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Building damage due to structural pounding during earthquakes

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Building damage due to structural pounding during earthquakes

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Abstract. Earthquake-induced pounding between adjacent buildings has been identified as one of the reasons for substantial damage or even total collapse of colliding structures. A major reason leading to interactions in buildings results from the differences in their dynamic parameters and also from insufficient distance between the structures. Although the research on structural pounding has been much advanced, the studies have mainly been conducted for concrete structures. The aim of this paper is to show the results of the non-linear numerical analysis focuses on damage due to pounding between two steel buildings under earthquake excitation. The numerical analysis has been performed using models of steel asymmetric structures with different number of storeys which makes them vibrate out-of-phase. Pounding between buildings has been controlled using three-dimensional gap-friction elements which become active when contact is detected. In order to identify the dynamic characteristics of analyzed structures, the modal analysis has been first conducted. Then, the detailed non-linear dynamic analysis of colliding structures has been performed. The acceleration time histories of the El Centro earthquake have been used in the numerical analysis. The results of the study clearly indicate that pounding may substantially influence the response of steel buildings intensifying their damage during earthquakes.

1. Introduction

As a result of high urbanization, the need to build closely-spaced buildings forces the designers to take under consideration earthquake-induced interaction between insufficiently separated structures. Observations after earthquakes confirm that structural pounding may cause some local damages to the elements, like it happened during moderate ground motion in the north-eastern Poland in 2004 [1]. The phenomenon may also lead to the total collapse of structures, as for example during the Mexico earthquake in 1985 [2] or the Loma Prieta earthquake in 1989 [3]. The main reason of collisions between adjacent buildings under earthquake excitation, besides insufficient distance between structures, is the difference in stiffness and/or mass. This difference leads to the out-of-phase vibrations and finally may cause structural interactions [4,5]. The phenomenon of earthquake-induced pounding between buildings has been intensively studied using various structural models and applying different models of collisions (see, for example [6-13]). However, most of the analyses concerned

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collisions between reinforced concrete buildings and the studies on pounding between steel structures are very limited (see, for example, [14]).

The aim of this paper is to show the results of the numerical study on colliding two asymmetric steel structures with different dynamic parameters under earthquake excitation. In the first part of the work, the dynamic properties of both structures have been identified. Afterwards, the detailed nonlinear dynamic analysis on earthquake-induced pounding between the structures has been conducted.

2. Numerical model of colliding structures

Two adjacent steel buildings with different geometry and different number of storeys have been considered in the numerical analysis (see Figure 1). The structural members of 3-storey and 4-storey buildings have been modelled by 10560 and 9376 four-node quadrilateral shell elements, respectively. I-shaped columns, made of steel S275, have been rigidly fixed to the ground (soil-structure interaction has not been taken into account). The initial separation gap between structures equal to 2 cm has been considered. To investigate the pounding-involved response of the buildings, six three-dimensional gap-friction elements have been used (two for each storey, placed between the corner nodes of the buildings). These elements assure frictional and gapping connection - when contact is detected, the nodes become fixed in the longitudinal direction and friction forces are imposed in the transverse and vertical directions [15]. The friction coefficient of 0.5 has been applied in the analysis.

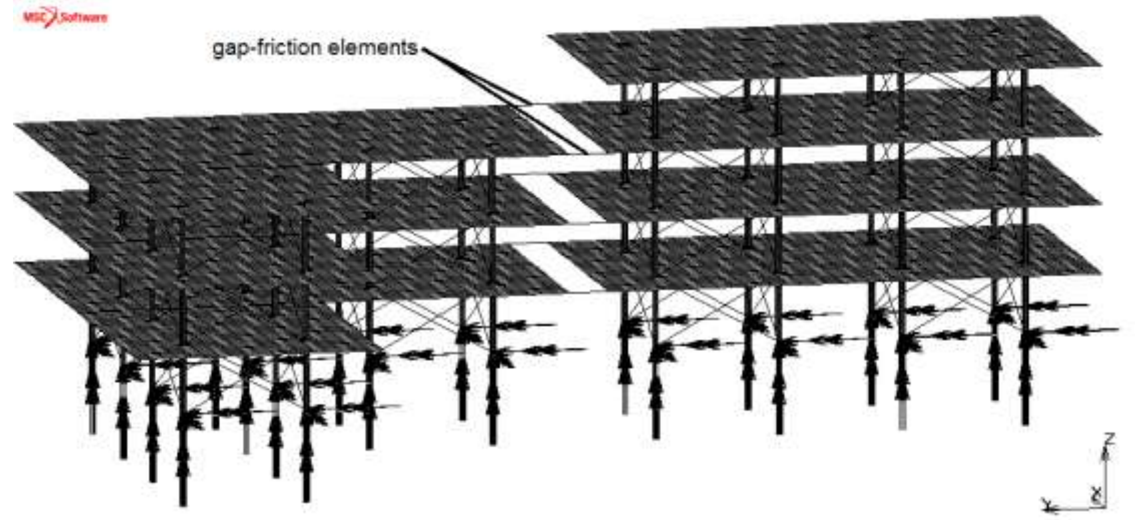


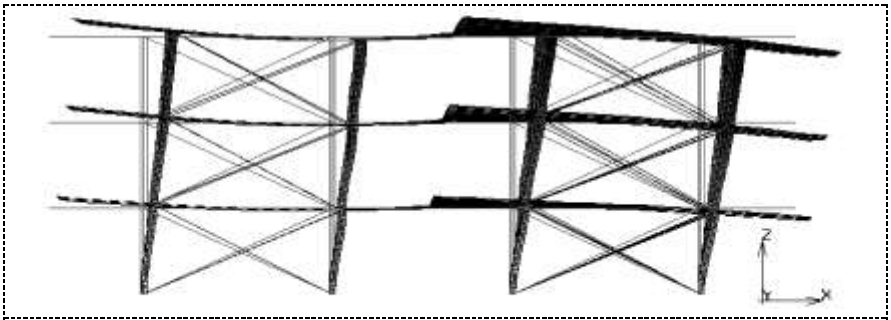
Figure 1. FE model of colliding steel buildings.

3. Modal analysis

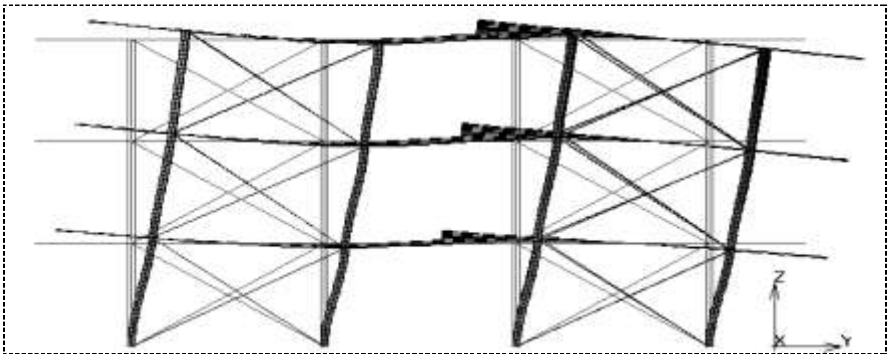
In order to identify the dynamic properties of the structural models created, the modal analysis has been first conducted. The examples of the first three natural vibration modes of both buildings, as the result of the analysis, are presented in Figure 2 and Figure 3. The corresponding natural frequencies for the modes are also summarized in Table 1.

Table 1. Natural frequencies for free vibrations modes.

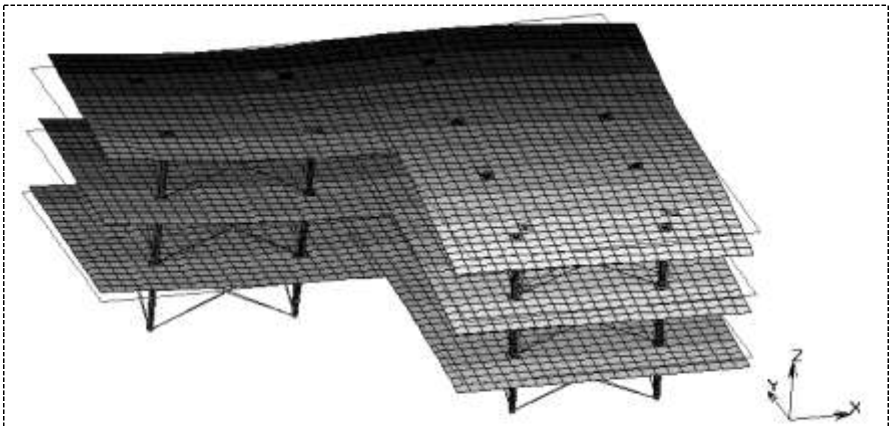
	Transverse (Hz)	**Longitudinal (Hz)**	**Torsional (Hz)**
3-storey building	2.636	2.588	2.721
4-storey building	1.134	1.234	1.151



(a) 1st mode

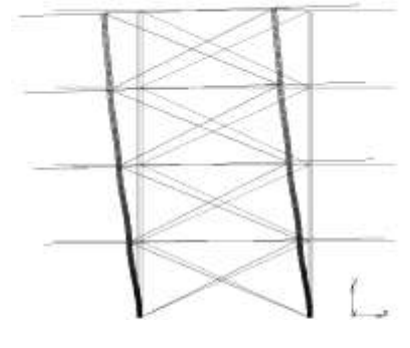


(b) 2nd mode

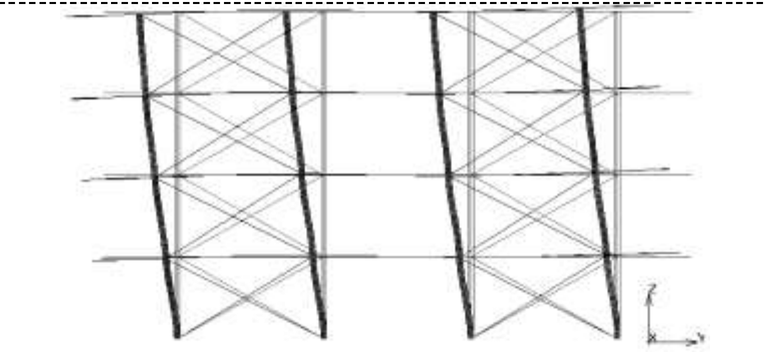


(c) 3rd mode

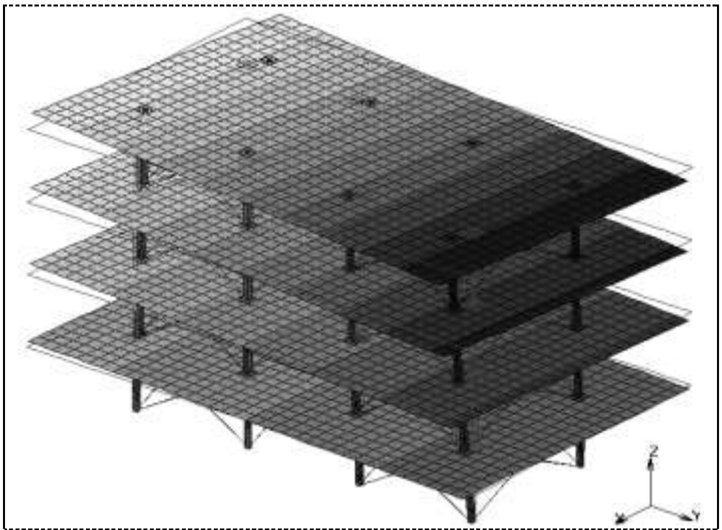
Figure 2. Modes of free vibrations for 3-storey building.



(a) 1st mode



(b) 2nd mode



(c) 3rd mode

Figure 3. Modes of free vibrations for 4-storey building.

4. Dynamic analysis of colliding buildings

The detailed dynamic analysis, focused on the response of interacting structures under seismic excitation, has been carried out in the second part of the study. The El Centro earthquake (18.05.1940) records have been used in the numerical analysis (see Figure 4). The NS and EW components of the ground motion have been applied in the longitudinal (Y) and transverse (X) direction, respectively. Elastic-perfectly plastic behaviour of steel has been taken into account (material damage model). The examples of the results of the analysis are shown in Tables 2-3 and Figures 5-10. In particular, Table 2 summarizes the peak values of displacement in the longitudinal and transverse direction for both structures. Figure 5 and Figure 6 present a comparison between the displacement time histories in the longitudinal and transverse direction for the 3-storey building (node no. 34668 at the corner of the third storey) with and without pounding (large separation gap); whereas Figure 7 and Figure 8 show the corresponding results for the 4-storey building (node no. 30364 at the corner of the third storey). Moreover, Figure 9 and Figure 10 demonstrate the maps of plastic strains for chosen columns of 3-storey building and 4-storey building with and without pounding. Finally, Table 3 summarizes the peak values of plastic strain for both structures.

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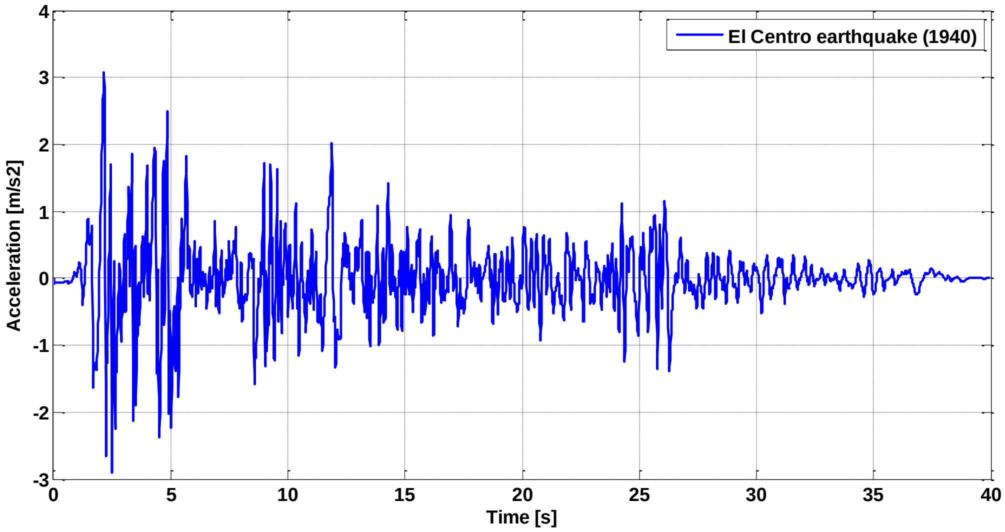
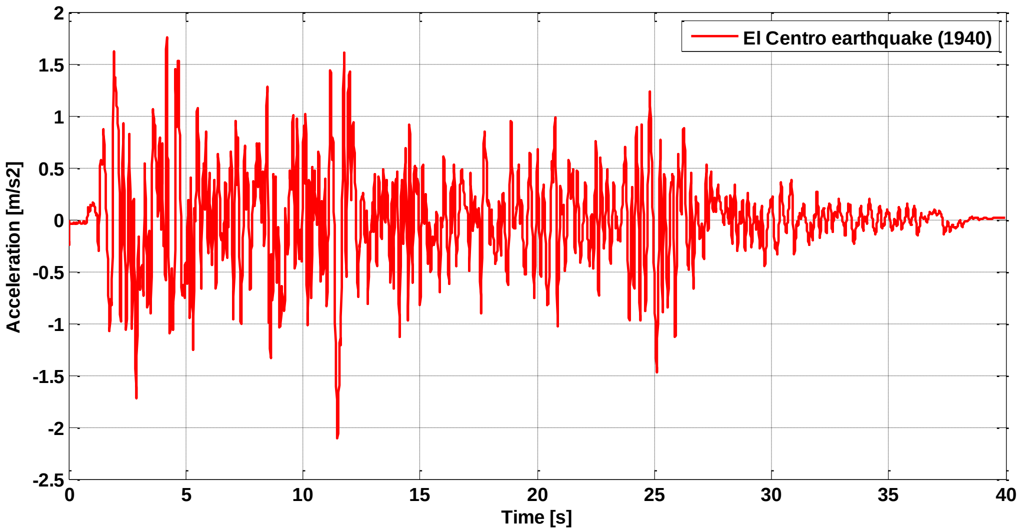


a) NS component (longitudinal direction)



b)

b) EW component (transverse direction)

Figure 4. Acceleration time histories for the El Centro earthquake (1940)

Table 2. Peak values of displacement.

		Without pounding (m)	With pounding (m)	Difference (%)
3-storey building	Longitudinal (Y) direction	0.0263	0.0245	Decrease by 6.8%
	Transverse (X) direction	0.0411	0.0322	Decrease by 21.7%
4-storey building	Longitudinal (Y) direction	0.0353	0.0659	Increase by 86.7%
	Transverse (X) direction	0.0535	0.1046	Increase by 95.5%

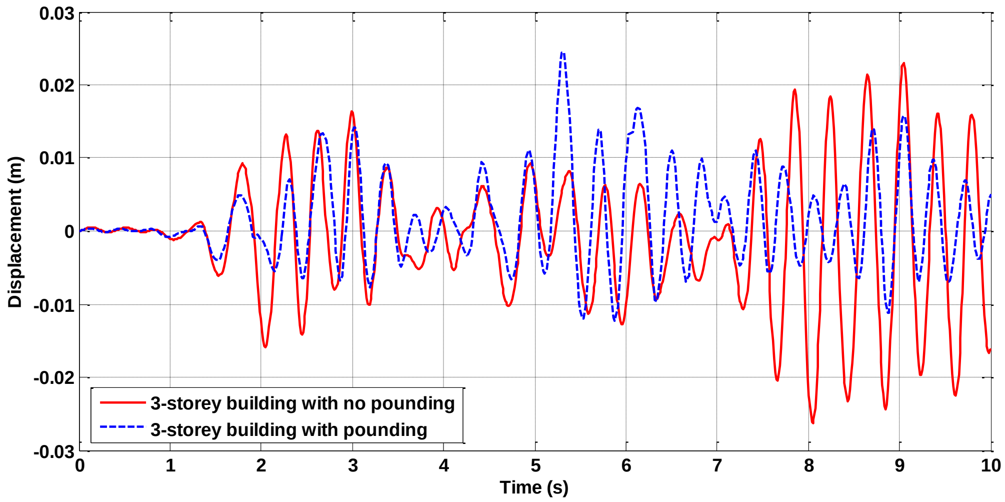


Figure 5. Displacement time histories in the longitudinal (Y) direction for the 3-storey building with and without pounding.

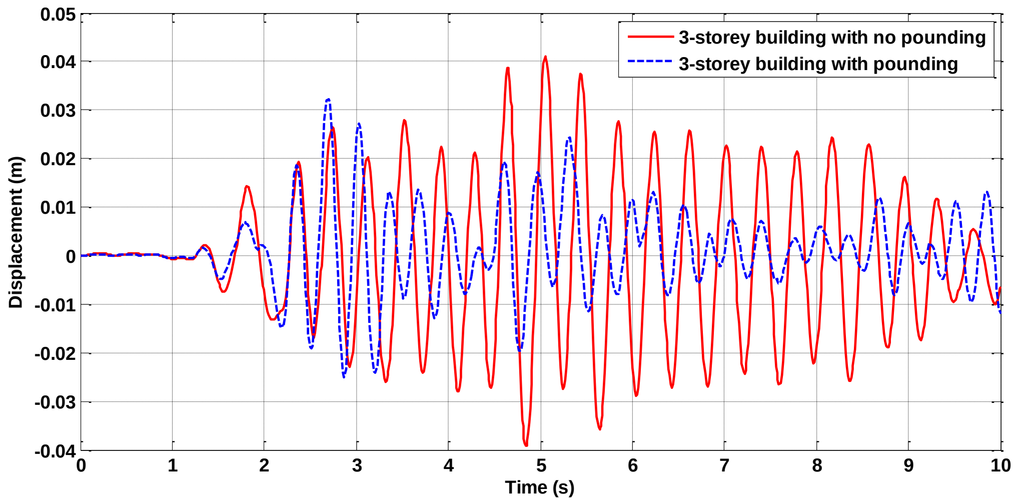


Figure 6. Displacement time histories in the transverse (X) direction for the 3-storey building with and without pounding.

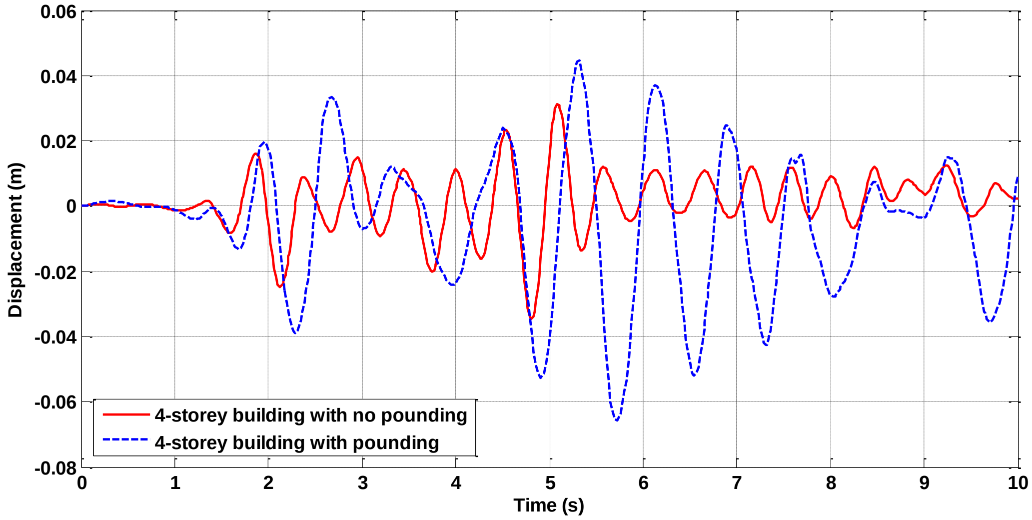


Figure 7. Displacement time histories in the longitudinal (Y) direction for the 4-storey building with and without pounding.

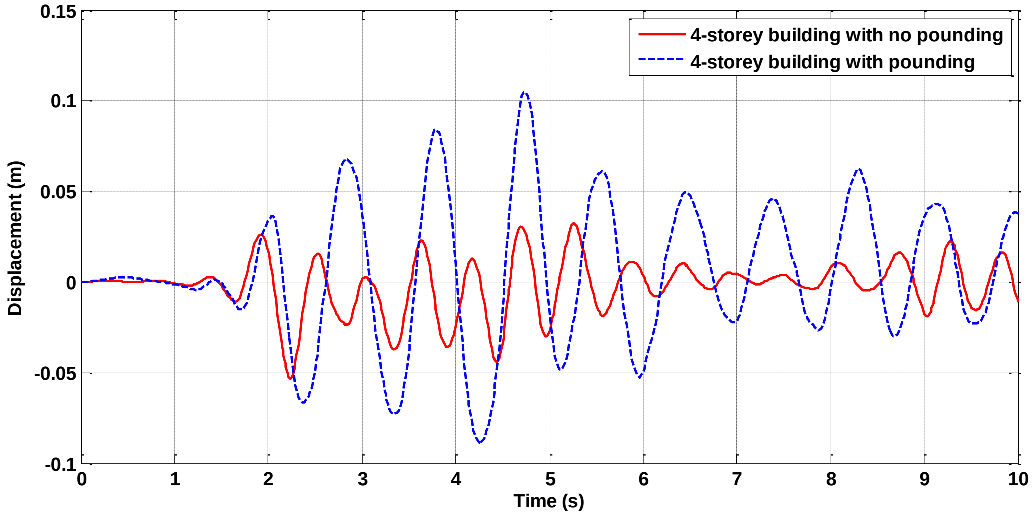


Figure 8. Displacement time histories in the transverse (X) direction for the 4-storey building with and without pounding.

Figures 5-8 clearly show that structural pounding may substantially influence the response of two adjacent steel buildings in the longitudinal and transverse direction under earthquake excitation. It can be seen from Table 2 as well as from Figure 5 and Figure 6 that the peak response of the 3-storey structure decreases due to collisions by 6.8% and 21.7% in the longitudinal and transverse direction, respectively. On the other hand, Figure 7 and Figure 8 indicate that collisions between two steel structures lead to the increase in the peak displacement of the 4-storey building, and this increase is as large as 86.7% and 95.5% for the longitudinal and transverse direction, respectively (see Table 2).

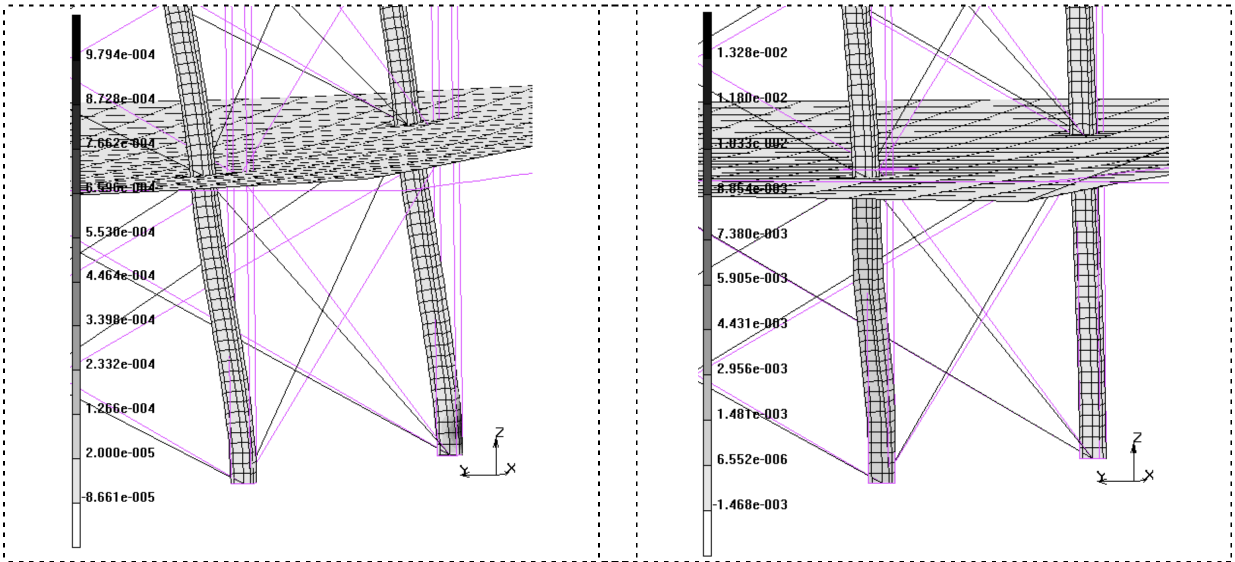


Figure 9. Maps of plastic strains for ground columns of 3-storey building without pounding (on the left) and with pounding (on the right).

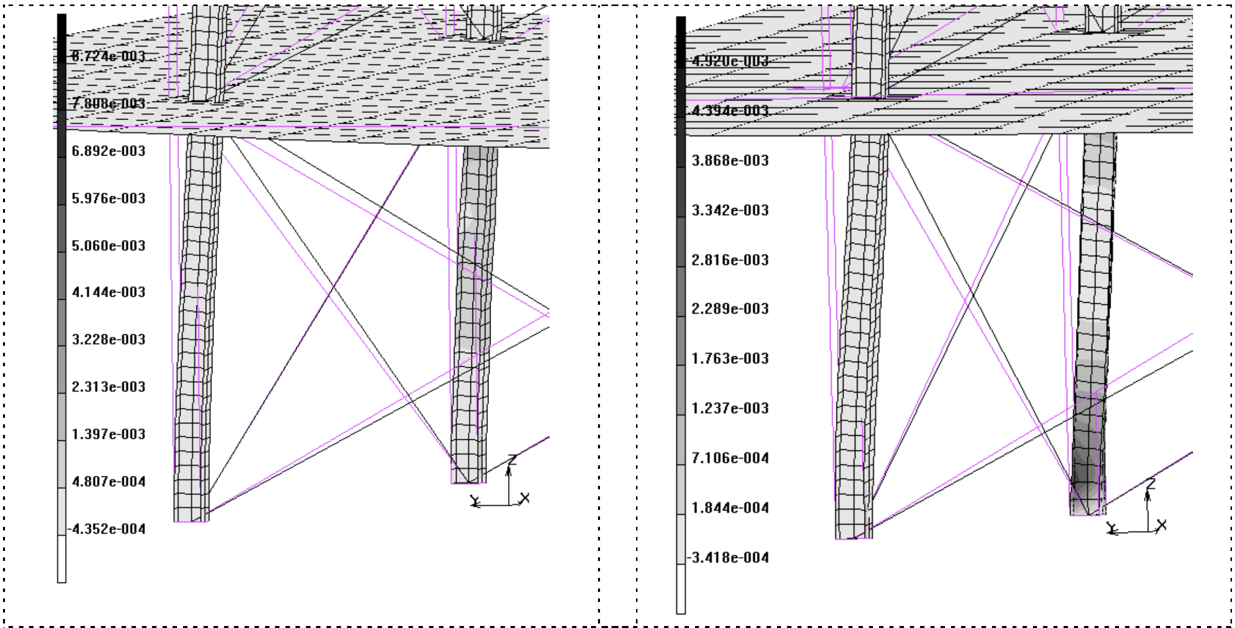


Figure 10. Maps of plastic strains for ground columns of 4-storey building without pounding (on the left) and with pounding (on the right).

Table 3. Peak values of plastic strain.

	Without pounding	**With pounding**	**Difference (%)**
3-storey building	3.924×10^{-2}	1.214×10^{-2}	Decrease by 69.1%
4-storey building	4.938×10^{-2}	7.289×10^{-2}	Increase by 47.6%

The results of the study also indicate that the ground columns of both buildings experience considerable inelastic behaviour at the bases, what results in the permanent deformation of structures. Moreover, it can be seen from Figure 9 and Figure 10 that the size of yielding zone is substantially different for the cases with and without pounding. Also, the peak values of the plastic strains from Table 3 are substantially different for the responses with and without structural interactions. In the case of 4-storey building, pounding results in substantial increase in the size and intensity of yielding zone (increase in the peak plastic strains by 47.6%). On the other hand, Figure 9 and Table 3 show that the earthquake-induced collisions have positive effect on the response of the 3-storey building leading to the decrease in the peak plastic strains by 69.1%.

5. Concluding remarks

The results of the non-linear numerical analysis, focused on damage due to earthquake-induced pounding between two steel buildings, have been presented in this paper. The elastic-perfectly plastic material properties have been implemented in the numerical model. The results of the study clearly indicate that pounding may substantially influence the response of steel buildings during earthquakes, both in the longitudinal and transverse directions. Collisions resulted in the substantial increase in the response of one of the structures, intensifying its damage, while had a positive role in the case of the second building. The use of the FEM with a detailed representation of the geometry, as well as the non-linear material behaviour, allows us to investigate the earthquake-induced pounding-involved response of steel structures quite precisely. However, further research is still needed so as to study in more details the behaviour of colliding steel buildings with different numbers of storeys under different earthquake excitations.

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