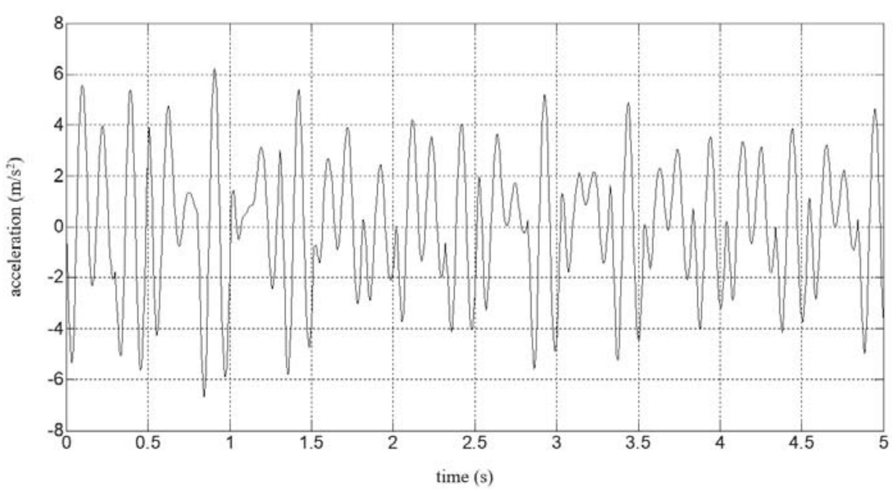


FIGURE 5. Acceleration time history for Model B under Load Case 2 (Y direction)

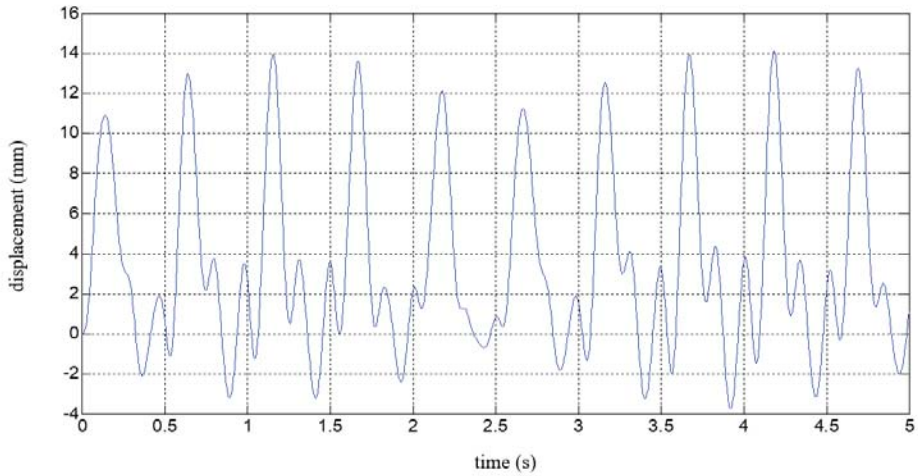


FIGURE 6. Displacement time history for Model A under Load Case 1 (Y direction)

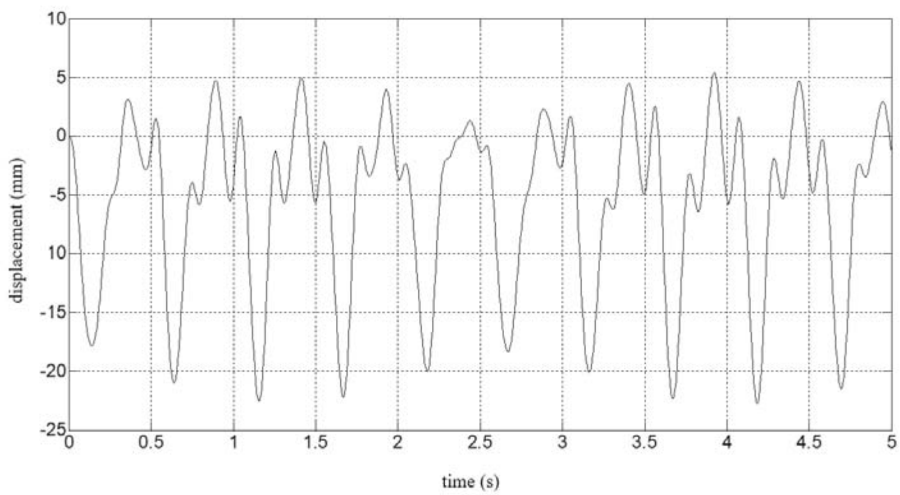


FIGURE 7. Displacement time history for Model A under Load case 2 (Y direction)

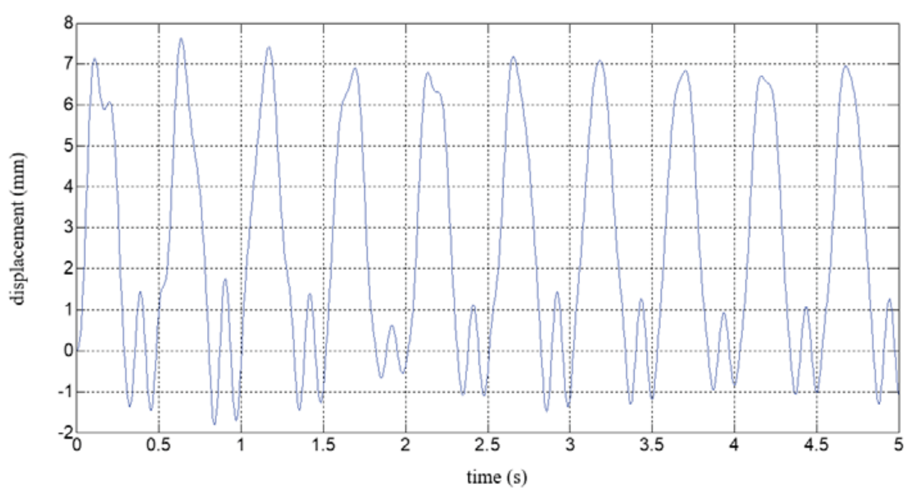


FIGURE 8. Displacement time history for Model B under Load Case 1 (Y direction)

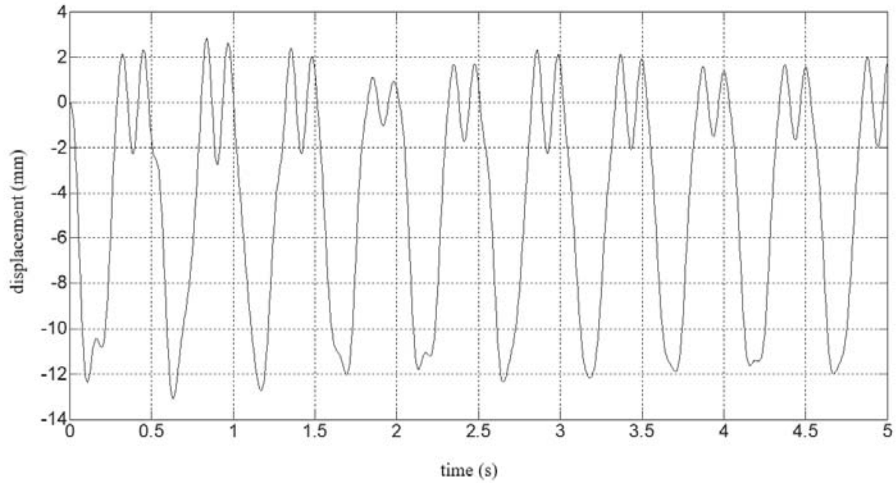


FIGURE 9. Displacement time history for Model B under Load Case 2 (Y direction)

TABLE 1. Peak values of accelerations and displacements (Y direction) for Model A under two load cases.

Load case	Acceleration (m/s^2)	Displacement (mm)
Load Case 1	7.32	14.13
Load Case 2	11.30	22.77

TABLE 2. Peak values of accelerations and displacements (Y direction) for Model B under two load cases.

Load case	Acceleration (m/s^2)	Displacement (mm)
Load Case 1	4.28	7.63
Load Case 2	6.70	13.11

The observed peak values of accelerations differ significantly when comparing different numerical models. In the case of structure where polymer damper is applied, a decrease by 42% (for Load Case 1) and 41% (for Load Case 2) is observed, as compared to the structure equipped with typical tubular member. A similar situation also concerns peak displacements. The decrease by 46% (for Load Case 1) and 42% (for Load Case 2) is visible for Model B, as compared to Model A. Moreover, by comparing two load cases, a significant increase (as large as 54% and 57%) in the peak value of acceleration is observed in the case of Model A and Model B, respectively. A similar situation is noticed for peak value of displacements. In the case of Model A, the peak values increase by as much as 38%, while in the case of Model B 42% of increase is observed.

CONCLUDING REMARKS

The dynamic numerical investigation, focused on the response of a steel temporary grandstand subjected to human-induced vibrations due to jumping assuming two different values of horizontal load (6% and 10% of the total vertical load), has been conducted in this paper. Two different numerical models of temporary steel grandstand have been generated. The first one has been equipped with typical tubular bracing element, while the polymer damper has been installed in the second one.

The results of the study clearly show that the response of a temporary steel scaffolding grandstand equipped with two different bracing elements taking into account two different approaches is substantially different. A substantial decrease in the values of peak accelerations and peak displacements has been observed for the structure with polymer damper, as compared to the case when typical tubular member is used. Moreover, a significant increase in the peak responses has been noticed for the grandstand with larger additional horizontal load applied on the structure.

It is also important to underline that British and Polish Standards present different approaches in the case of additional horizontal load acting on a grandstand. Authors recommend considering both approaches for different load cases so as to prevent damage or failure of the temporary steel grandstand and ensure human comfort.

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