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Investigation of behaviour of metal structures with polymer dampers under dynamic loads

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Abstract

A large number of accidents concerning structures subjected to dynamic loads have been recently observed. One of the examples of such a structure is a temporary steel grandstand erected using scaffolding system. Dynamic load that is generated by crowd movement has a significant influence on the behaviour of the structure and may lead to excessive structural vibrations.

The aim of the study is to consider the idea of using polymer dampers in reduction of vibrations of metal structures exposed to dynamic loads. Firstly, the preliminary analysis of a cantilevered composite beam, consisting of two aluminium flat bars bonded with polymer mass, has been conducted. Dynamic parameters, such as modes of free vibrations, corresponding natural frequencies and damping ratios, have been determined and compared with values estimated for the plain aluminium cantilevered beam. In the second stage of the investigation, the effectiveness of using polymer damper in reduction of vibrations of a steel scaffolding grandstand under crowd load has been considered. The behaviour of the structure equipped with typical tubular stiffener as well as with the additional damper has been analysed and dynamic parameters for both models have been compared. Dynamic analyses have been focused on the peak values of accelerations and displacements of the structures analysed.

The results of the study clearly show that the response of the composite aluminium beam as well as a steel scaffolding grandstand with and without polymer members is substantially different. In the case of the aluminium beam, the application of the polymer layer may lead to even ten times higher values of damping ratio and results in lower values of peak accelerations and displacements. A similar situation concerns also a steel scaffolding grandstand for which the reduction in structural vibrations after installation of additional polymer damper has been found to be substantial.

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Keywords: metal structures; polymer damper; dynamic load; human-induced vibrations; damping ratio;

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1. Introduction

Excessive structural vibrations due to different dynamic loads are among the most serious and dangerous situations that can occur in the case of civil engineering structures [1-3]. Temporary steel grandstands are the example of structures that are commonly subjected to dynamic loads generated by crowd movement [4,5]. Relatively light and slender structural members are very easily induced to vibrations [6]. A large number of accidents concerning these structures subjected to dynamic loads were observed in the past [7]. To avoid such effects, an application of specially designed bracing system, so as to improve the stiffness of the structure of steel grandstands, is commonly used. The second solution that can be taken under consideration is to increase the damping properties of the structure, i.e. by the installation of additional damping elements [8,9].

The aim of the present study is to verify the effectiveness of using polymer mass as a component of elements that leads to increase damping properties of the metal structures. Firstly, aluminium cantilevered beam bonded with polymer mass has been analysed (see also [10]). The polymer mass that has been used is a specially designed flexible two-component grout, which has high damping properties [11,12]. Dynamic parameters of the composite element have been estimated and compared with the plain aluminium beam. The results obtained from the first stage of the investigation have been used in the next one concerning the application of specially designed polymer damper in the temporary steel grandstand. The damper consists of two L-shape elements bonded with polymer mass. Previous experimental study has confirmed that using polymer mass increases values of structural damping ratio [8]. In the present paper, dynamic parameters of the structure equipped with typical tubular stiffener member and polymer damper have been also numerically analysed and compared. Dynamic analyses have been focused on the peak values of accelerations and displacements of the structure analysed.

2. Investigation on composite aluminium beam with polymer adhesive

2.1. Experimental study

The first stage of the investigation has been devoted to the analysis of composite beam with polymer adhesive inside (compare [10]). The cantilevered element, that consists of two aluminium flat bars bonded with polymer mass, had the following dimensions: 9x30x1250 mm (see Fig. 1). Thickness of the polymer adhesive was equal to 5 mm. The study has been focused on determination of dynamic parameters, such as modes of free vibrations and corresponding natural frequencies of two cantilevered aluminium beams (with and without polymer adhesive).

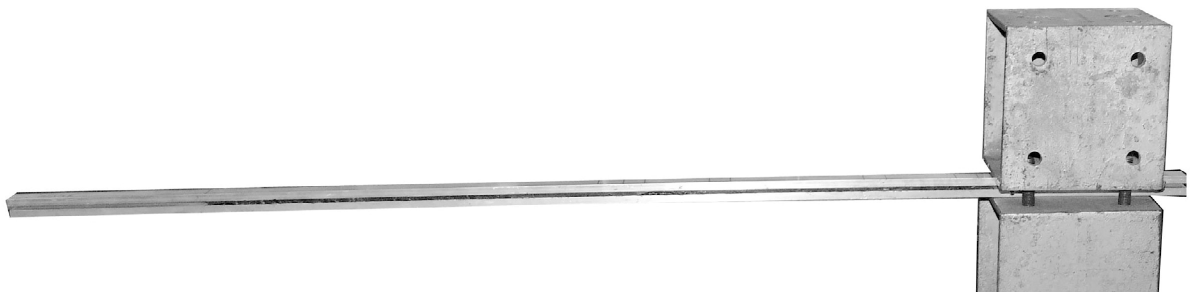

Fig. 1. A cantilevered aluminium beams with polymer adhesive inside.

Beams have been induced to vibrations by applying an initial drift at the end of the beam. The behaviour of the elements has been observed and recorded by two accelerometers installed on the metal side at the end of each beam. The total time of each measurement was equal to 12.5 seconds. The examples of the results are shown in Fig. 2. For the first mode of free vibration, the following values of natural frequencies have been obtained: 4 Hz for the plain aluminium cantilevered beam and 7.6 Hz for the composite one. Based on the acceleration time histories, damping ratios have been estimated. The value of to 0.17% has been calculated for the plain aluminium beam, while the value of 1.97%. has been obtained for the composite beam (increase in damping ratio by as much as 1158%).

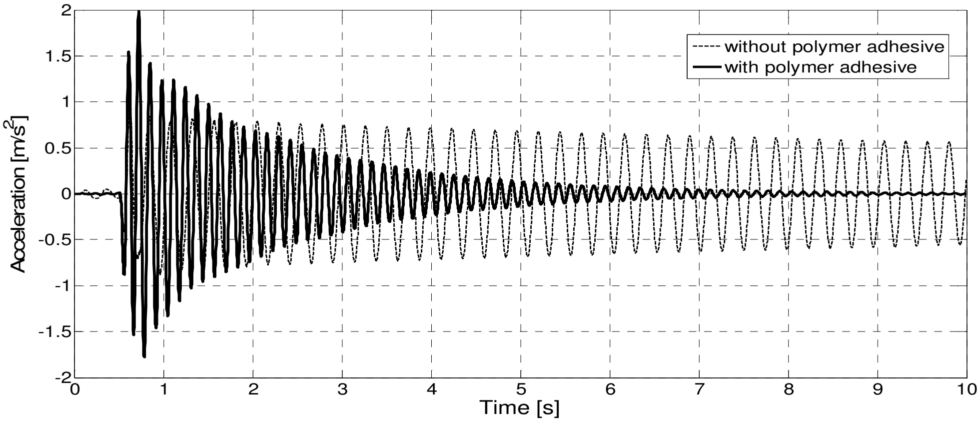

Fig. 2. Acceleration time histories for plain and composite cantilevered aluminium beams.

2.2. Numerical analysis

Numerical analysis of plain and composite aluminium beams have also been conducted using commercial software MSC Marc. Three-dimensional models have been generated using eight-node solid elements (six degrees of freedom). Aluminium, as a structural material, has been described by the following values of material properties: E=70 GPa, v=0.3, ρ=2700 kg/m^3. The behaviour of polymer has been simulated with the use of the Mooney-Rivlin material model that is the most frequently adopted method for modelling complex mechanical behaviour of elastomers and rubber-like solids [13]. 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. The bulk modulus has been set to be 2.5 GPa. The mass density of ρ=1000 kg/m^3 has been considered in the analysis. The natural frequencies estimated from the modal analysis are equal to 4.4 Hz for the plain aluminium beam and 7.5 Hz for the composite one. Relatively small differences between these values and the experimental results (only 1% in the case of the composite beam) confirms somehow the accuracy of the numerical model created.

3. Experimental and numerical analysis of steel grandstand equipped with polymer damper

3.1. Experimental study

The results obtained from the first stage of investigation have been used in the second stage devoted to temporary steel grandstand erected using scaffolding system. The application of polymer damper instead of using typical solution (tubular steel member) has been considered. Two L-shape steel elements have been bonded with polymer adhesive of thickness 5 mm and installed as a diagonal structural member. Due to relative movement of two different steel parts of the damper, the polymer mass between them is always under the state of shearing. Experimental study has concerned the behaviour of an empty and occupied structure (see [8]). It has been assumed that twelve spectators of mass around 100 kg each occupy the grandstand. Dynamic parameters, such as natural frequencies and damping ratios, have been estimated from experimental study and are shown in Table 1 and Table 2.

Table 1. The natural frequencies and values of damping ratio estimated for an empty steel grandstand.

Type of the stiffener	Natural frequency [Hz]	Damping ratio [%]
Tubular member	5.50	0.54
Polymer damper	5.88	1.05

Table 2. The natural frequencies and values of damping ratio estimated for an occupied steel grandstand.

Type of the stiffener	Natural frequency [Hz]	Damping ratio [%]
Tubular member	3.12	0.98
Polymer damper	3.38	3.05

As it can be seen from Table 1, the value of natural frequency of an empty structure determined for both types of stiffener members are quite similar. Application of polymer adhesive, as the component of the damper, has no significant influence on stiffness of the structure. It should be underlined, however, that using the polymer damper leads to substantial increase in damping ratio (increase by 194%). A similar situation concerns also the occupied grandstand. In the case of this structure, the application of polymer damper leads to the significant increase in damping ratio (increase by as much as 311%).

3.2. Numerical analysis

The numerical analysis has also been conducted. Two models of temporary steel grandstand have been generated using commercial software MSC Marc (see Fig. 3). The first one represents structure equipped with typical tubular member, while the second one includes the application of polymer damper (both elements are diagonal ones attached at the back part of structure as shown in Fig. 3). Two load case situations have been considered (empty and occupied structure). Based on the modal analysis, the following values of natural frequencies for the empty structure have been obtained: 5.71 Hz (with tubular member) and 5.66 Hz (with polymer damper). In the case of occupied grandstand, the estimated values of natural frequencies have been found to be equal to: 3.47 Hz (with tubular member) and 3.35 Hz (with polymer damper). The results of the numerical analysis are consistent with the experimental ones (the difference is between 1% and 11%).

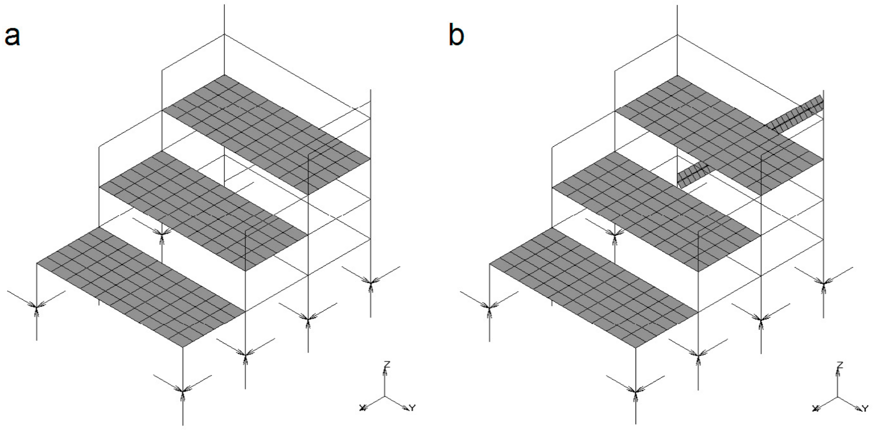

Fig. 3. Numerical model of temporary steel grandstand (a) with tubular member; (b) with polymer damper.

The second part of the numerical study has been devoted to the dynamic transient analysis. The goal of the analysis was to estimate horizontal displacement and acceleration time histories of the grandstand under human-induced vibrations due to jumping. In the analysis, the dynamic load has been assumed to consist of synchronous repetitive vertical impacts, as expressed by Fourier series (see [4]). The total time of dynamic analysis has been set to 5 s and the time step of 0.005 s has been applied. The examples of the results in the form of the horizontal (Y direction) acceleration and displacement time histories at the top of the structure are shown in Fig. 4 and Fig. 5, respectively. The peak values of accelerations and displacements, estimated for temporary steel grandstand equipped with different types of stiffeners, are also summarized in Table 3. It can be seen from the table that the peak response values of structure equipped with polymer damper are almost two times lower than values estimated for grandstand in which typical solution has been used.

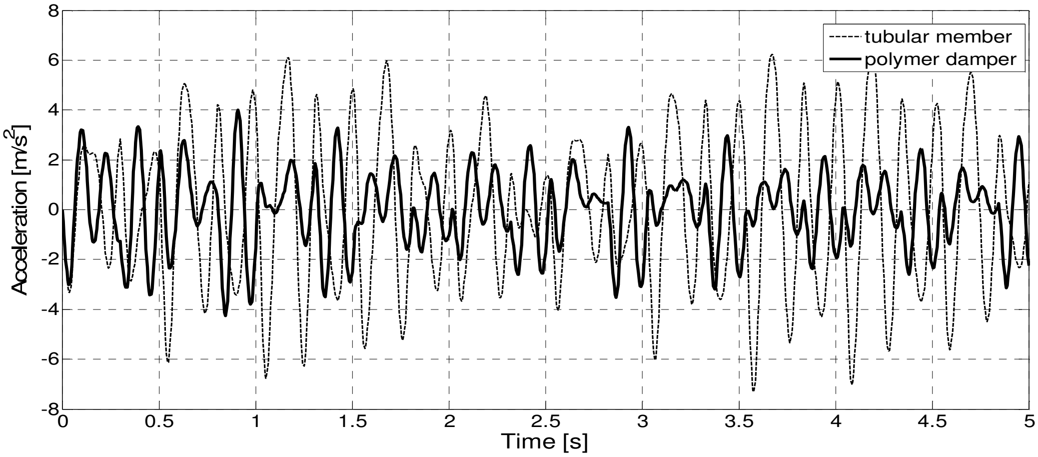

Fig. 4. Acceleration time history (Y direction) for jumping at 2 Hz of temporary steel grandstand equipped with different types of stiffener members.

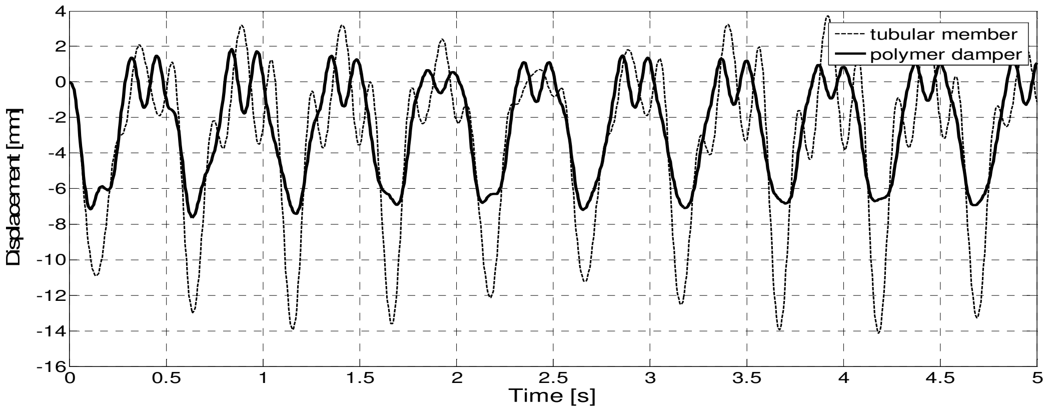

Fig. 5. Displacement time history (Y direction) for jumping at 2 Hz of temporary steel grandstand equipped with different types of stiffener members.

Table 3. Peak values of acceleration and displacement for grandstand equipped with different types of stiffener member (Y direction).

Type of the stiffener	Acceleration [m/s^2]	Displacement [mm]
Tubular member	7.32	14.13
Polymer damper	4.28	7.63

4. Conclusions

The results of the investigations devoted to the effectiveness of polymer adhesive in reduction of vibrations of metal structures have been presented in this paper. The first stage of the study has been focused on cantilevered aluminium beams bonded with polymer mass. Dynamic parameters have been estimated and compared with the results obtained for the beam where polymer mass has not been used. The results of the study clearly show that the application of polymer adhesive leads to substantial increase in the damping ratio of the beam (increase by 1158%). The result obtained from the first stage of the study has allowed us to consider the application of polymer adhesive as an effective method in reduction of vibrations of real civil engineering metal structures. To confirm that statement, the second stage of the investigation has been conducted in which the effectiveness of polymer damper in reduction of temporary steel grandstand vibrations has been analysed. The behaviour of the structure equipped with typical tubular stiffener as well as with the additional damper has been analysed and dynamic parameters for both models have been compared. The results of the modal analysis show that using the polymer damper leads to substantial increase in the structural damping ratio (increase by 194% for the empty structure and by 311% in the case of the occupied one). Further study has been focused on the response of the grandstand under human-induced vibrations due to jumping. The results of the dynamic transient analysis indicate that the peak values of accelerations and displacement of structures equipped with polymer damper are almost two times lower than values estimated for grandstand in which typical solution has been used. It should be underlined that the application of polymer damper leads to significant reduction in vibrations of temporary steel grandstand, while keeping its stiffness at nearly the same level as in the case of typical stiffener.

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