TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
CIVIL ENGINEERING | BUDOWNICTWO

3-B/2016

DOI: 10.4467/2353737XCT.16.219.5968

BARBARA SOŁTYSIK, ROBERT JANKOWSKI*

THE RESPONSE OF THREE COLLIDING MODELS OF STEEL TOWERS TO SEISMIC EXCITATION

BADANIA ODPOWIEDZI ZDERZAJĄCYCH SIĘ MODELI TRZECH WIEŻ STALOWYCH PODDANYCH WYMUSZENIU SEJSMICZNEMU

Abstract

A number of past and recent observations have confirmed that collisions between adjacent, insufficiently-separated structures occurring as a result of seismic excitation (structural pounding) may result in serious damage to structural elements and can even lead to their total destruction. This paper summarises the results obtained from a shaking table experimental study which investigated structural pounding between three adjacent models of steel towers. The study included different configurations of towers and distances between the structures. The results of the study confirmed that collisions have a significant influence upon the behaviour of the towers, leading to the increase as well as decrease in the structural response.

Keywords: structural pounding, collisions, experimental study, seismic excitations, steel towers

Streszczenie

Wielokrotne obserwacje potwierdzają, iż zderzenia podczas trzęsień ziemi pomiędzy zbyt blisko sąsiadującymi ze sobą budynkami mogą powodować znaczące zniszczenia elementów konstrukcyjnych, a czasem mogą nawet prowadzić do całkowitego zniszczenia konstrukcji. Niniejszy artykuł przedstawia wyniki badań eksperymentalnych przeprowadzonych na stole sejsmicznym dotyczących odpowiedzi zderzających się trzech modeli stalowych wież. W analizie tej uwzględniono różne ustawienie konstrukcji oraz zmieniającą się odległość pomiędzy nimi. Wyniki badań potwierdzają, iż interakcje pomiędzy konstrukcjami mają znaczący wpływ na zachowanie się wież, prowadząc zarówno do wzrostu, jak i redukcji odpowiedzi.

Słowa kluczowe: zderzenia, kolizje, badania eksperymentalne, wstrząsy sejsmiczne, wieże stalowe

* M.Sc. Barbara Sołtysik (Ph.D. student), Prof. Ph.D. D.Sc. Robert Jankowski, Department of Metal Structures and Construction Management, Faculty of Civil and Environmental Engineering, Gdansk University of Technology.

1. Introduction

In this age of high urbanization, the need to build structures very close one to another forces the designer to take interactions between closely separated buildings during ground motions into consideration. This phenomenon, referred to in the literature as earthquake-induced structural pounding, may cause local damage to structural elements [1, 11, 15, 16], and can even lead to the total collapse of the structure. Dangerous interactions between insufficiently separated structures during moderate to strong seismic excitations may occur due to differences in the dynamic properties of each structure [5]. Differences in mass or stiffness may lead to out-of-phase vibrations, which could finally result in collisions [2, 12].

Bertero & Collins [3] and Mahin et al. [9] reported that during the San Fernando earthquake in 1971, collisions between the main building of the Olive View Hospital and one of its independently standing stairway towers caused permanent titling of the tower. Serious pounding damage to parts of school buildings was observed and reported after the Athens earthquake of 7th September 1999 [15]. Additionally, the SSK Hospital in Izmit experienced major damage during the Kocaeli earthquake (17th August 1999) [4]. Extensive damage to and collapses of some buildings due to collisions were recorded after the Loma Prieta earthquake (17th October 1989) [8]. Structural interactions leading to some local damage at contact points was also observed during earthquakes which took place in Poland in 2004 [16, 17].

Earthquake-induced pounding between adjacent, insufficiently separated buildings has been investigated through the use of various structural models of interacting structures and different simulations of collisions [6, 10]. This phenomenon involves deformations at contact points, local cracking or crushing, fracturing due to impact, friction, etc., so it is very difficult for the mathematical analysis. The studies were mainly focused upon reinforced concrete buildings, and research into the behaviour of steel structures under similar circumstances is very limited [13]. Anagnostopoulos conducted a fundamental study of the interactions between adjacent structures in series, using single degree-of-freedom systems with linear and viscoelastic models [1]. Further analyses were performed on more detailed and advanced models of structures using multi degree-of-freedom models with masses lumped on each floor [7] and applying the finite element method [12–14] .

The aim of this paper is to summarise the results obtained from the shaking table experimental study concerning structural pounding between three adjacent models of steel towers subjected to ground motions. The experimental research was performed for different gap distances between the structures. In this paper, examples of the results for three distances (0 mm, 10 mm and 20 mm) are shown.

2. Experimental study

2.1. Experimental setup

The experimental study described in the paper concerned earthquake-induced structural pounding between three steel towers with different dynamic properties (differences in mass) arranged in different configurations (Fig. 1). The study was focused on the structural response of each tower. Towers were constructed out of four columns with heights of 100 cm made of square box sections with dimensions of 15 mm×15 mm and wall thicknesses of 1.5 mm. At the base and the top, columns were connected with horizontal elements with the same cross-section. To prevent transverse and torsional vibrations, skew bracings were used (in addition to square box sections measuring 15 mm×15 mm×1.5 mm). Concrete plates with dimensions of 50 cm×50 cm×7 cm and weighing 42.2 kg were mounted at the top of each tower. The towers were rigidly fixed to the platform of the shaking table (see Fig. 1) and the influence of the foundation type, soil-structure interaction and the ground water conditions were not considered in the study. Two configurations were examined: configuration *C*1 was arranged in such a way that two concrete plates were mounted on the external towers (tower 1 and tower 3) and only one plate was mounted at the top of the middle tower (tower 2); for configuration *C*2, only one plate was mounted at the top of external towers and two plates were mounted on the middle tower.

To simulate the behaviour of each structure under ground motions, the unidirectional shaking table located at the Laboratory of Department of Metal Structures and Construction Management, Gdansk University of Technology was used [12]. This table allows the simulation of the strongest seismic excitations. A platform measuring 200 cm×200 cm, upon which the table is positioned, can be used to test structural models with a maximum weight of 1000 kg. The linear actuator, which may induce movement with a maximum acceleration of 10 m/s^2 and a maximum strength of 44.5 kN, is connected to the platform. The following equipment was used during the measurements:

- Four single-axis accelerometers (with mechanical restriction of frequency at 4 kHz);
- Twelve-channel amplifier with low pass filter of 100 Hz;
- Analogue-digital card to record the measurements.

Four accelerometers were used during the study. Three of the sensors were located at the top of each tower and one was placed on the shaking table platform (to control its movement).

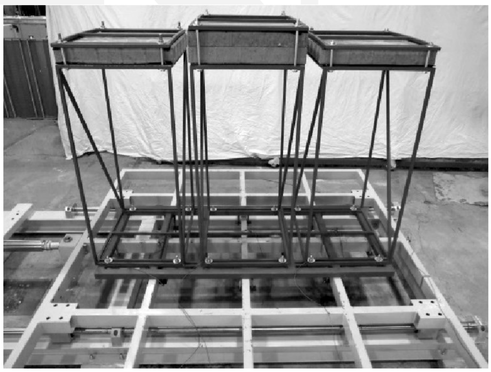

Fig. 1. Experimental setup: configuration *C*1 and configuration *C*2

2.2. Free vibration tests

To determine the dynamic characteristics of each tower, free vibration tests were first conducted. The tests were carried out by releasing a pre-angled tower. All measurements were recorded with a sampling rate of 500 Hz for a time of 100 seconds. The results obtained from the tests, in the form of values of natural frequency for tower 1, tower 2 and tower 3 for two configurations are summarised in Table 1. The exemplary acceleration time histories are also shown in Fig. 2.

Table 1

Natural frequency values for the towers

	Natural frequency [Hz]	
	Configuration *C1*	Configuration *C2*
Tower no. 1	2.400	3.190
Tower no. 2	3.380	2.450
Tower no. 3	2.260	3.120

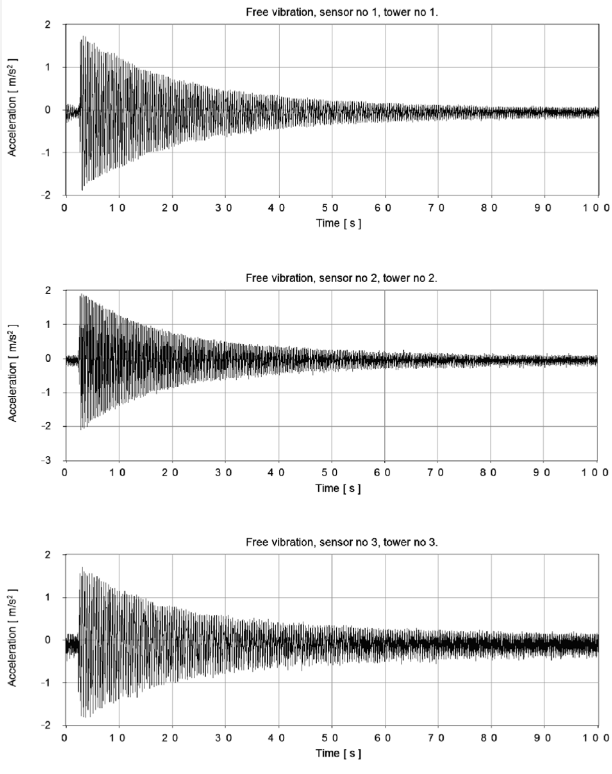

Fig. 2. Exemplary results from free vibration tests for tower 1, 2 and 3 for the configuration *C*1

2.3. Sweep sine test

In the next stage of the research, the sweep sine test was carried out. A single test involved measurements of the acceleration amplitude at the same four points as in the case of free vibration tests. Harmonic excitation of different frequencies was generated by the shaking table actuator. Measurements were recorded with a sampling rate of 500 Hz for a duration of 60 seconds. Table 2 shows the peak values of acceleration for towers arranged in two configurations. Fig. 3 and 4 present the dynamic characteristics of the structural response for configurations *C*1 and *C*2, respectively.

Table 2

Peak values of acceleration

	Acceleration [m/s^2]			
	Configuration *C*1		Configuration *C*2	
	Max	Min	Max	Min
Tower no 1	5.052	–5.124	10.996	–10.918
Tower no 2	10.657	–10.995	7.950	–8.034
Tower no 3	4.496	–4.675	10.127	–10.122

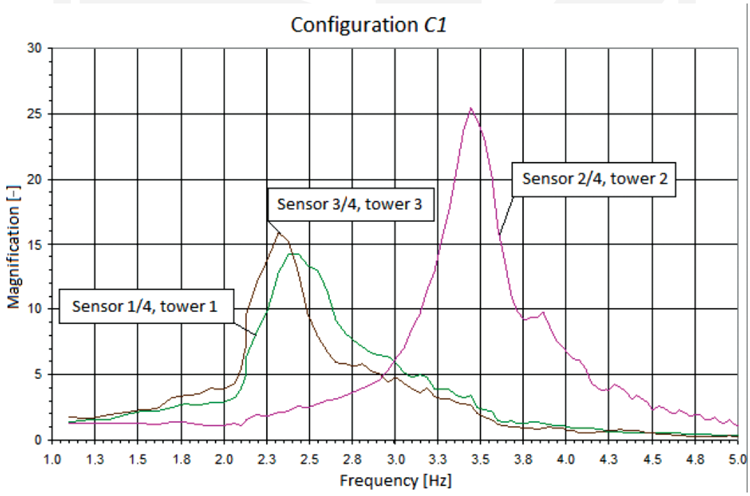

Fig. 3. Dynamic characteristics of the structural response for configuration *C*1

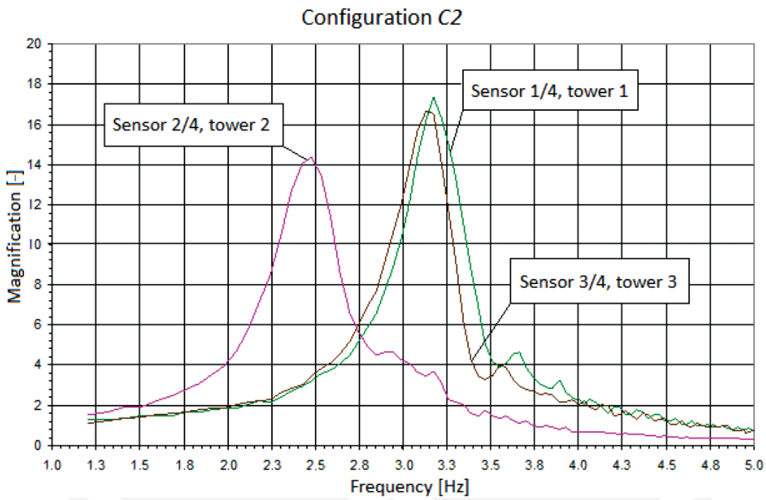

Fig. 4. Dynamic characteristics of the structural response for configuration *C2*

2.4. Seismic test

In the last stage of the experimental study, the response of colliding structures under real earthquake excitation was studied. The seismic test was conducted for the San Fernando earthquake (9th February 1971). The N16° component of the earthquake recorded at the Pacoima Dam station was applied in the study. The earthquake record was scaled to 25% (peak ground acceleration was 2.85 m/s^2) so as to prevent damage of the tower structures. In the test, three different gap sizes between structures were taken into consideration – $\Delta_1 = 0$ mm and $\Delta_2 = 10$ mm and $\Delta_3 = 20$ mm. The peak values of the structural response acceleration for two different configurations are summarised in Table 3. Exemplary results in the form of the acceleration time histories are also presented in Fig. 5.

Results summarised in Table 3 clearly indicate that interactions between insufficiently separated structures have a significant influence upon the structural response under seismic excitation. Comparing different configurations, it can be seen from the table that, in the case of the 0mm gap, the response of all towers is lower for configuration *C*2, even by as much as 58% (tower 3). Additionally, all peak values of acceleration for the gap size of 10mm decrease in the case of configuration *C*2 (by 53% for tower 2). On the other hand, for the gap size of 20 mm, the peak acceleration for configuration *C*2 decreases for only one tower, while the increase trend is observed for the other two structures.

When we focus our attention on only one configuration, i.e. configuration *C*1, it can also be seen from Table 3 that increasing the gap distance from 0 mm to 20 mm leads to the increase in the structural response of tower 1 and tower 2 (even by over 778% in the case of tower 2). On the other hand, in the case of tower 3, the increase in the gap leads to an initial increase in the peak response which is followed by the decrease trend.

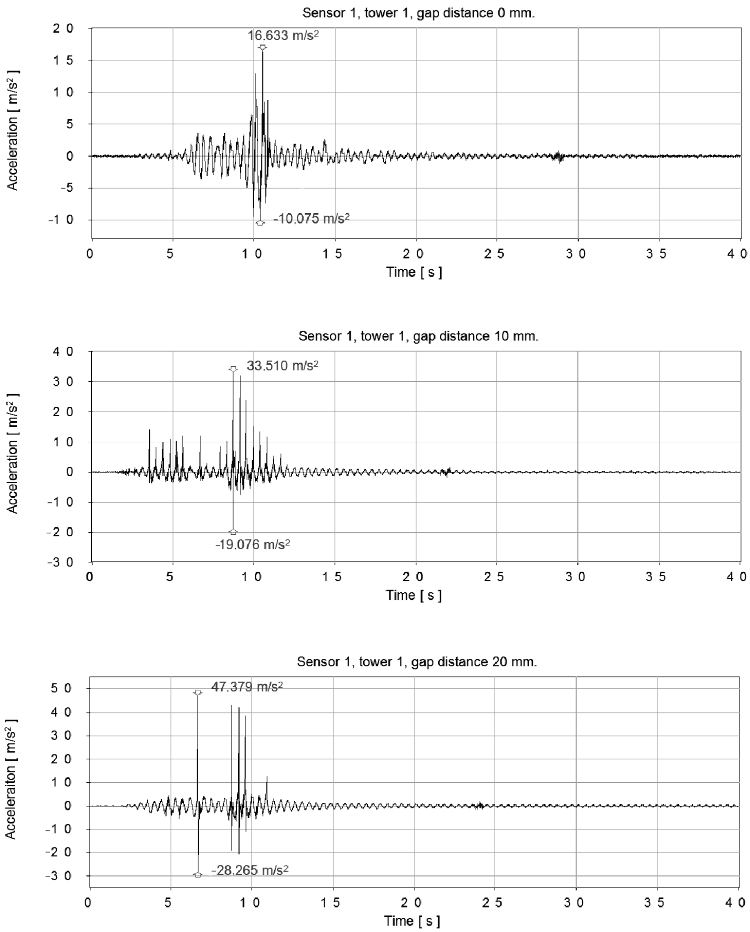

Fig. 5 Acceleration time history of the structural response for configuration *C*1 under the San Fernando earthquake for gaps of 0 mm, 10 mm and 20 mm for tower 1

Table 3

Peak values of acceleration under the scaled San Fernando earthquake for Towers 1, 2 and 3 for different configurations and gap sizes

	Peak values of acceleration [m/s^2]		
	Configuration *C*1		
	Δ_1 = 0 mm	**Δ_2 = 10 mm**	**Δ_3 = 20 mm**
Tower no. 1	13.228	33.510	47.379
Tower no. 2	9.638	56.932	84.653
Tower no. 3	13.922	40.976	37.267

cd. tab. 3

	Configuration *C*2		
	Δ_1 = 0 mm	Δ_2 = 10 mm	Δ_3 = 20 mm
Tower no. 1	6.667	29.630	98.507
Tower no. 2	5.899	26.873	61.190
Tower no. 3	5.913	40.960	44.470

3. Concluding remarks

The results of the shaking table experimental investigation focusing on earthquake-induced pounding between three adjacent steel towers under earthquake excitation have been described in this paper. The study was performed for different configurations and distances between the structures.

The results of the study indicate that interactions between insufficiently separated structures may cause significant changes in structural response during periods of ground motion. In the case of the structures analysed in the present paper, pounding resulted in the decrease as well as in the increase of the peak responses.

Further experimental as well as numerical studies are required in order to investigate the effect of earthquake-induced pounding between structures in series in more detail. This remark especially concerns experimental tests on full scale models of real steel structures under different earthquake excitations. It should be underlined, however, that such tests would require appropriate laboratory equipment not available in Poland. On the other hand, the numerical investigation with the incorporation of the strain rate effect under dynamic excitation is also important and such analyses are planned to be conducted by the authors in the nearest future.

The authors would like to thank Mr. Henryk Michniewicz and Mr. Hytham Ali Abd Elaziz Elwardany for their help in conducting the experiments.

References

[1] Anagnostopoulos S.A., *Pounding of buildings in series during earthquakes,* Earthquake Engineering and Structural Dynamics, Vol. 16, 1988, 443–456.

[2] Anagnostopoulos S.A., Spiliopoulus K.V., *An investigation of earthquake induced pounding between adjacent building*, Earthquake Engineering and Structural Dynamics, Vol. 21, 1992, 289–302.

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

[4] Gillies A.G., Anderson D.L., Mitchell D., Tinawi R., Saatcioglu M., Gardner N.J., Ghoborah A., The August 17, 1999, *Kocaeli (Turkey) earthquake – lifelines and preparedness*, Canadian Journal of Civil Engineering, Vol. 28, No. 6, 2001, 881–890.

[5] Jankowski R., *Impact force spectrum for damage assessment of earthquake-induced structural pounding*, Key Engineering Materials, Vol. 293–294, 2005, 711–718.

[6] Jankowski R., *Theoretical and experimental assessment of parameters for the non-linear viscoelastic model of structural pounding*, Journal of Theoretical and Applied Mechanics, Vol. 45, No. 4, 2007, 931–942.

[7] Karayannis C.G., Favvata M.J., *Earthquake-induced interaction between adjacent reinforced concrete structures with non-equal heights*, Earthquake Engineering and Structural Dynamics, Vol. 34, 2005, 1–20.

[8] Kasai K., Maison B., B*uilding pounding damage during the 1989 Loma Prieta earthquake*, Engineering Structures, Vol. 19, 1997, 195–207.

[9] Mahin S., Bertero V., Chopra A. & Collins R., *Response of the Olive View Hospital Main Building during the San Fernando Earthquake*, Earthquake Engineering Research Center Report (EERC 76–22), Univ. of California, Berkeley 1976.

[10] Mahmoud S., Jankowski R., *Modified linear viscoelastic model of earthquake-induced structural pounding*, Iranian Journal of Science and Technology, Vol. 35, No. C1, 2011, 51–62.

[11] Rosenblueth E., Meli R., *The 1985 earthquake: causes and effects in Mexico City*, Concrete International, Vol. 8, 1986, 23–34.

[12] Sołtysik B., Jankowski R., *Badania eksperymentalne zderzeń pomiędzy wieżami w szeregu poddanymi wymuszeniu sejsmicznemu*, Nowe trendy w naukach inżynieryjnych 4, Vol. I, 2013, 27–36.

[13] Sołtysik B., Jankowski R., *Non-linear strain rate analysis of earthquake-induced pounding between steel buildings*, International Journal of Earth Sciences and Engineering, Vol. 6, No. 3, 2013, 429–433.

[14] Sołtysik B., Jankowski R., *Numeryczna analiza zachowania się kolidujących ze sobą budynków stalowych poddanych obciążeniom sejsmicznym*, XIII Sympozjum Wpływy Sejsmiczne i Parasejsmiczne na Budowle, Kraków 2012, 1–12.

[15] Vasiliadis L., Elenas A., *Performance of school buildings during the Athens earthquake of 7 September 1999*, 12th European conference on earthquake engineering, Paper ref. 264, 2002.

[16] Zembaty Z., Cholewicki A., Jankowski R., Szulc J. *Trzęsienia ziemi 21 września 2004 r. w Polsce północno-wschodniej oraz ich wpływ na obiekty budowlane*, Inżynieria i Budownictwo, Vol. 61, No. 1, 2005, 3–9.

[17] Zembaty Z., Jankowski R., Cholewicki A., Szulc J., *Trzęsienie ziemi 30 listopada 2004 r. na Podhalu oraz jego wpływ na obiekty budowlane*, Inżynieria i Budownictwo, Vol. 61, No. 9, 2005, 507–511.