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Behaviour of Deformed Steel Columns Exposed to Impact Load During Earthquakes: Experimental Study

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Abstract: It has been observed during major earthquakes that the so called soft-storey failure of an upper floor of a structure results in large impact load acting on structural members of the lower storeys. It may further lead to progressive collapse of the whole structure substantially intensifying human and material losses. The aim of this study was to investigate experimentally the behaviour of horizontally deformed columns (deformation as the result of earthquake loading) that are additionally subjected to vertical impact load. Steel columns with high slenderness ratio were considered in the study. In the experiment, impact load was generated by a steel sphere dropped onto a pad of technical clay, so as to simulate nearly plastic impact observed in the reality during earthquakes. The results of the experiment show that with the increase of the pre-deformation of a column (initial relative horizontal displacement between the base and the top) the value of the peak force acting on its top initially decreases and then shows the considerable increase trend. Moreover, with the increase of the pre-deformation, the peak horizontal displacement of the middle part of column substantially increases for all height drop values considered. The results indicate, however, that even the deformed column is still capable to carry substantial dynamic load before its failure due to stability loss.

Key words: Experimental study, steel columns, horizontal deformation, impact load, earthquakes

INTRODUCTION

Earthquakes are usually considered to be the most dangerous and, at the same time, the most unpredictable dynamic loads acting on civil engineering structures (El-Kafrawy and Bagchi, 2007; Amiri *et al*., 2008; Aziminejad and Moghadam, 2009; Davoodi *et al*., 2009; Hasan *et al*., 2010; Naeini and Zarincheh, 2010; Khari *et al*., 2011; Sasan and Mohammadsadegh, 2011; Wafula, 2011). The so called soft-storey failure is one of the most typical types of damage observed in buildings as the result of ground motion excitations. During the Hyougoken-Nanbu (Kobe) earthquake of Kobe (1995), for example, most of the damaged buildings experienced failure of the first or intermediate storey (Fig. 1) due to the lack of lateral strength and ductility of columns (Watanabe, 1997). The soft-storey failure was also very common during the south east Asia earthquake of 2004 causing major damage in downtown of Banda Aceh (Ghobarah *et al*., 2006). It has been observed during earthquakes that the failure of an upper soft storey of a structure results in large impact load acting on the lower floors. If the resistance of the structural members of the lower storeys is not sufficient it may further lead to progressive collapse of the whole building (Talaat and Mosalam, 2009) substantially intensifying human and material losses.

Fig. 1: Soft-storey failure of the intermediate storey of building (Kobe 1995)

The study on earthquake-induced impacts in buildings has been carried out in earthquake engineering

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for several years now. The previous research, however, was only focused on the horizontal structural interactions between insufficiently separated structures which is referred in the literature as the earthquake-induced structural pounding. The basic study on such collisions between buildings in series, modelled as single-degree-of-freedom systems, was conducted by Anagnostopoulos (1988). More detailed analyses were carried out on discrete multi-degree-of-freedom structural models with the mass of each storey lumped on the floor level. Maison and Kasai (1992) employed such models to study the response of a light high-rise structure colliding against a massive low building. The lumped mass models of 5-storey and 10-storey buildings were used by Anagnostopoulos and Spiliopoulos (1992). Further investigation concerned non-linear analysis of pounding between two neighbouring 3-storey and 4-storey buildings with substantially different dynamic properties (Jankowski, 2008; Mahmoud and Jankowski, 2009). A study on multi-degree-of-freedom models of colliding structures of unequal storey heights was also carried out by Karayannis and Favvata (2005). Relatively simple finite element models of colliding buildings were employed in the analysis conducted by Papadrakakis *et al.* (1996), More detailed, three-dimensional non-linear analysis of interactions between two buildings using finite element method was conducted by Jankowski (2009, 2012).

On the contrary to the earthquake-induced horizontal collisions in buildings, impact between the damaged upper part of the building falling onto the lower storeys after the soft-storey collapse during ground motions has not been studied so far. Therefore, the aim of the present study was to investigate experimentally the dynamic behaviour of horizontally deformed steel columns (deformation as the result of earthquake loading) that are additionally subjected to vertical impact load (schematic diagram, Fig. 2). Steel columns with high slenderness ratio were considered in the study. In the experiment, impact load was generated by a steel sphere dropped onto a pad of technical clay, so as to simulate nearly plastic impact observed in the reality during earthquakes.

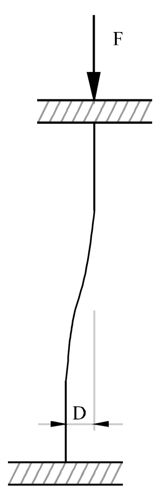

Fig. 2: Schematic diagram of vertical impact load acting on horizontally deformed column during earthquake

MATERIALS AND METHODS

Setup of the experiment: The experimental study was conducted using the stand structure shown in Fig. 3. It consisted of a thick steel plate at the bottom, to which four steel rods (precision shafts) were mounted. The top ends of the rods were connected using a steel diaphragm. Another diaphragm was located in the lower part of the stand in order to increase the overall rigidness. Along the steel rods, a moving platform with the mass of 6 kg, acting as a top support for the investigated specimens, was installed (Fig. 4). The platform was equipped with four industrial linear bearings, so that only a free vertical movement of the platform was allowed. The bottom support plate was equipped with a mechanism (Fig. 5) that allowed us to introduce a horizontal displacement of the bottom end of the specimen, making it possible to

Fig. 3: Experimental setup (general view)

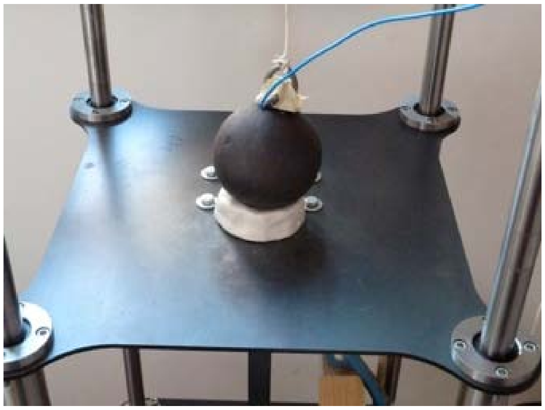

Fig. 4: Moving platform with the steel sphere and clay pad

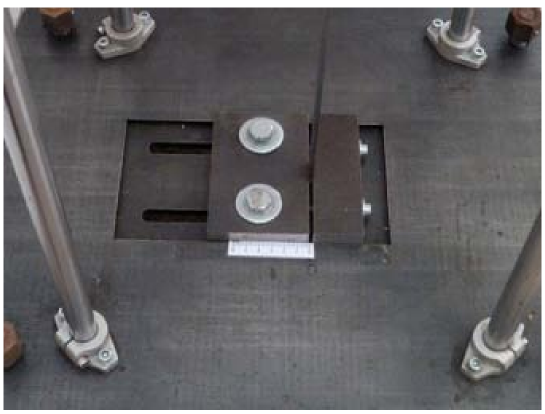

Fig. 5: Bottom support with the mechanism of column pre-deformation

simulate impact load on a pre-deformed column. During the experiment, a steel sphere with a mass of 2.1 kg was dropped from a pre-defined height onto the platform, where a pad of technical clay was placed with a diameter of approximately 100 mm and a thickness of 20 mm. The use of this pad allowed the impact between the sphere and the platform to be nearly plastic which is observed in the reality during earthquakes. It also prevented the sphere from bouncing of the platform and kept it in place after impact. Acceleration of the sphere (accelerometer shown in Fig. 4) as well as acceleration of the platform (accelerometer shown in Fig. 6) were recorded during the experiment. Furthermore, the horizontal displacement of the specimen was measured at its mid-height using the laser displacement meter (Fig. 3).

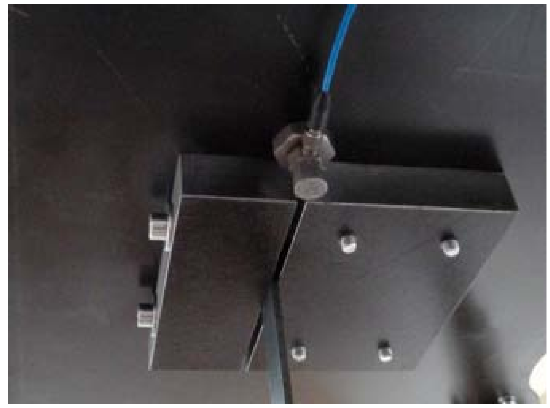

Fig. 6: Bottom part of the moving platform with top support of column and accelerometer

A number of steel columns, with the length of 800 mm and cross section of 3×20 mm, were prepared to be tested experimentally. Each column specimen was mounted in fixed supports located at the bottom and at the moving platform (Fig. 5, 6). The critical static load of the specimen was analytically calculated as equal to 395.2 N. The initial pre-deformation of the column, D, i.e., the horizontal displacement between the theoretical axis of the top and the bottom support (Fig. 2) was increased from 0 mm by 10 mm up to 60 mm. The drop height, H, was increased from 50 mm up to 350 mm with a step of 50 mm. The above conditions allowed the steel columns to remain in the elastic range as well as to prevent from dynamic stability loss during all experimental tests.

RESULTS

The experimental study was conducted for all combinations of pre-deformations of columns, D and drop heights, H. The examples of the results for a drop height of 20 cm are shown in Fig. 7-12. They illustrate the directly recorded values of acceleration of the sphere (Fig. 7, 10), acceleration of the platform (Fig. 8, 11) and the horizontal displacement of the column at its mid-height (Fig. 9, 12) for the case without pre-deformation (straight column) and for D = 60 mm, respectively. It can be seen comparing Fig. 7 with 10 that the difference between the peak acceleration values for two different pre-deformation cases is equal 13.7% which is not really much. On the other hand, the results shown in Fig. 8, 9 and 11, 12 indicate that the pre-deformation has a substantial influence on the acceleration of platform as well as on the horizontal displacement of the column. The increase in the

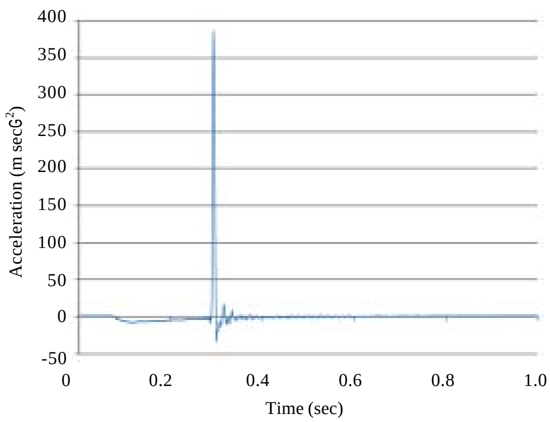

Fig. 7: Acceleration recorded in the sphere during impact without pre-deformation for a drop height of 20 cm

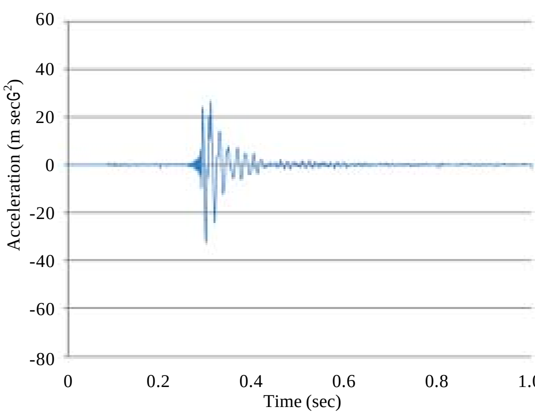

Fig. 8: Acceleration recorded in the platform during impact without pre-deformation for a drop height of 20 cm

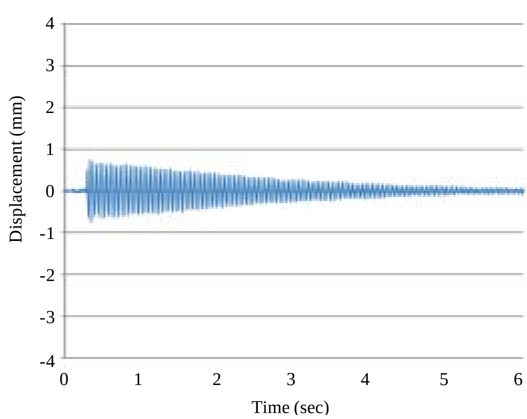

Fig. 9: Horizontal displacement recorded in the mid-height of the column during impact without pre-deformation for a drop height of 20 cm

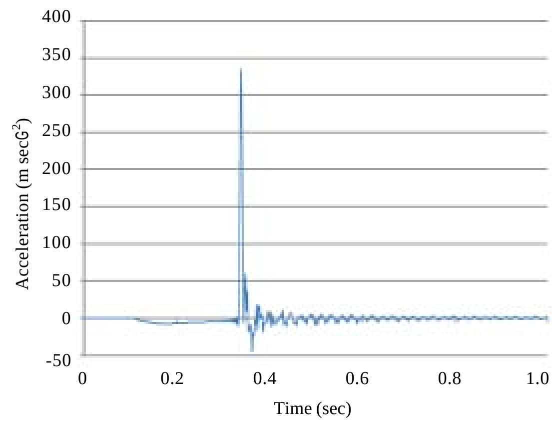

Fig. 10: Acceleration recorded in the sphere during impact for a pre-deformation of 60 mm and a drop height of 20 cm

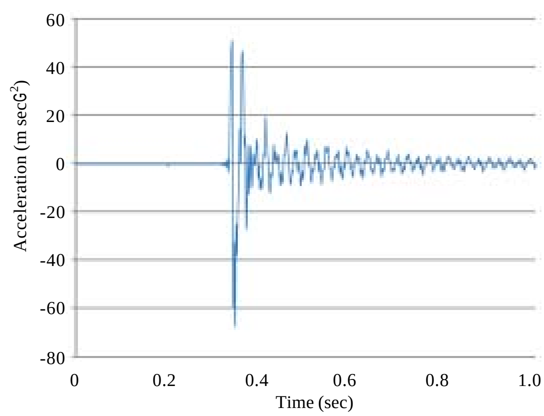

Fig. 11: Acceleration recorded in the platform during impact for a pre-deformation of 60 mm and a drop height of 20 cm

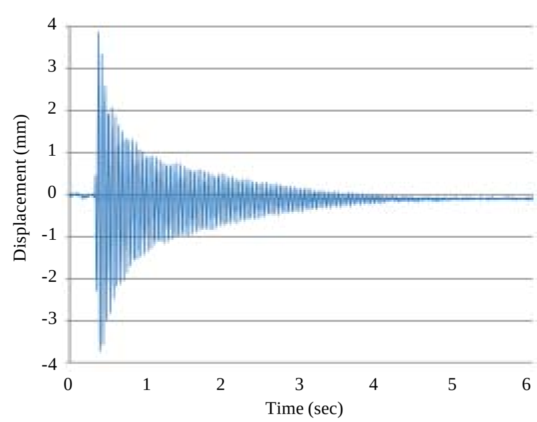

Fig. 12: Displacement recorded in the mid-height of the column during impact for a pre-deformation of 60 mm and a drop height of 20 cm

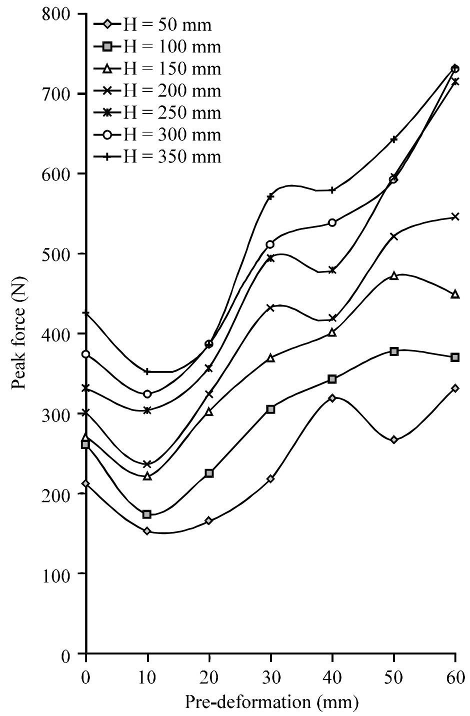

Fig. 13: Relation between the peak force F_{peak} acting on the top of column and its pre-deformation for different drop heights, H

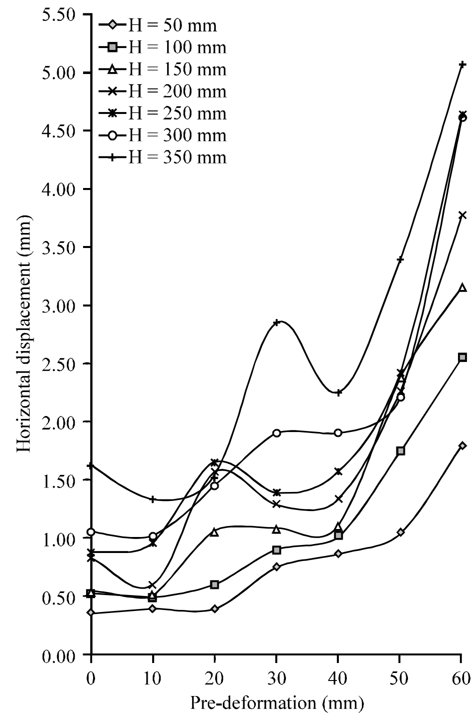

Fig. 14: Relation between the peak horizontal displacement of the column and its pre-deformation for different drop heights, H

peak measured values is as large as 88.0% in the case of platform acceleration and 413.3% in the case of column displacement.

In order to determine the peak force acting during impact on the top of the column, the following formula was used (Goldsmith, 1960; Mahmoud *et al.*, 2008; Jankowski, 2010):

$$F_{peak} = a_{peak} \bullet (m_{sphere} + m_{platform}) \quad (1)$$

Where:

- a_{peak} = Peak value of the recordered acceleration on the platform
- m_{sphere} = Mass of the sphere (2.1 kg)
- $m_{platform}$ = Mass of the platform (6.0 kg)

The peak force acting on the top of the column gives an insight on the actual impact load to which the column is exposed to. The values of the peak forces acting on specimens for different drop heights and pre-deformations are summarised in Table 1. The graphical representation of these results is shown in Fig. 13. It can be observed from the figure that the value of the peak force generally increases starting from the first pre-deformation increment of 10 mm, after a little decrease between a non

Table 1: Peak forces acting on specimens for different drop heights, H and pre-deformations, D

	H (mm)						
D (mm)	50	100	150	200	250	300	350
0	211.50	261.56	271.19	301.21	330.35	374.39	425.66
10	152.98	173.55	221.56	236.05	303.22	323.92	352.94
20	165.32	224.96	302.85	323.64	356.12	386.45	385.92
30	218.16	304.77	368.71	432.26	494.12	511.40	571.54
40	318.72	342.57	401.87	419.24	479.51	538.93	579.17
50	267.07	377.64	471.62	521.06	596.08	592.36	642.89
60	331.92	369.96	448.79	546.19	714.67	729.99	732.57

pre-deformed state and the first deformation. It is believed that this decline is the result of higher vertical stiffness of undeformed column as compared to the case of pre-deformation equal to 10 mm. In addition, it can be noticed, that the dynamic peak force exceeds the theoretical critical static force by more than 85.4% for H = 350 mm and D = 60 mm, while still the plastic yield and the stability loss have not been reached.

The larger affecting impact force leads also to larger amplitudes in horizontal vibrations of the column (compare Fig. 9 with 12). The relation between the peak horizontal displacement of the column at its mid-height and its pre-deformation for different drop heights is shown in Fig. 14. An evident trend of larger peak amplitude for greater drop height and greater pre-deformation is visible. This is the effect of the increased impact energy in the case of the increased drop height; while, for larger pre-deformation, the gain of the displacement amplitude is caused by greater potential energy present in the pre-deformed column. The gain of horizontal vibrations are believed to be responsible for the higher damping ratio of vibrations, as can be seen in Fig. 12.

CONCLUSIONS

The results of the experimental study focused on dynamic behaviour of deformed steel columns, that are additionally subjected to vertical impact load as the result of soft-storey collapse during earthquake, have been presented in this paper. The investigation has been conducted for different values of the initial relative horizontal displacement between the base and the top of the columns. In the experiment, impact load was generated by a steel sphere dropped from different heights onto a pad of technical clay, so as to simulate nearly plastic impact observed in the reality during earthquakes.

The results of the experiment show that with the increase in the pre-deformation of a column the value of the peak force acting on its top initially decreases and then shows a considerable increase trend. Moreover, with the increase of the pre-deformation, the peak horizontal displacement of the middle part of column substantially increases for all height drop values considered. The above conclusions show that the deformation of columns introduced due to earthquake loading has a substantial negative influence. The experimental results indicate, however, that even the deformed column is still capable to carry considerable dynamic load before its failure due to stability loss.

The experiment described in this study was performed on relatively small column models. Therefore, further experimental studies are required on larger structural models in order to verify the results obtained. There is also a need for the detailed numerical simulations concerning the dynamic behaviour of the whole building (not only chosen structural members) after soft-storey collapse under earthquake excitation.

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