Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 199 (2017) 278–283

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

Preventing of earthquake-induced pounding between steel structures by using polymer elements – experimental study

Barbara Sołtysik[a]*, Tomasz Falborski[a], Robert Jankowski[a]

[a]*Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, ul. Narutowicza 11/12, Gdańsk 80-233, Poland*

Abstract

Pounding between two, or more, adjacent buildings during earthquakes has been identified as one of the reasons for substantial damage or even total collapse of colliding structures, so it has been the subject of numerous studies in the recent years. A major reason leading to interactions between adjacent, insufficiently separated structures results from the differences in their dynamic properties. A number of different methods have been considered to mitigate earthquake-induced structural pounding. One of the techniques is linking structures which allow the forces to be transmitted between buildings and thus eliminate interactions. The aim of the present paper is to show the results of the experimental study focused on the application of polymer elements placed between the colliding members so as to mitigate earthquake-induced pounding between adjacent steel structures in series. In the study, three steel model towers with different dynamic parameters and various in-between distances were considered. The unidirectional shaking table was used in the experimental study. Models of steel towers were prepared and mounted to the platform of the shaking table. Additional mass was added at the top of each tower so as to obtain different dynamic characteristics of the structures. The results of the study indicate that earthquake-induced pounding may have a significant influence of the structural response. Moreover, the application of polymer elements between the structures can be an effective pounding mitigation technique. It allows us to prevent damaging collisions between adjacent structures during earthquakes. It also improves the structural behaviour leading to the reduction in vibrations under different seismic excitations.

Peer-review under responsibility of the organizing committee of EURODYN 2017.

Keywords: Structural pounding; earthquakes; steel structures; polymer elements

---

* Corresponding author. Tel.: +48 791 296 897
E-mail address: barwiech@pg.gda.pl

Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.029

1. Introduction

Observations after past earthquakes have demonstrated that buildings may experience major damage if they are not appropriately designed for dynamic loads observed during earthquakes. On the other hand, due to high cost of land in the urban areas, there is a kind of pressure on designers to construct structures with very small in-between separation gap. This situation may result in structural interactions between adjacent buildings during seismic excitations (known as earthquake-induced structural pounding). Pounding of closely separated structures increases damage to structural elements and it may even cause collapse of structures. Rosenblueth and Meli [1] referred that the earthquake that struck the Mexico City in 1985 caused significant damage of structures and that more than 40% of these damages occurred as the result of pounding. Also, after the Kocaeli earthquake (17.08.1999), interactions between too closely situated apartment buildings were recognized as a main reason of substantial damage of elements in the places of collisions. Vasiliadis and Elenas confirmed that a number of buildings suffered due to pounding during the earthquake in Athens in 1999 [2]. Similar observations confirmed that pounding was also the main reason of permanent titling of a stairway tower, which resulted from collisions with the main building of the Olive View Hospital during the San Fernando earthquake in 1971 [3]. The building damages due to earthquake-induced structural pounding during other seismic excitations were also reported by Anagnostopoulos [4].

The main recognized reason leading to interactions between insufficiently separated structures is usually the difference in dynamic parameters of each structure [5-7]. The difference in mass or stiffness leads to the out-of-phase vibrations, and finally to collisions. Another reason, more important in the case of large buildings and bridge structures, is related to the spatial seismic effects due to propagation of seismic wave [8]. The phenomenon of earthquake-induced structural pounding has been intensively studied for nearly three decades (see, for example, [9-13]). However, most of the analyses have concerned collisions between reinforced concrete buildings and the studies on pounding between steel structures are very limited (see [14-16]).

A number of different methods have been considered to mitigate earthquake-induced structural pounding. The most natural one is to assume large enough in-between gap size so as to prevent collisions. Another technique is linking structures which allow the forces to be transmitted between buildings and thus eliminate interactions [17]. Stiff links as well as some viscoelastic elements have been tested for such purposes. The aim of the present paper is to show the results of the experimental study focused on the application of polymer elements placed between the colliding members so as to mitigate earthquake-induced pounding between adjacent steel structures in series.

2. Experimental setup

2.1. Experimental model

The experimental study presented in this paper is focused on structural pounding between three models of steel structures standing in a raw and subjected to different seismic excitations. The shaking table located in the Laboratory of Department of Metal Structures and Construction Management of Gdańsk University of Technology (Poland), was used in the experimental study. This unidirectional device is equipped with the platform with dimensions of 200x200 cm which allows us to test models of the maximum weight of 1000 kg. The linear actuator, which may induce movement with maximum acceleration of 10 m/s^2 and a maximum strength of 44.5 kN, is connected to the platform.

In order to simulate the behaviour of small (up to few-storey in height) buildings under earthquake excitations, the tower models with different dynamic characteristics were prepared (Fig.1). Each steel tower was constructed out of four vertical columns with cross section 15x15x1.5 mm and height of 1000 mm. Vertical elements with the same cross section were connected with the horizontal ones at the base and at the top. To make the structures more rigid and to prevent torsional and transverse vibrations, additional skew bracings were used. Additional concrete plates with dimension 500x500x70 mm and weight of 42.2 kg were used to build towers with different dynamic parameters, making the structures to act as single degree-of-freedom systems. The configuration with two concrete plates mounted at the top of the external towers and only one plate on the middle tower has been analyzed in this paper. Additionally, the influence of different earthquake excitations as well as different thickness of polymer elements mounted between models (see Fig.1) has been tested and the results have been presented in this paper.

The following measurement equipment was used in the study:

- Four accelerometers (three of the sensors were located at the top of the towers and one was placed at the platform in order to control its movement),
- Eight-channel amplifier,
- analogue-digital card to record the measurements.

Fig. 1. Experimental setup and tower models with polymer elements with thickness of 20 mm.

2.2. Free vibration test

The preliminary goal of experimental study was to determine the values of natural frequency of each tower so as to confirm that the natural frequencies of the models are similar to the parameters of small, few-storey buildings, which would justify the acceptance of the scaled structural models and allow us to draw more general conclusions related to real structures. Values of natural frequency for each tower obtained from the free vibration test are summarized in Table 1.

As it can be seen from Table 1, the dynamic characteristics of the experimental models fall within the range of parameters typical for small (up to few storeys in height) steel buildings. It should be also underlined that adding polymer elements between structures did not have any influence on the dynamic parameters of towers due to small mass of the elements.

Table 1.The natural frequency values of steel models.

	Natural frequency [Hz]
Tower no 1	1.825
Tower no 2	3.257
Tower no 3	1.792

2.3. Seismic tests

The second stage of the study was devoted to measuring the structural response of adjacent models incorporating collisions as the result of earthquake excitation. The experimental tests included moderate seismic excitations as well as strong earthquakes. In this paper, the results for two ground motions are shown:

- El Centro (19.05.1940, 100% of the nominal amplitude of NS component, PGA=3.07 m/s^2)
- Kobe (16.01.1995, 25% of the nominal amplitude of NS component, PGA=2.01 m/s^2)

It should be underlined that the Kobe earthquake record was scaled down so as to prevent damage to analyzed models of tower structures.

Firstly, the structural response of each tower under earthquake excitation was measured for the in-between gap size was equal 40 mm. After this test, the influence of additional polymer elements (see also [18,19]) with different thickness (t_1=10 mm, t_2=20 mm, t_3=30 mm, t_4=40 mm), mounted between the towers was studied (see Fig. 1). The peak values of acceleration for each tower are summarized in Table 2 for the case without polymer elements and in Table 3 for the case when polymer elements of different thickness are used. Exemplary acceleration time histories for Tower no 1 under the El Centro earthquake are also shown in Figure 2 and Figure 3.

Table 2. Peak values of acceleration for three towers without polymer elements (gap size 40 mm).

Tower no	El Centro (1940)	Kobe (1995)
	[m/s^2]	
Tower no 1	146.524	8.253
Tower no 2	463.441	161.989
Tower no 3	116.526	95.648

Table 3. Peak values of acceleration for three towers with polymer elements (gap size 40 mm).

Tower no	Thickness of polymer elements			
	10 mm	20 mm	30 mm	40 mm
	Peak values of acceleration [m/s^2]			
	El Centro (1940)			
Tower no 1	88.388	36.962	21.369	14.935
Tower no 2	165.170	59.772	30.109	12.588
Tower no 3	27.191	17.889	15.942	10.887
	Kobe (1995)			
Tower no 1	12.653	7.723	6.694	7.888
Tower no 2	18.664	11.238	6.712	6.860
Tower no 3	9.313	8.864	7.410	10.075

Presented results of the experimental study clearly indicate that the influence of collisions on the structural response can be significant (see sharp peaks in the responses occurring as the result of impacts). The smallest acceleration response of structures has been observed for the case of zero gap size as well as when the gap size is large enough to prevent pounding (similar situation concerns also displacements and stresses). Moreover, it can be seen from Table 2 and Table 3 that the use of polymer elements results, in most of the cases, in the decrease in the response of structures subjected to the El Centro and Kobe earthquake. In the case of the polymer elements with thickness of 10 mm, the largest decrease, equal to 90.26 %, was obtained for Tower no 3 under the Kobe earthquake. On the other hand, for the same conditions, Tower no 1 experienced some increase in the peak value of acceleration (increase by 53.31%). The results of the study also indicate that the largest decrease in the structural response for all the cases and ground motions was obtained for polymer elements with thickness of 40 mm, and this decrease was as large as 97.28 %.

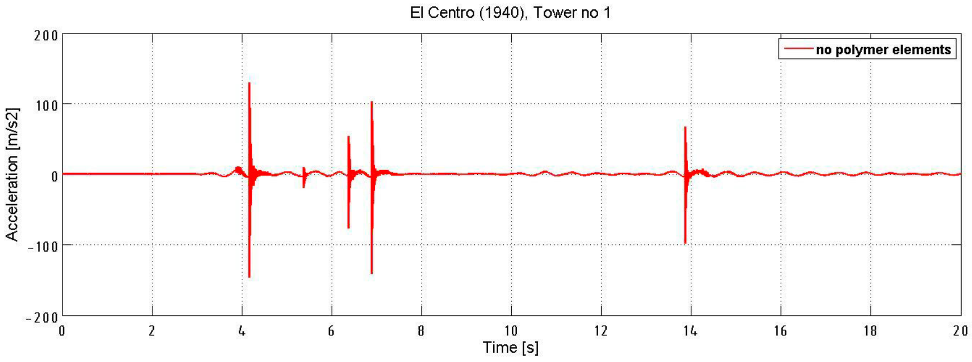
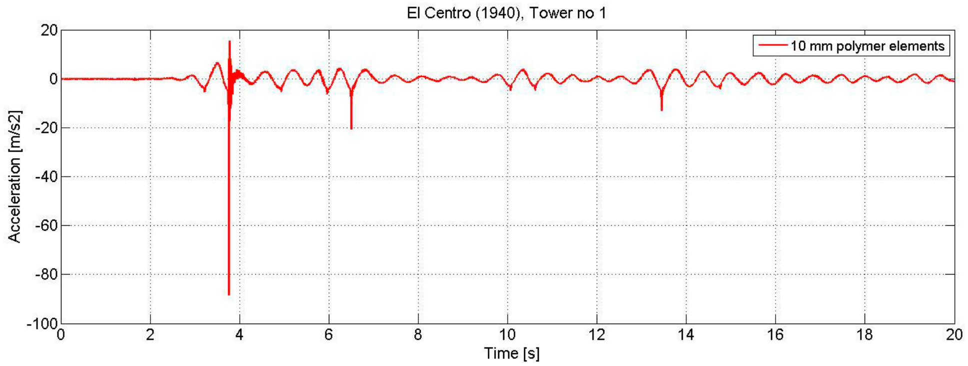
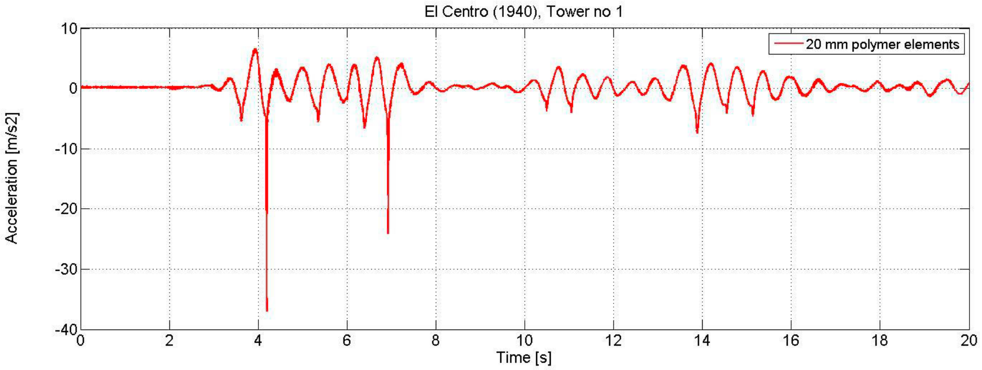


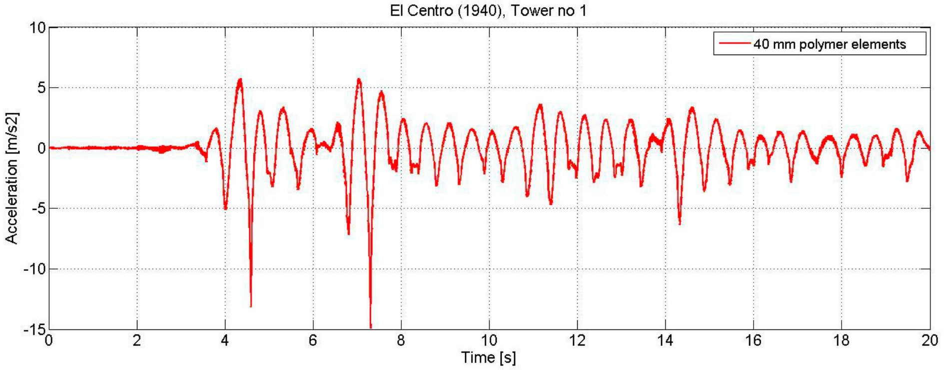
Fig.2. Acceleration time history for Tower no 1 under El Centro earthquake without polymer elements.



(a) polymer elements with 10 mm thickness



(b) polymer elements with 20 mm thickness



(c) polymer elements with 40 mm thickness

Fig.3. Acceleration time history for Tower no 1 under El Centro earthquake with polymer elements.

3. Concluding remarks

The results of experimental study focused on the application of additional polymer elements mounted to the colliding parts of adjacent steel models in series, subjected to the seismic excitations, have been presented in this paper. The influence of polymer elements on the structural response of each model was tested through the shaking table investigation.

Conducted measurements clearly indicate that earthquake-induced pounding may have a meaningful influence of the pounding-involved response of structures. Moreover, the results of the study show that additional polymer elements with different thickness play positive role in most of the cases leading to the decrease in the structural response. The smallest structural response has been observed for the case of 40 mm gap size when the polymer elements fully fill the distance between the models.

The application of polymer elements between the structures can be considered as an effective pounding mitigation technique. It allows us to prevent damaging collisions between adjacent structures during earthquakes. It also improves the structural behaviour leading to the reduction in vibrations under different seismic excitations.

References

[1] E. Rosenblueth, R. Meli, The 1985 earthquake: Causes and effects in Mexico City, in: Concrete International. 8, 1986, pp. 23-24.

[2] L. Vasiliadis, A. Elenas, Performance of school buildings during the Athens earthquake of September 7 1999, in: 12th European Conference on Earthquake Engineering, paper ref. 264, 2002.

[3] VV. Bertero, RG. Collins, Investigation of the failures of the Olive View stairtowers during the San Fernando earthquake and their implications on seismic design, EERC Report No. 73–26. Berkeley (USA): Earthquake Engineering Research Center, University of California, 1973.

[4] SA. Anagnostopoulos, Earthquake induced pounding: State of the art, in: Proceedings of 10th European conference on earthquake engineering, 1994, p. 897–905.

[5] SA. Anagnostopoulos, KV. Spiliopoulos, An investigation of earthquake induced pounding between adjacent buildings, in: Earthquake Engineering and Structural Dynamics 21 (1992), pp. 289–302.

[6] BF. Maison, K. Kasai, Dynamics of pounding when two buildings collide, in: Earthquake Engineering and Structural Dynamics 21 (1992), pp.771–86.

[7] H. Naderpour, R.C. Barros, S.M. Khatami, R. Jankowski, Numerical study on pounding between two adjacent buildings under earthquake excitation, in: Shock and Vibration 2016 (2016), article ID 1504783.

[8] R. Jankowski, Pounding between superstructure segments in multi-supported elevated bridge with three-span continuous deck under 3D non-uniform earthquake excitation, in: Journal of Earthquake and Tsunami 9 (2015), paper no. 1550012.

[9] S.A. Anagnostopoulos SA, Pounding of buildings in series during earthquakes, in: Earthquake Engineering and Structural Dynamics 16 (1988), pp. 443-456.

[10] C.G. Karayannis, M.J. Favvata, Inter-story pounding between multistory reinforced concrete structures, in: Journal of Structural Engineering and Mechanics 20 (2005), pp. 505-526.

[11] C.G. Karayannis, M.J. Favvata, Earthquake-induced interaction between adjacent reinforced concrete structures with non-equal heights, in: Earthquake Engineering and Structural Dynamics 34 (2005), pp. 1-20.

[12] P.C. Polycarpou, L. Papaloizou, P. Komodromos, An efficient methodology for simulating earthquake-induced 3D pounding of buildings, in: Earthquake Engineering and Structural Dynamics 43 (2014), pp. 985-1003.

[13] R. Jankowski, S. Mahmoud, Earthquake-Induced Structural Pounding, Springer, Switzerland (2015).

[14] B. Sołtysik, R. Jankowski, Non-linear strain rate analysis of earthquake-induced pounding between steel buildings, in: International Journal of Earth Sciences and Engineering 6 (2013), pp. 429-433.

[15] B. Sołtysik, R. Jankowski, Building damage due to structural pounding during earthquakes, in: Journal of Physics: Conference Series 628 (2015), article no. 012040.

[16] B. Sołtysik, R. Jankowski, Earthquake-induced pounding between asymmetric steel buildings, in: Seismic Behaviour and Design of Irregular and Complex Structures II, Springer (2016), pp. 255-261.

[17] R. Jankowski, S. Mahmoud, Linking of adjacent three-storey buildings for mitigation of structural pounding during earthquakes, in: Bulletin of Earthquake Engineering 14 (2016), pp. 3075-3097.

[18] T. Falborski, R. Jankowski, A. Kwiecień, Experimental study on polymer mass used to repair damaged structures, in: Key Engineering Materials 488-489 (2012), pp. 347-350.

[19] T. Falborski, R. Jankowski, Polymeric bearings - a new base isolation system to reduce structural damage during earthquakes, in: Key Engineering Materials 569-570 (2013), pp. 143-150.