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Behaviour of Deformed Steel Columns Exposed to Impact Load During Earthquakes: Numerical Analysis

Wojciech Migda and Robert Jankowski
Faculty of Civil and Environmental Engineering, Gdansk University of Technology,
Ul. Narutowicza 11/12, 80-233 Gdansk, Poland

Abstract: It has been observed during earthquakes that the so called soft-storey failure of an upper floor of a building leads to considerable vertical impact load acting on structural members of the lower storeys. The aim of this study is to investigate numerically the behaviour of horizontally deformed columns (deformation as the result of earthquake loading) that are additionally subjected to vertical impact load. In the first stage of the study, different static pre-deformations of the column as well as various impact load time histories have been considered. Then, the detailed nonlinear analysis has been conducted by exciting dynamically the base of the specimen as well as by applying impact vertical load at different times of the harmonic ground motion excitation. The results of the first stage of the study show that with the increase in the static pre-deformation of the column the peak mean normal stress values induced at the bottom of the specimen as well as the peak horizontal displacement at the middle of the column show a substantial increase trend for all height drop values considered. The results of further study show that vertical impact may substantially influence the response of the column which is dynamically excited in its horizontal direction. Moreover, the time of impact has been found to play a substantial role in the overall behaviour indicating that the response may be increased significantly if impact takes place when the specimen is in the range of its peak horizontal deformation.

Key words: Numerical analysis, steel columns, horizontal deformation, impact load, earthquakes

INTRODUCTION

Reports after major ground motions indicate that the so called soft-storey failure is one of the most typical types of damage concerning buildings. During the Loma Prieta earthquake of 1989, for example, many wood-frame buildings experienced extensive damage concentrated at the level of one of the storeys (Maison *et al*., 2011). The soft-storey failure was also observed during the Hyougoken-Nanbu (Kobe) earthquake of 1995 causing damage to a large number of steel and reinforced concrete buildings (Elkholy and Meguro, 2004). It has been observed during earthquakes that the failure of an upper damaged storey induces large vertical impact loading acting on the lower part of the building. In the case, when the load-bearing capacity of the structural elements of lower storeys is not sufficiently large, the progressive collapse of the whole structure can be initiated which is considered to be the worst-case scenario (Talaat and Mosalam, 2009).

The research concerning impacts in buildings during earthquakes has been carried out for more than two decades now. However, previous investigations were mainly focused on structural collisions between buildings in the horizontal direction. This phenomenon is known in the literature as the earthquake-induced structural pounding. The fundamental study on such collisions between insufficiently separated buildings with different dynamic properties (modelled as single-degree-of-freedom systems) was conducted by Anagnostopoulos (1988). Single-degree-of-freedom structural systems were also used by other researchers (Chau and Wei, 2001; Mahmoud *et al*., 2008; Jankowski, 2010). More advanced investigations were carried out on discrete multi-degree-of-freedom models with the mass of each storey lumped on the floor level (Maison and Kasai, 1992; Anagnostopoulos and Spiliopoulos, 1992; Karayannis and Favvata, 2005; Mahmoud and Jankowski, 2009). Quite simple analysis concerning impacts between two adjacent buildings, with the use of finite element method, was also conducted by Papadrakakis *et al*. (1996). More detailed, three-dimensional, non-linear finite element models of colliding buildings with different dynamic characteristics were employed in the studies carried out by Jankowski (2009, 2012).

Corresponding Author: Robert Jankowski, Faculty of Civil and Environmental Engineering, Gdansk University of Technology, Ul. Narutowicza 11/12, 80-233 Gdansk, Poland Tel: +48 58 3472200 Fax: +48 58 3471670

On the contrary to the earthquake-induced horizontal collisions in buildings, the results concerning investigations on vertical impacts between the damaged upper part of the building falling onto the lower storeys after the soft-storey collapse during ground motions are very limited. Migda and Jankowski (2012) conducted the experimental investigation on the behaviour of horizontally deformed steel columns (deformation as the result of earthquake loading) that are additionally subjected to vertical impact load (Fig. 1). In that study, however, the introduced pre-deformation was a static one and the influence of the dynamic effects of the ground motion was not considered (limitations of the experimental setup). Therefore, the aim of the present paper is to extend the study and investigate numerically the dynamic response of a model of steel column under ground motion excitation that is additionally subjected to vertical impact load. The numerical model of the specimen has been created and its accuracy has been confirmed by comparing the results of the numerical analysis with the experimental results. In the first stage of the numerical study, a number of cases, concerning different pre-deformations of the column as well as various impact load time histories (related to different drop-heights) have been considered. Then, the detailed nonlinear analysis has been conducted by exciting horizontally the base of the specimen using the harmonic ground motion excitation as well as by applying impact vertical load at different times of the excitation. The geometric nonlinearity (large strain analysis) as well as the elasto-plastic material behaviour with the strain rate effect have been considered in the numerical analysis.

NUMERICAL MODEL AND ITS VALIDATION

For the purposes of numerical analysis, a finite element model of steel columns which were previously tested experimentally (Migda and Jankowski, 2012), has been created using the commercial software MSC Marc (Fig. 2). The numerical model of the specimen, with the length of 800 mm and cross section of 3×20 mm, has been constructed out of 640 four-node shell elements. The

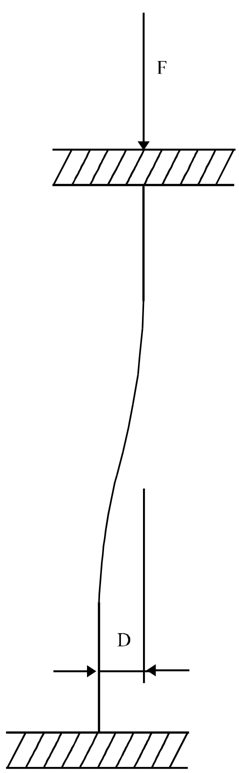

Fig. 1: Schematic diagram of vertical impact load (F) acting on horizontally deformed column with initial pre-deformation (D)

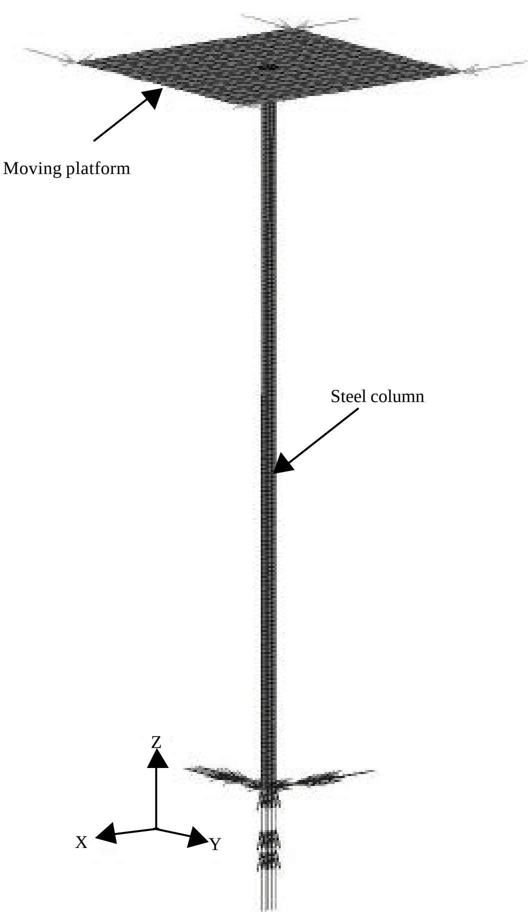

Fig. 2: Numerical model of the steel column with moving platform

moving platform which was mounted at the top of the column and used during the experiments to drop a steel sphere onto it, has been considered to be important element to be also included in the numerical analysis. Its model has been constructed out of 240 four-node shell elements. All material properties as well as original dimensions have been assured to be the same as in the experimental study. Taking into account the boundary conditions valid during the experiment, the numerical model of the specimen has been fixed at the bottom of the column and only vertical movement at four corners of the platform (locations of linear bearings) has been allowed.

The accuracy of the numerical model has been first verified by comparing the results of the numerical analysis with the results obtained form the experimental tests (Migda and Jankowski, 2012). For this purpose, similarly as in the case of the experimental study, a static horizontal pre-deformation has been introduced at the bottom of the numerical model of the column and the specimen has been subjected to vertical impact load acting on its top (Fig. 3). The same impact load time histories as measured during the experiment, by dropping a steel sphere onto the platform, have been used. The geometric nonlinearity, by conducting the large strain numerical analysis, has been taken into account. A number of cases, concerning different pre-deformations (relative horizontal displacement between the top and the bottom of the column) as well as various impact load time histories (related to different drop-heights) have been considered in the study. The difference between the results of the experiment and the results of the numerical analysis has been assessed by calculating the normalized Root Mean Square (RMS) error (Bendat and Piersol, 1971; Jankowski, 2003; Jankowski and Walukiewicz, 1997):

$$\mathrm{RMS} = \frac{\sqrt{\sum_{i=1}^{NV} \left(V_i - \bar{V}_i\right)^2}}{\sqrt{\sum_{i=1}^{NV} V_i^2}} \cdot 100\% \qquad (1)$$

where, V_i, $\bar{V}_i$ are the values from the time history record obtained from the experiment and from the numerical analysis, respectively and NV denotes a number of values in these history records.

The example of the comparison between the results of the numerical analysis and the results obtained form the experimental tests, in the form of the horizontal displacement time histories at the middle of the column (pre-deformation of 20 mm, drop height of 200 mm), is presented in Fig. 4. For this case, the natural frequency of vibrations of a specimen as well as the damping ratio is

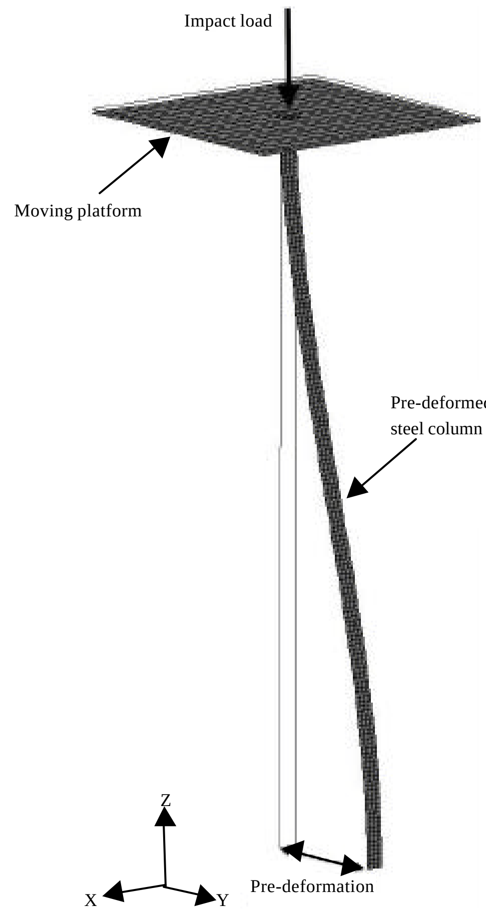

Fig. 3: Numerical model of the pre-deformed steel column subjected to vertical impact load

equal to 24.91 Hz and 0.68%, respectively. Using Eq. 1, the RMS error for the time histories shown in Fig. 4 has been calculated as equal to 7.90%. The average RMS error for all cases considered has been found to be as small as 6.43% confirming the accuracy of the numerical model created.

NUMERICAL ANALYSIS

Parametric analysis for statically pre-deformed columns: In the first stage of the numerical analysis, the parametric investigation has been conducted in order to assess the influence of the pre-deformation of the column as well as the influence of the impact load on the response of the steel column. The analysis has been conducted for the statically pre-deformed columns (Fig. 3) subjected to different impact load time histories. The horizontal pre-deformation was increased from 0 mm by 10 mm up to

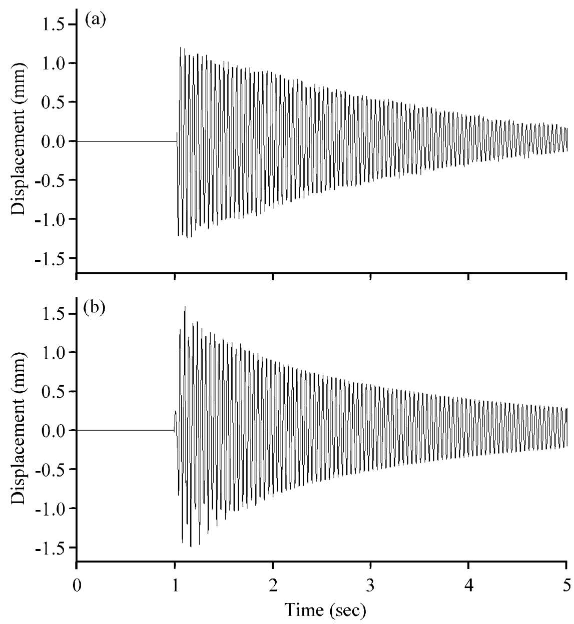

Fig. 4(a-b): Horizontal displacement time histories at the middle of the column (pre-deformation of 20 mm, drop height of 200 mm) (a) Experiment and (b) Numerical analysis

60 mm. The impact load time histories, as measured during the experiment for different drop heights (Migda and Jankowski, 2012), were applied onto the platform. The above conditions allowed the numerical models of the steel column to remain in the elastic range as well as to prevent from dynamic stability loss.

The examples of the preliminary results in the form of the maps of mean normal stress distributions at the bottom part of the pre-deformed specimen, for the case of 60 mm pre-deformation, are presented in Fig. 5 and 6. In particular, Fig. 5 shows the mean normal stresses before impact while Fig. 6 presents the mean normal stresses at the stage of the peak impact force acting at the top of the pre-deformed column. By comparing Fig. 5 with Fig. 6, it has been observed that the increase in the stress values at the bottom part of the specimen due to impact load can be as large as 235.9%.

The results from the parametric analysis are presented in Fig. 7 and 8. Figure 7 shows the peak values of the mean normal stress at the bottom of the specimen with respect to pre-deformation (for different drop heights). It can be observed from the figure that the value of the peak mean normal stress uniformly and substantially increases with the increase in the pre-deformation. In the case of the drop height of 350 mm, for example, the increase in the mean normal stress value

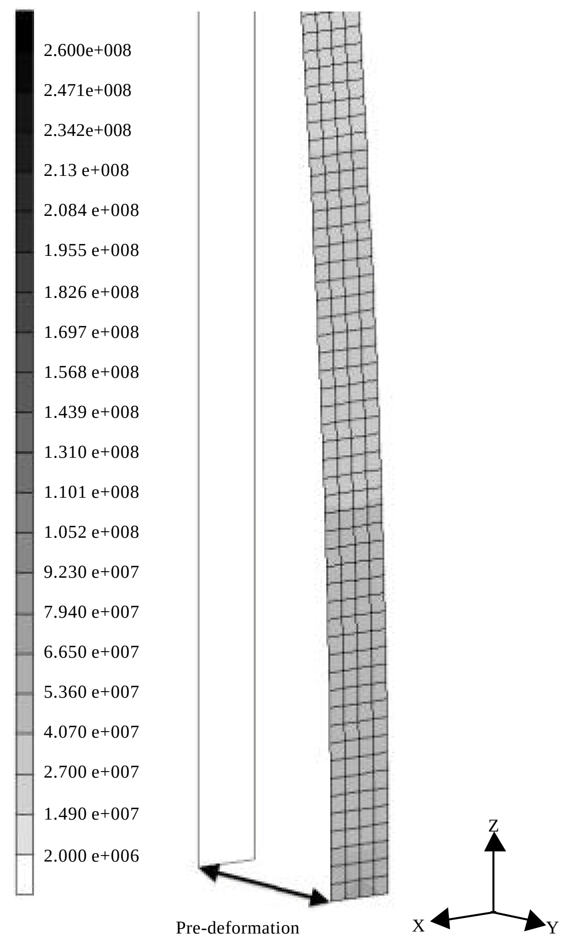

Fig. 5: Map of mean normal stresses at the bottom part of the deformed specimen (pre-deformation of 60 mm) before impact

for the deformed column (pre-deformation of 60 mm) with relation to the undeformed specimen is as large as 1321.4%.

The peak values of the horizontal displacement of the column at its mid-height with respect to pre-deformation (for different drop heights) are presented in Fig. 8. It can be seen from the figure that larger pre-deformation results in larger amplitudes in horizontal vibrations of the column. An evident trend of larger peak horizontal displacement for greater drop heights is also visible. In the case of the drop height of 350 mm, for example, the increase in the peak horizontal displacement of the column at its mid-height for the pre-deformed column (pre-deformation of 60 mm) with relation to the undeformed specimen is as large as 469,0%.

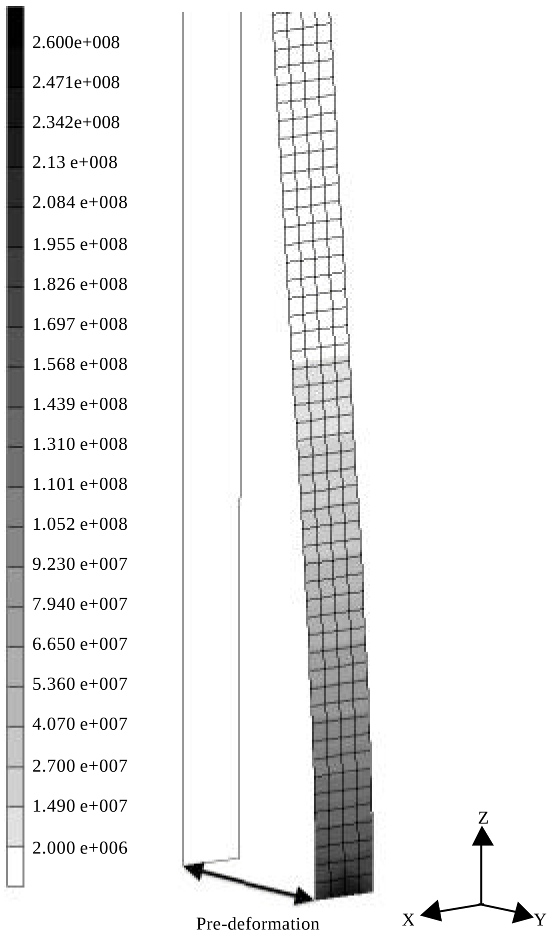

Fig. 6: Map of mean normal stresses at the bottom part of the deformed specimen (pre-deformation of 60 mm) at the time of the peak impact force acting at the top of the column

Nonlinear analysis under dynamic excitation: In the second stage of the numerical analysis, the advanced nonlinear analysis has been conducted by exciting horizontally the base the column (Fig. 2) using the harmonic ground motion excitation. The sine wave having the excitation frequency tuned with the natural frequency of the specimen has been used in the analysis. Together with the geometric nonlinearity (large strain analysis), the nonlinear, elasto-plastic material behaviour has also been considered. Additionally, the strain rate effect has been taken into account in the numerical analysis by relating the yield strength of steel with the strain rate following the relation obtained from the experimental study conducted by Ansell (2006).

It has been assumed in the analysis that vertical impact takes place at different times of the excitation. Figure 9 shows the horizontal displacement time history of the column at its mid-height (response at time rage 0.82-0.92 s) with marks indicating moments of impact for five different cases considered in the study. The peak values of impact force has been applied at the following times:

Case 1: t_1 = 0.859 sec
Case 2: t_2 = 0.862 sec
Case 3: t_3 = 0.869 sec
Case 4: t_4 = 0.877 sec
Case 5: t_5 = 0.880 sec

Related to different stages of horizontal deformation of the specimen. Similarly as in the parametric investigation, the impact load time histories measured during the experiment (Migda and Jankowski, 2012) have been used in the study. The examples of the results, in the form of the horizontal displacement time histories of the column at its mid-height for five different cases of impact, as compared to the time history when impact is not

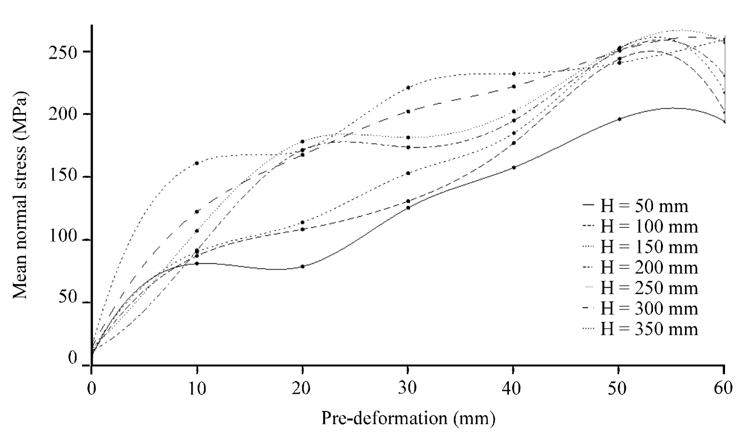

Fig. 7: Peak mean normal stress vs. pre-deformation of the column for different drop heights (H)

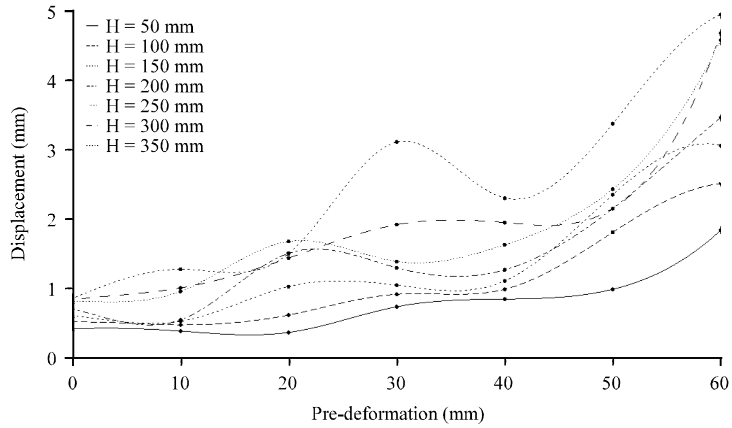

Fig. 8: Peak horizontal displacement of the column at its mid-height vs. its pre-deformation for different drop heights (H)

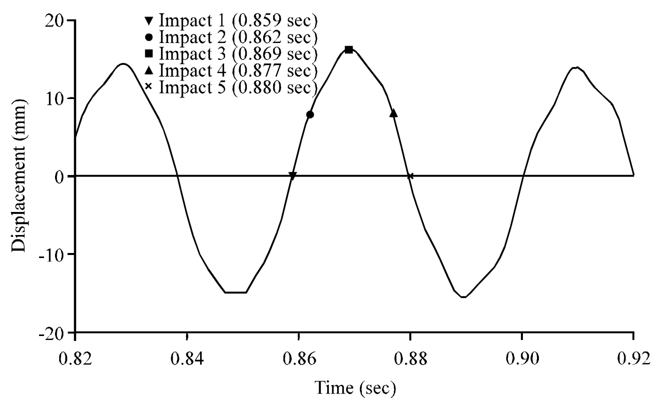

Fig. 9: Horizontal displacement time history of the column at its mid-height under harmonic ground motion (time rage 0.82-0.92 sec) with marks indicating different moments of peak values of impact force

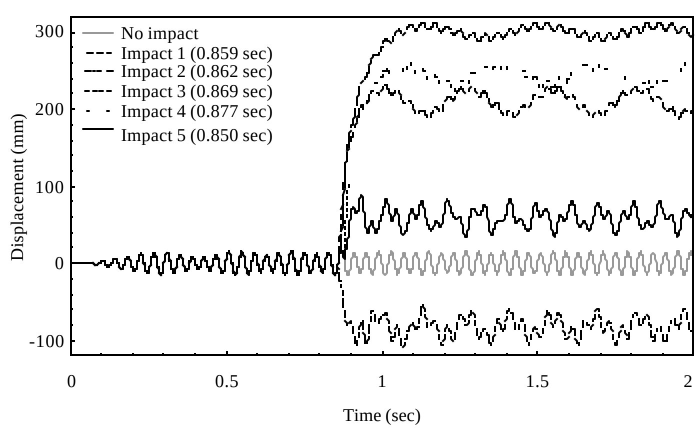

Fig. 10: Horizontal displacement time histories of the column at its mid-height under harmonic ground motion for five different cases of impact as compared to the time history when impact is not applied

applied, are shown in Fig. 10. Additionally, the comparison between the displacement time histories for impact with peak value of impact force at t_3 = 0.869 sec (case 3 related to the peak horizontal deformation of the column) with and without considering the strain rate effect is also presented in Fig. 11.

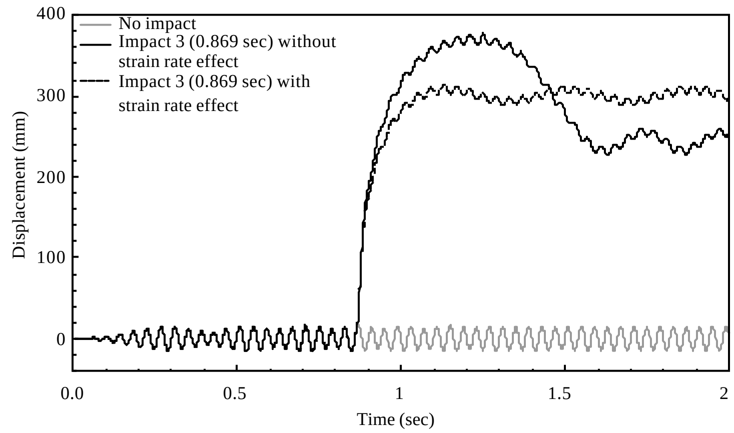

Fig. 11: Comparison between the displacement time histories under harmonic ground motion for impact case 3 with and without considering the strain rate effect

It can be seen from Fig. 10 that vertical impact has a significant influence on the behaviour of the steel column under dynamic ground motion excitation leading to the increase in its response. It can be seen that incorporation of the nonlinearity of material behaviour has resulted in entering into the plastic range in all the cases considered (see permanent displacement of the column at Fig. 10). Moreover, the obtained results clearly indicate that the time of impact plays a substantial role in the overall behaviour. It can be seen from Fig. 10 that, for the case when impact takes place at the time of peak horizontal deformation of the column (impact case 3), the increase in the peak structural response is as large as 1808,4% with relation to the peak response without impact. On the other hand, when impact takes place when the actual displacement of the horizontally excited column is relatively small (impact cases 1 and 5), the influence of vertical impact on the response is less significant. Figure 10 shows that, in such situations, the increase in the peak horizontal displacement of the column at its mid-height is equal to 438.4%, as compared to the peak response without impact.

It can also be seen from Fig. 11 that incorporation of the strain rate effect in the numerical analysis is really important and the difference between the responses with and without considering this effect can be substantial. In the case when the strain rate effect is taken into account and vertical impact takes place at the time of the peak horizontal deformation of the column (impact case 3), the increase in the peak structural response is equal to 20.32%, as compared to case when the effect in not considered.

DISCUSSION

The detailed numerical investigation concerning the behaviour of deformed steel columns, that are additionally subjected to vertical impact load (the result of soft-storey failure during earthquake), has been presented in this paper. In the first stage of the study, the analysis has been conducted for different values of the static horizontal pre-deformation of the column. Then, the base of the column has been dynamically excited by harmonic ground motion and vertical impact load has been applied at different times of the excitation. The geometric nonlinearity (large strain analysis) as well as the elasto-plastic material behaviour with the strain rate effect have been taken into account.

The results of the first stage of the numerical study show that with the increase in the static pre-deformation of the column the peak mean normal stress values induced at the bottom of the specimen as well as the peak horizontal displacement at the middle of the column show a substantial increase trend for all height drop values considered. The above conclusions indicate that the initial pre-deformation of columns has a substantial negative influence, what is fully consistent with the results of the experimental study concerning the behaviour of horizontally deformed steel columns that are additionally subjected to vertical impact load (Migda and Jankowski, 2012). It has been observed, however, that even the deformed column is still capable to carry considerable vertical impact load before its failure due to stability loss. This fact was also confirmed during the experiments (Migda and Jankowski, 2012).

The results of the second stage of the numerical study show that vertical impact may substantially influence the response of the column which is dynamically excited in its horizontal direction. The results indicate that the time of impact plays a substantial role in the overall behaviour under ground motion excitation. It has been shown that the response may be increased significantly if impact is initiated when the specimen is in the range of its peak horizontal deformation. On the other hand, when impact takes place when the actual displacement of the horizontally excited column is relatively small, the influence of vertical impact on the response is less significant. Moreover, the results indicate that the incorporation of the strain rate effect in the numerical analysis is really important in order to increase its accuracy.

The study described in this paper has provided us valuable results concerning the behaviour of deformed steel columns subjected to vertical impact load. However, the response of buildings during earthquakes after a soft-storey failure still needs to be further investigated. This concerns in particular a need for the detailed numerical simulations concerning the dynamic behaviour of the whole building (not only chosen structural members) under different real earthquake excitations.

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