

## PROBLEMS OF COLLISIONS BETWEEN ADJACENT STEEL STRUCTURES UNDER EARTHQUAKE EXCITATION

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### Abstract

Nowadays, the high level of urbanization forces the engineers to design closely-separated structures and to take into account many factors influencing their response, including collisions between them due to insufficient separation distance during moderate to strong ground motions. Recent observations as well as experimental and numerical investigations have confirmed that interactions between structures may lead to significant damage of structural elements and even to its total collapse. The aim of this paper is to investigate the influence of collisions between three insufficiently separated models of steel structures on structural response under earthquake excitation. The experimental tests as well as numerical analyses have been conducted in the study.

Keywords: earthquake excitation, structural pounding, steel structures, experimental study, numerical analysis

### 1. INTRODUCTION

The high level of urbanization in the XXIst century forces the engineers to design closely-separated structures. During moderate to strong ground motions, collisions between such structures may occur due to insufficient separation between them as well as due to differences in dynamic parameters, which may

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result in the change in structural response [2, 14]. Interactions between structures under earthquake excitation may result in local damage, substantial destruction of structural elements and may even lead to their total collapse [9, 13, 17, 18].

A major reason leading to such interactions, referred in the literature as the earthquake-induced structural pounding, results from the inappropriate distance and differences in dynamic parameters of adjacent structures. These differences lead to the out-of-phase vibrations under earthquake excitations and finally to collisions between buildings [9, 11].

Pounding between neighbouring, insufficiently separated structures has been investigated so far applying various models of colliding structures and using different models of collisions [7]. The fundamental study on interactions between adjacent buildings in series, modelled as single degree-of-freedom systems, was conducted by Anagnostopoulos [1]. Further analyses were carried out using more detailed models, including discrete multi degree-of-freedom systems, in which mass of each storey is lumped at each floor level [2, 8, 10]. The detailed linear and non-linear analyses of pounding between adjacent buildings using the Finite Element Method (FEM) were also carried out [5, 15, 16].

On the contrary to numerical analyses, the results of experimental tests on pounding between adjacent structures during earthquakes are very limited. Papadrakakis and Mouzakis [12] used a shaking table to test models of two-storey building frames without any in-between gap. The experimental investigation on pounding between models of two adjacent three-storey and eight-storey steel framed model structures was also carried out [4]. Moreover, the experimental study was conducted on the response of models of two steel towers with different dynamic properties [3]. More recently, the shaking table tests were performed on models of two equal-height towers equipped with colliding elements made of different materials [6].

## **2. EXPERIMENTAL STUDY**

### **2.1. Experimental setup**

The study described in this paper has been focused on the earthquake-induced structural pounding between three adjacent models of steel tower structures with different dynamic parameters (Fig.1). Towers (each 100 cm high) were constructed out of four vertical columns (rectangular box section 15x15x1.5 mm) connected at the base and the top with horizontal elements made of the same cross section. Additionally, skew bracing, also made of rectangular box

section, were used to prevent the transverse and torsional vibrations. To obtain different dynamic properties of each tower, additional mass was mounted at the top of each model. The configuration with two concrete plates 50x50x7 cm and weight of 42.4 kg mounted on the external towers and only one plate mounted on the middle tower was analysed in this paper (see Fig. 1).

The unidirectional shaking table located at in the Laboratory of Department of Metal Structures and Construction Management, Gdansk University of Technology, was used to simulate the seismic load (see also [14]). The device can be used to obtain seismic excitations which take place during moderate as well as strong earthquakes. The table is equipped with a platform which allows us to test the structural models of the maximum weight of 1000 kg. In this paper, the results under three earthquake excitations have been shown:

- El Centro (19.05.1940, 100% of the nominal amplitude of NS component,  $PGA=3.07 \text{ m/s}^2$ )
- Loma Prieta (18.10.1989, 50% of the nominal amplitude of NS component,  $PGA=3.16 \text{ m/s}^2$ )
- Kobe (16.01.1995, 25% of the nominal amplitude of NS component,  $PGA=2.01 \text{ m/s}^2$ ).

It should be underlined that some of the earthquake records were scaled down so as to prevent damage to analysed models of tower structures. The experimental study was performed for the 30 mm and 40 mm separation gaps.

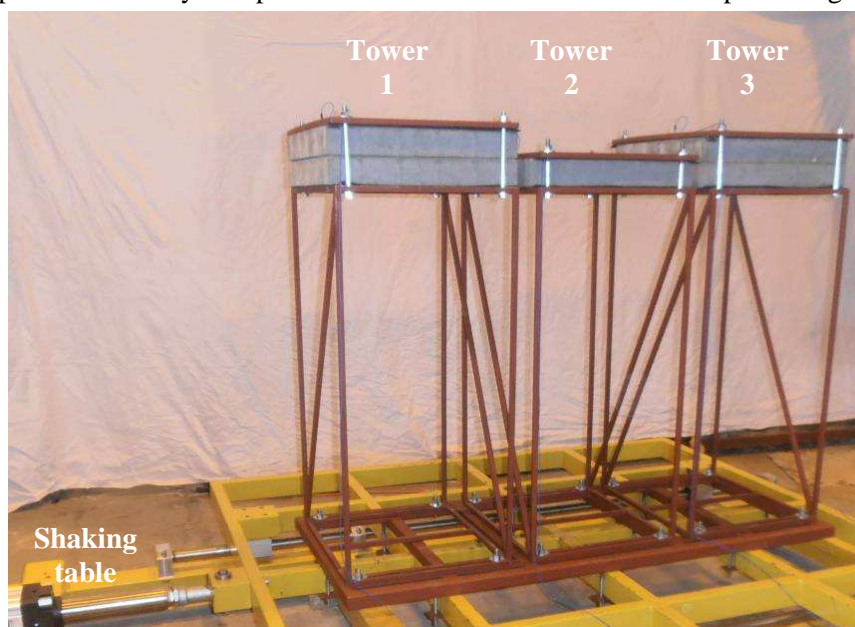


Fig. 1. Experimental setup

## 2.2. Free vibration tests

In order to identify the dynamic characteristics of each tower, the free vibration tests were first conducted. Tests were carried out by releasing towers after applying the initial drift. During the tests, the acceleration time histories were measured using accelerometers mounted at the top of each tower. The natural frequency values (vibrations in the longitudinal direction) identified during the tests are summarized in Table 1. As it can be seen from the table, the natural frequencies of the models are within the range of typical frequency values of small buildings, up to few storeys in height. This fact justifies the acceptance of the scaled structural models and allows us to draw more general conclusions related (up to some extent) to real civil engineering structures. It is also worth mentioning that Tower 1 and Tower 3 have slightly different frequency values (see Table 1), although both of them were supposed to be identical. It is believed that the difference results from some unintentional differences in constructing as well as inaccurate connecting the towers to the shaking table platform.

Table 1. Natural frequency values of towers (longitudinal direction)

Tower no.	Natural frequency [Hz]
1	2.400
2	3.380
3	2.260

## 2.3. Seismic tests

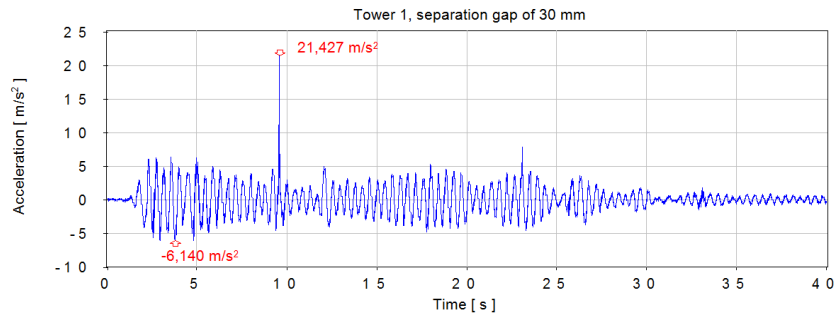
After the free vibration tests, the seismic tests were performed on the shaking table and the structural response was analysed for the gap values of 30 mm and 40 mm. During the tests, the acceleration time histories were measured using four accelerometers. Three of them were mounted at the top of each tower, and the reference one was located on the platform to control its movement. In this paper, the exemplary results for the acceleration time histories of the El Centro earthquake are shown in Fig. 2. Also the peak values of response acceleration for the El Centro, Loma Prieta and Kobe earthquakes are summarized in Table 2.

The results of the study indicate that the influence of collisions between adjacent towers on the response of the structures is significant. Moreover, the increase in the gap value by 10 mm leads to reduction in the peak values of acceleration in most of the cases, even by 57.8% as it was obtained, for example, for Tower 1 under the Loma Prieta earthquake. It should be underlined; however, that structural pounding may also play a negative role by increasing structural response (see, for example, the increased value of the peak acceleration for Tower 1 under the El Centro earthquake in Table 2).

Table 2. Peak acceleration values for the El Centro, Loma Prieta and Kobe earthquakes

Peak acceleration value [m/s <sup>2</sup> ]			
	Separation gap 30 mm	Separation gap 40 mm	Difference [%]
The El Centro earthquake (1940)			
Tower 1	21.427	38.717	Increase by 80.7%
Tower 2	88.871	79.945	Reduction by 10.0%
Tower 3	73.341	30.951	Reduction by 57.8%
The Loma Prieta earthquake (1989)			
Tower 1	21.970	10.880	Reduction by 50.5%
Tower 2	72.917	55.988	Reduction by 23.2%
Tower 3	57.854	43.770	Reduction by 24.3%
The Kobe earthquake (1995)			
Tower 1	6.569	6.497	Reduction by 1.1%
Tower 2	67.682	35.420	Reduction by 47.7%
Tower 3	49.352	26.771	Reduction by 45.8%

a)



b)

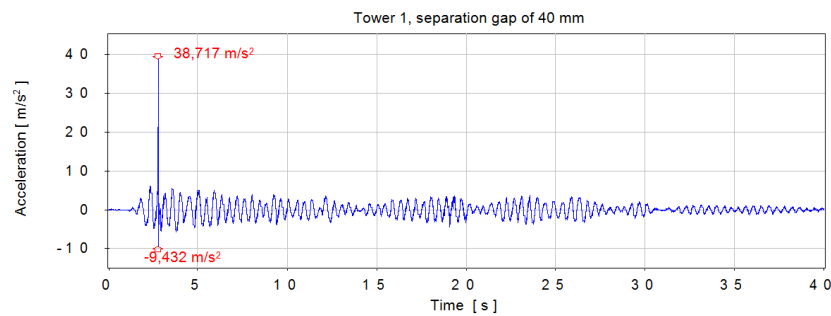


Fig. 2. Acceleration time histories for Tower 1 under the El Centro earthquake: a) Separation gap of 30 mm; b) Separation gap of 40 mm

### 3. NUMERICAL ANALYSES

#### 3.1 Numerical model

In the second stage of the study, a number of numerical analyses were conducted using the commercial software MSC Marc 2008. In the numerical model (see Fig. 3), columns and bracings made of steel S235 JR ( $\nu=0.3$ ,  $\rho=7860$  kg/m<sup>3</sup>) were modelled by beam-column elements, whereas the concrete plates ( $\nu=0.2$ ,  $\rho=1800$  kg/m<sup>3</sup>) located at the top of each tower were simulated by the use of solid elements with all dimensions described in subchapter 2.1. Structures were considered to be rigidly fixed to the ground. Collisions between towers were modelled using 12 three-dimensional gap-friction elements. These elements, placed between main nodes of the models (see Fig. 3), assure frictional and gapping connection. In the moment when contact is detected, the nodes become fixed in the longitudinal direction and friction forces are imposed in the transverse and vertical directions. In numerical simulations, the initial gaps between structures of 30 mm and 40 mm were considered.

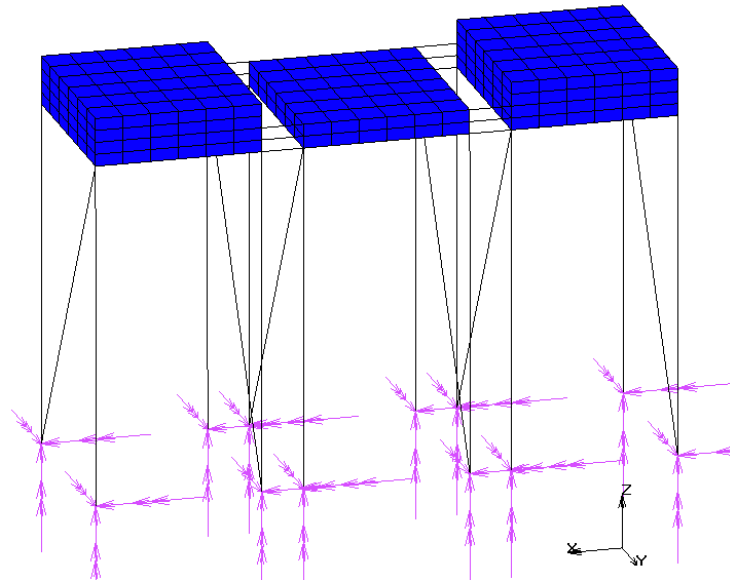


Fig. 3. Numerical model of three colliding towers implemented in MSC Marc software with gap-friction elements

### 3.2 Modal analysis

In order to confirm the dynamic properties of numerical models of interacting structures, the multi-dimensional modal analysis, using the Lanczos method, was first conducted. The results of the analysis, in the form of free vibrations models together with the natural frequencies, are shown in Figs. 4-5 and summarized in Table 3, respectively. It can be seen comparing the results shown in Table 1 and Table 3 that the natural dynamic properties of the numerical models of towers are consistent with the values obtained from the experiment what somehow confirms the accuracy of the numerical models created. It is also worth underlining that, on the contrary to the experimental results, the frequency values for Tower 1 and Tower 3 obtained in the longitudinal direction from the numerical analysis are identical. This is due to the fact of applying the simplified way of numerical modelling of two external towers.

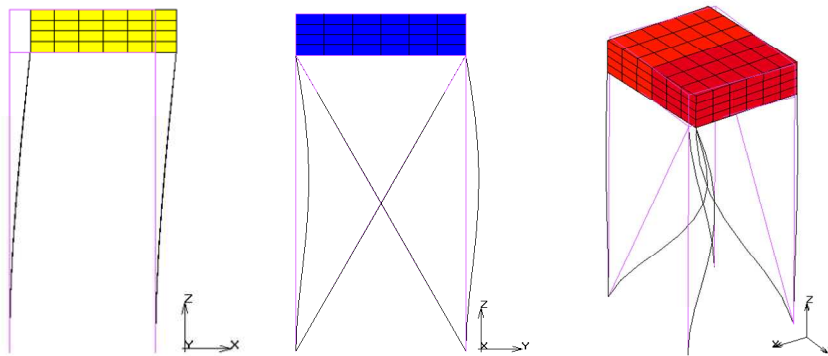


Fig. 4. Free vibration modes for Tower 1 and 3

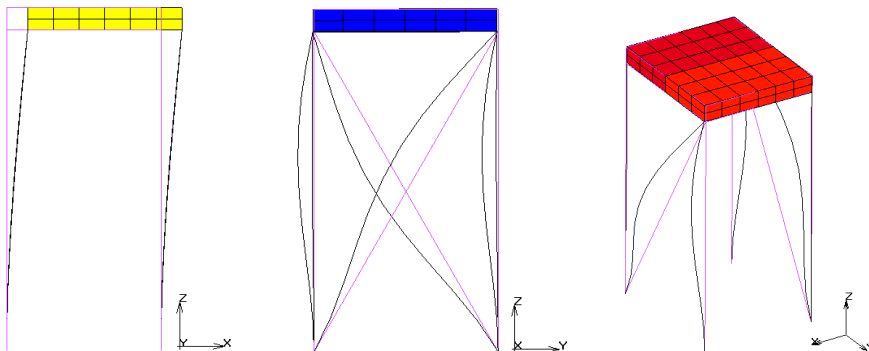


Fig. 5. Free vibration modes for Tower 2

Table 3. Natural frequency values for free vibration modes obtained from modal analysis

Tower no.	Natural frequencies for free vibration modes [Hz]		
	Longitudinal (X direction)	Transverse (Y direction)	Torsional (XY direction)
1	2.38	51.31	71.31
2	3.33	59.17	69.79
3	2.38	51.31	71.31

### 3.3 Dynamic analysis

After conducting modal analysis, the dynamic tests for colliding three towers during earthquakes were performed. Towers, separated with the separation gaps of 30 mm, were subjected to the one-dimensional real (not scaled down) earthquake excitation. The example of the results of the analysis, in the form of the displacement time history in the longitudinal direction for Tower 1 under the El Centro earthquake, is shown in Fig. 6. The peak values of displacements in the longitudinal direction for all towers for the case with and without pounding (large separation gap preventing collisions) are also summarized in Table 4. The results of the dynamic numerical analysis indicate that collisions between adjacent structures may lead to significant change in their structural behaviour. In the case of the structures analysed, pounding resulted in the decrease in the peak displacement (see Table 4).

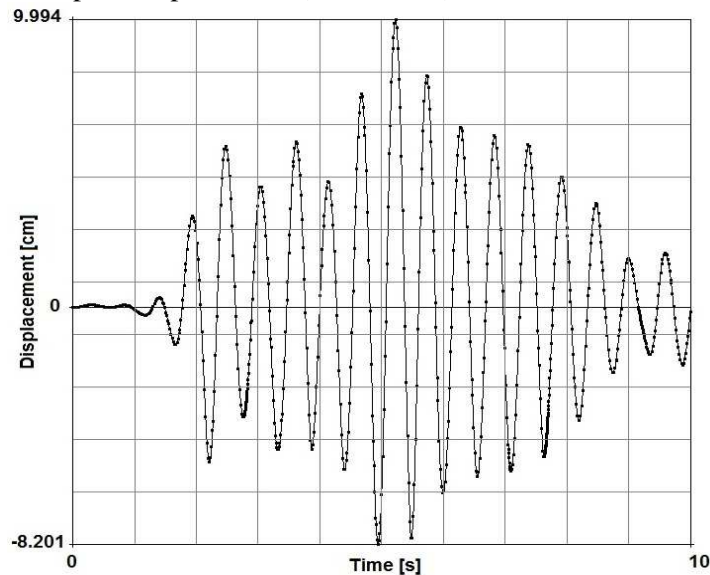


Fig. 6. Displacement time history for Tower 1 under the El Centro earthquake



Table 4. Peak values of displacement in the longitudinal direction for the El Centro earthquakePeak values of displacement for separation gap of 30 mm [cm]

	Without pounding	With pounding	Difference [%]
Tower 1	8.525	9.994	17.2
Tower 2	4.216	5.883	39.5
Tower 3	8.525	8.605	6.7
Peak values of displacement for separation gap of 40 mm [cm]			
	Without pounding	With pounding	Difference [%]
Tower 1	8.525	9.633	13.0
Tower 2	4.216	5.867	39.2
Tower 3	8.525	9.407	10.3

#### 4 CONCLUSIONS

In this paper, the experimental and numerical investigation for earthquake-induced pounding between adjacent structures in series has been conducted. The investigation was performed using models of three steel towers with different dynamic characteristics. The influence of collisions between adjacent structures was analysed.

The results of the study clearly indicate that collisions between adjacent structures may lead to significant change in their response during earthquakes. In the case of the structures analysed in the present paper, pounding resulted in the decrease as well as in the increase in the peak responses. It should be underlined, however, that even if the response is reduced, the effect of interactions may result in considerable damage to the locations of impacts between structures under earthquake excitations (see [13, 17]).

Further experimental as well as numerical studies are required so as to investigate the effect of earthquake-induced pounding between structures in series in more detail. This remark concerns especially experimental tests on full scale models of real steel structures under different earthquake excitations.

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## REFERENCES

1. Anagnostopoulos S.A.: *Pounding of buildings in series during earthquakes*, Earthquake Engineering and Structural Dynamics, **16** (1988) 443-456.
2. Anagnostopoulos S.A., Spiliopoulos K.V.: *An investigation of earthquake induced pounding between adjacent building*, Earthquake Engineering and Structural Dynamics, **21** (1992) 289-302.
3. Chau K.T., Wei X.X., Guo X., Shen C.Y.: *Experimental and theoretical simulations of seismic poundings between two adjacent structures*, Earthquake Engineering and Structural Dynamics, **32** (2003) 537-554.
4. Filiatrault A., Wagner P., Cherry S.: *Analytical prediction of experimental building pounding*, Earthquake Engineering and Structural Dynamics, **24** (1995), 1131-1154.
5. Jankowski R.: *Assessment of damage due to earthquake-induced pounding between the main building and the stairway tower*, Key Engineering Materials, **347** (2007) 339-344.
6. Jankowski R.: *Experimental study on earthquake-induced pounding between structural elements made of different building materials*, Earthquake Engineering and Structural Dynamics, **39** (2010) 343-53.
7. Jankowski R.: *Theoretical and experimental assessment of parameters for the non-linear viscoelastic model of structural pounding*, Journal of Theoretical and Applied Mechanics, **45** (2007) 931-942.
8. Karayannis C.G., Favvata M.J.: *Earthquake-induced interaction between adjacent reinforced concrete structures with non-equal heights*, Earthquake Engineering and Structural Dynamics, **34** (2005) 1-20.
9. Kasai K., Maison B.: *Building pounding damage during the 1989 Loma Prieta earthquake*, Engineering Structures, **19** (1997) 195-207.
10. Mahmoud S., Jankowski R.: *Elastic and inelastic multi-storey buildings under earthquake excitation with the effect of pounding*, Journal of Applied Sciences, **9** (2009) 3250-3262.
11. Maison B., Kasai K.: *Dynamics of pounding when two buildings collide*, Earthquake Engineering and Structural Dynamics, **21** (1992) 771-786.
12. Papadrakakis M., Mouzakis H.: *Earthquake simulator testing of pounding between adjacent buildings*, Earthquake Engineering and Structural Dynamics, **24** (1995) 811-834.
13. Rosenblueth E., Meli R.: *The 1985 earthquake: causes and effects in Mexico City*, Concrete International, **8** (1986) 23-34.
14. Sołtysik B., Jankowski R.: *Badania eksperymentalne zderżeń pomiędzy wieżami w szeregu poddanymi wymuszeniu sejsmicznemu*, Nowe trendy w Naukach Inżynierskich 4, Tom I, 2013, 27-36.

15. Sołtysik B., Jankowski R.: *Non-linear strain rate analysis of earthquake-induced pounding between steel buildings*, International Journal of Earth Sciences and Engineering, **6** (2013) 429-433.
16. 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.
17. Vasiliadis L., Elenas A.: *Performance of school buildings during the Athens earthquake of September 7 1999*, 12th European Conference on Earthquake Engineering, 2002, paper ref. 264.
18. 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, **61** (2005) 3-9.

#### PROBLEMY ZDERZEŃ POMIĘDZY SĄSIADUJĄCYMI KONSTRUKCJAMI STALOWYMI PODDANYMI OBCIĄŻENIOM SEJSMICZNYM

##### Streszczenie

Wieloletnie obserwacje oraz badania eksperymentalne i numeryczne potwierdziły związek wielkości dynamicznego obciążenia z odpowiedzią konstrukcji. Wysoki poziom urbanizacji w XXI wieku zmusza inżynierów do projektowania budynków w coraz większym zagęszczeniu. W wyniku niedostatecznej odległości pomiędzy konstrukcjami oraz w związku z różnymi parametrami dynamicznymi obiektów budowlanych, podczas umiarkowanych i silnych trzęsień ziemi dochodzi do zderzeń pomiędzy konstrukcjami, co prowadzi do zmiany ich odpowiedzi. Interakcje wynikające z obciążeń sejsmicznych prowadzą do zniszczeń w elementach konstrukcyjnych, ale również mogą skutkować całkowitym zniszczeniem budynku. Zderzenia pomiędzy sąsiadującymi konstrukcjami wynikają głównie z niedostatecznej odległości pomiędzy nimi i równocześnie z różnic w parametrach dynamicznych poszczególnych konstrukcji. Różnice w masach czy sztywnościach powodują przesunięte w fazie drgania, te natomiast doprowadzają do zderzeń. Celem niniejszej pracy jest analiza zderzeń pomiędzy modelami trzech stalowych konstrukcji poddanych obciążeniom sejsmicznym. Uzyskane wyniki z badań eksperymentalnych i numerycznych pokazują, iż zderzenia pomiędzy sąsiadującymi konstrukcjami mogą prowadzić do znaczących zmian w ich odpowiedziach. Analizy przeprowadzone w pracy potwierdzają, iż kolizje mogą powodować zarówno zmniejszenie, jak i zwiększenie odpowiedzi konstrukcji.

Słowa kluczowe: obciążenia sejsmiczne, konstrukcje stalowe, analiza numeryczna

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