Numerical Investigation on Dynamic Performance of a Multi-storey Steel Structure Model and Comparison with Experimental Results

Tomasz Falborski, Barbara Sołtysik and Robert Jankowski

Abstract Shaking table testing is the most commonly adopted method to simulate earthquake forces. This approach allows us to analyze the dynamic performance and provides a valuable insight into the dynamics of building structures, which helps to improve their future safety and reliability. The present study aims to conduct a numerical evaluation of dynamic response of a multi-storey steel structure model, which was previously examined during an extensive shaking table investigation. The experimental model was subjected to a number of different earthquake ground motions and a mining tremor. In order to perform this numerical research, the analyzed two-storey steel structure model was considered as a 2-DOF system with lumped parameters, which were determined by conducting free vibration tests. The results obtained demonstrate that not only seismic excitations but also mining tremors may considerably deteriorate structural behaviour by inducting strong structural vibrations. The time-acceleration history plots computed for the multi-storey structure model idealized as a 2-DOF system are consistent with those recorded during the previously conducted shaking table investigation, which confirms high accuracy in assuming lumped parameters to characterize the analyzed two-storey steel structure model.

Keywords Structural dynamics · Earthquake excitations
Multi-degree-of-freedom system · Differential equation of motion

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1 Introduction

Earthquakes are identified among the most severe and unpredictable dynamic excitations, which building structures can be exposed to. Strong ground motions may cause a lot of damage in a wide variety of ways and, therefore, have become an issue of major concern of both professional and research communities (see, for example, [1–11]). Earthquakes produce large-magnitude forces of short duration that must be resisted by a structure without causing collapse and preferably without significant damage to the structural members. For that reason, ground motions resulting from earthquakes present unique challenge to the design of structures and became an issue of major concern in many seismically active regions.

Shaking table testing is the most commonly adopted approach to simulate earthquake forces. It allows us to analyze the seismic performance and provides a valuable insight into the dynamics of building structures, which helps to improve their future safety and reliability. Therefore, the present study aims to conduct a numerical evaluation of dynamic response of a two-storey steel structure model, which was previously examined during an extensive shaking table investigation. The experimental model was subjected to a number of different earthquake ground motions and one mining tremor as an example of so-called mining-induced seismicity (see, for example, [12]). In order to perform this numerical research, the analyzed two-storey steel structure model was considered as a two-degree-of-freedom (2-DOF) system with lumped parameters, which were determined by conducting free vibration tests.

2 Experimental Model and Shaking Table Investigation

In order to conduct the experimental investigation, a two-storey steel structure model was firstly prepared, as indicated in Fig. 1. It was built using two welded steel frames and three concrete plates. The welded steel frames were constructed using the rectangular hollow section elements (RHS $15 \times 15 \times 1.5$ mm). The columns were arranged in a rectangular pattern with spacing of 0.465 m in the longitudinal direction and 0.556 m in the transverse one. Additional diagonal bracing was used in the sidewall planes to counteract transverse and torsional vibrations. Concrete plates ($50 \times 50 \times 7$ cm) were used to simulate the weight of floors and a foundation slab. The two-storey structure model was 2.30 m high and weighs nearly 150 kg. The seismic response of the experimental model under a number of dynamic excitations, including earthquake ground motions and a strong mining tremor (see [13]), was extensively studied during a comprehensive shaking table investigation carried out with the use of a middle-sized shaking table located at Gdansk University of Technology, Poland. The more detailed results obtained from the shaking table study for both single- and two-storey steel structure models have already been presented in previous publications (see [14]).

Fig. 1 Two-storey experimental model mounted on the middle-sized shaking table

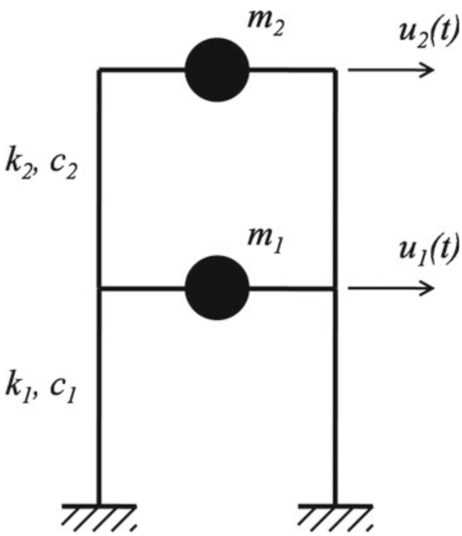

Fig. 2 Experimental model as a two-degree-of-freedom system

3 Numerical Analysis

In order to perform the numerical evaluation of dynamic response of the experimentally examined two-storey steel structure model, lumped-mass system has been applied (Fig. 2). The experimental model was idealized as a 2-DOF system, for which the dynamic equation of motion is given by (see, for example, [15, 16]):

$$M \cdot \ddot{u}(t) + C \cdot \dot{u}(t) + K \cdot u(t) = -MI \cdot \ddot{u}_g(t) \tag{1}$$

in which M, C, and K denotes mass, damping, and stiffness matrices, respectively, $u(t)$, $\dot{u}(t)$, and $\ddot{u}(t)$ the displacement, velocity, and acceleration of the structure model, respectively, $\ddot{u}_g(t)$ the ground acceleration, and I is the influence coefficient matrix, having 1 for elements corresponding to degrees of freedom in the direction of the applied ground motion and 0 for the other degrees of freedom. Matrices M, C, K, $u(t)$, $\dot{u}(t)$, $\ddot{u}(t)$, and I are defined as follows:

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \tag{2}$$

$$C = \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix} \tag{3}$$

$$K = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \tag{4}$$

$$\ddot{u}(t) = \begin{Bmatrix} \ddot{u}_1(t) \\ \ddot{u}_2(t) \end{Bmatrix} \tag{5}$$

$$\dot{u}(t) = \begin{Bmatrix} \dot{u}_1(t) \\ \dot{u}_2(t) \end{Bmatrix} \tag{6}$$

$$u(t) = \begin{Bmatrix} u_1(t) \\ u_2(t) \end{Bmatrix} \tag{7}$$

$$I = \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \tag{8}$$

The 2-DOF system was characterized by the following parameters:

$$m_1 = m_2 = 47.56\,\mathrm{kg} \tag{9}$$

$$k_1 = k_2 = \omega^2 m = 20,571\,\frac{\mathrm{N}}{\mathrm{m}} \tag{10}$$

$$c_1 = c_2 = 2m\omega\xi = 10.48\,\frac{\mathrm{kg}}{\mathrm{s}} \tag{11}$$

where m_1 and m_2 denote lumped masses concentrated at the mid-height and the roof level, k_1 and k_2 the values of lateral stiffness, c_1 and c_2 the values of viscous damping. The natural circular frequency ω and the damping ratio ξ were previously determined by conducting free vibration tests.

In order to solve the second-order differential equation of motion (Eq. 1), the unconditionally stable Newmark's average acceleration method was applied (see [17]), as it is the most frequently used integration procedure in the case of seismic analyses of structures. The 2-DOF system considered in the present study was subjected to the same dynamic excitations, which were previously applied to the experimental model during the shaking table investigation (see [13]).

The acceleration time histories computed for the 2-DOF system under various seismic excitations are presented in Figs. 3, 4, 5, 6 and 7. The comparison of the results obtained from the numerical analysis using lumped-mass model and the shaking table investigation are briefly reported in Table 1.

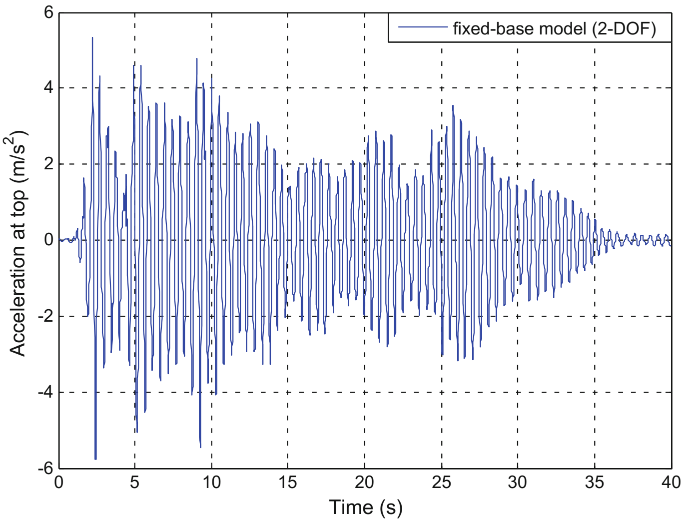

Fig. 3 Computed time-acceleration history for the 1940 El Centro earthquake

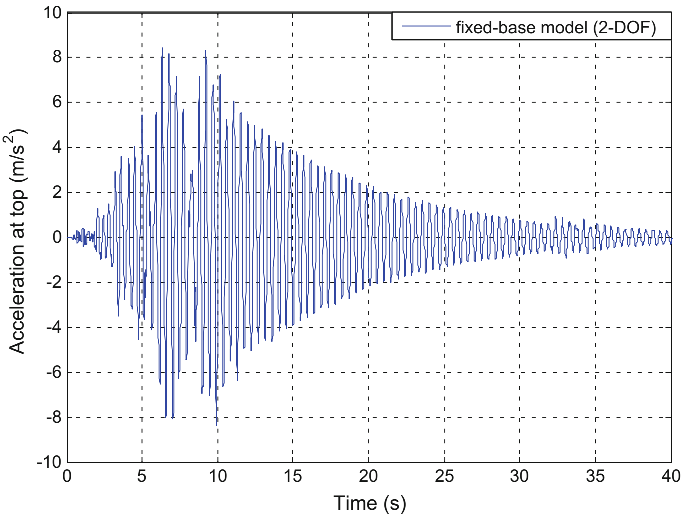

Fig. 4 Computed time-acceleration history for the 1971 San Fernando earthquake

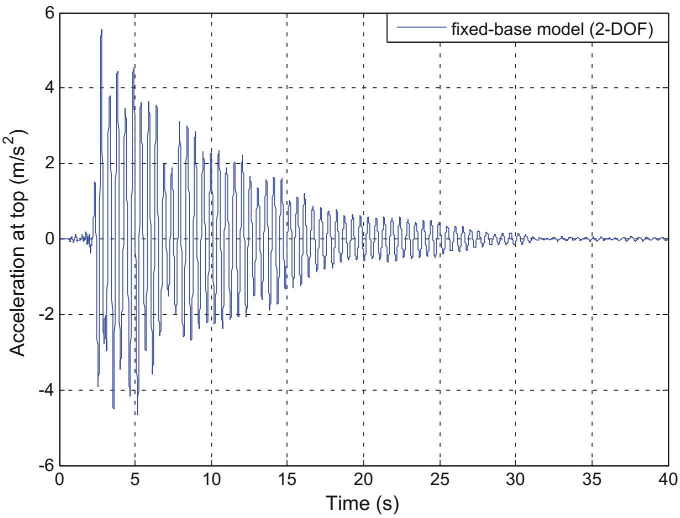

Fig. 5 Computed time-acceleration history for the 1989 Loma Prieta earthquake

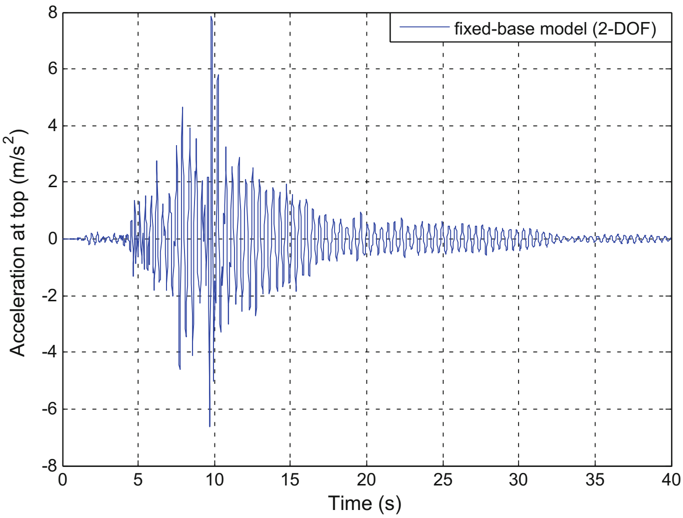

Fig. 6 Computed time-acceleration history for the 1994 Northridge earthquake

4 Final Summary and Conclusions

The present research was designed to perform a numerical evaluation of dynamic response of a two-storey steel structure model, which was previously examined during an extensive shaking table investigation. The analyzed structure model was idealized as a 2-DOF system and subjected to a number of different dynamic excitations. In

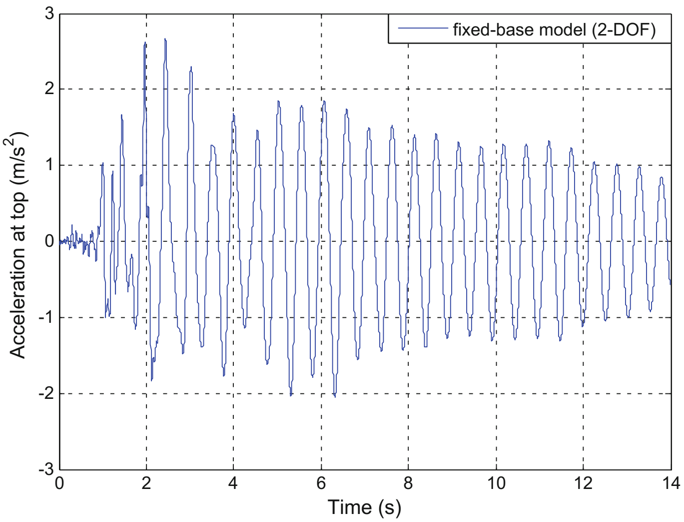

Fig. 7 Computed time-acceleration history for the 2002 Polkowice mining tremor

order to solve the second-order differential equation of motion, Newmark's average acceleration method was adopted.

As expected, the results obtained showed that strong dynamic excitations may considerably deteriorate structural safety by inducting structural vibrations. The time-acceleration history plots computed for the two-storey structure model idealized as a 2-DOF system are consistent with those recorded during the previously conducted shaking table investigation. Close inspection of Table 1 explicitly demonstrates that the peak values of the lateral accelerations at the top of the structure model from both experimental and numerical studies are almost the same which confirms high accuracy in assuming lumped parameters to characterize the analyzed two-storey structure. These parameters will be employed in further numerical research, which will cover the evaluation of dynamic response of both fixed-base and base-isolated structures including soil-structure interaction effects.

The results clearly show that not only seismic excitations but also mining tremors may considerably deteriorate structural behaviour by inducting strong structural vibrations.

Table 1 Comparison of numerical and experimental results

Dynamic excitation	Peak acceleration at the top of the two-storey steel structure model (m/s^2)	
	Lumped-mass numerical analysis	Shaking table investigation
El Centro earthquake, 18.05.1940 (NS component, PGA = 3.070 m/s^2)	5.77	5.98
San Fernando earthquake, 9.02.1971 (Pacoima Dam station, N74°E component, PGA = 5.688 m/s^2)	8.45	8.41
Loma Prieta earthquake, 17.10.1989 (Corralitos station, NS component, PGA = 3.158 m/s^2)	5.54	5.49
Northridge earthquake, 17.01.1994 (Santa Monica station, EW component, PGA = 4.332 m/s^2)	7.85	7.68
Polkowice mining tremor, 20.02.2002 (NS component, PGA = 1.634 m/s^2)	2.67	2.67

Where PGA denotes the *Peak Ground Acceleration*

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