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Shake-table tests to assess the behaviour of structural systems under seismic excitations

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Abstract

The continuous increase in population coupled with migration towards urban areas put pressure on the building stock and increased the demand for housing and office buildings. Some of the most densely populated regions are located in areas prone to natural disasters out of which earthquakes are of particular interest for designers and researchers in the field of civil engineering because of their consequences in terms of human casualties, property and economic losses. There are several approaches to mitigate such losses and experimental investigations on the behaviour of different structural systems to seismic excitations is an indispensable tool, albeit it being, sometimes, an expensive one. Most often this represents a significant obstacle in advancing the knowledge in the field due to the lack of experimental data documenting the realistic dynamic responses of structures tested under real or artificial seismic loads. The paper presents a comprehensive overview of the experimental investigations on the seismic behaviour of several structural systems by means of shake-table tests conducted at the Technical University "Gheorghe Asachi" of Iasi in the general context of the state of the art in the field. The experiments highlighted the importance of such investigation methods in understanding the behaviour of real buildings subjected to earthquake loads. The obtained results could also serve as calibration data for the numerical models that may be used to explore a wide range of varying parameters.

Key words: earthquake loads, shake table tests, experimental investigations, calibration data

1 Introduction

Earthquakes have always been one of the major natural disasters capable of causing casualties and significant economic losses, especially with the rapid development of densely populated areas. This has lead to a gradual increase in the awareness of the general public on the destructive potential of such natural disasters. A significant number of cities around the world were built in highly active seismic areas and are constantly subjected to severe earthquakes but mostly to frequent moderate magnitude seismic motions [1-3]. The scientific community intensified the efforts to better understand the way different types of structures behave under seismic excitation. Their main objectives were to increase structural safety and mitigate the risk of structures being damaged beyond repair or collapse during earthquakes [4, 5]. Every structure is designed to fulfil its intended purpose and to ensure the safety of its occupants. However, due to repeated seismic actions of moderate to high intensity during its lifetime, the structure may require repairing or strengthening interventions to either continue to serve its purpose or to comply with the new safety demands stipulated in the design codes [6].

Understanding the complex behaviour of new or existing buildings during seismic motions is of paramount importance for structural engineers because it helps them understand how to ensure the safety of occupants and prevent significant material losses. There are three possible scenarios that can lead to gathering the necessary knowledge: 1.The occurrence of the natural disaster, which offers real life data [1, 2, 7, 8] but may also prove disastrous; 2. Experimental investigations using specialized equipment (e.g. shake table tests, pseudo dynamic testing) [5, 9, 10] and 3. Numerical simulations using specialized software packages that are able to account for all complex phenomena in a structure during a seismic motion [11, 12]. While the first mentioned scenario produces the most accurate data, it is the least desired one because of its disastrous potential in terms of casualties and property damage. There is no control whatsoever in the "input parameters" in terms of occurrence, duration, direction and the intensity of the shaking motion. The second scenario requires specialized equipment and highly trained personnel to be able to simulate real life events. Due mostly to financial constraints coupled with the complex nature of such experiments, investigations on the behaviour of full-size models are limited [13-15]. However, there are numerous studies on scaled down models of various types of structures [5, 9, 10, 16-22]. The last scenario offers the largest flexibility in terms of the number of parameters that can be investigated. It has also become quite affordable in terms of raw calculation power with the advancements in the computer hardware. There are, however, limitations due to simplifying assumptions and the need to validate the models by means of experimental tests [23-25]. The paper presents an overview of the experimental investigations on the seismic behaviour of several structural systems by means of shake-table tests conducted at the Technical University "Gheorghe Asachi" of Iasi. The experiments highlighted the importance of such investigation methods in understanding the behaviour of real buildings subjected to earthquake loads.

2 Thin-walled cold-formed steel structure with wood fibre panels

The structural frame was made of thin walled steel profiles of type CW 147/52/1.5. These elements were used as ribs for holding together the wall panels and the slabs. The frame beams for the wall and slab panels consisted of UW 150/40/1.5 profiles. The braces were made of type MP275 elements with a thickness of 1.5 mm. The structural model is shown in Fig. 1a. A typical wall panel is presented in Fig. 1b, whereas Fig. 1c presents the structural system of the floor.

The seismic motions consisted in a sine-sweep function from 2 Hz to 10 Hz, with a rate of increasing of 0.5 Hz and varying amplitudes of the signal and two earthquake scenarios scaled to different amplitudes for accelerations (El Centro, 1940; Vrancea, 1986). The input signals are shown in Fig. 2.

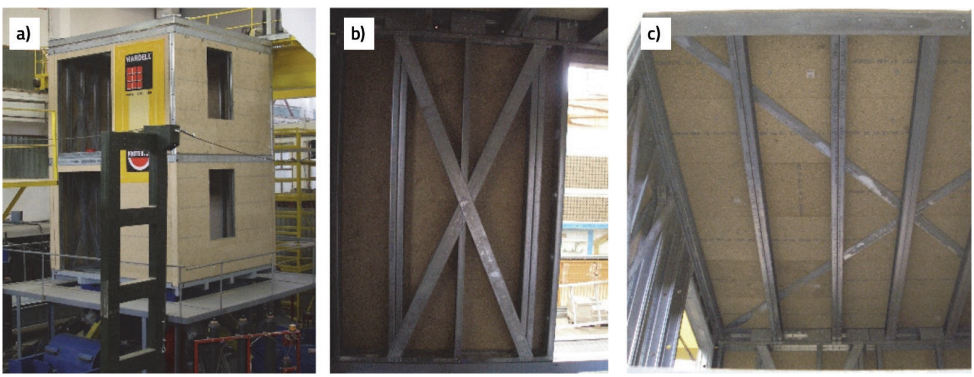
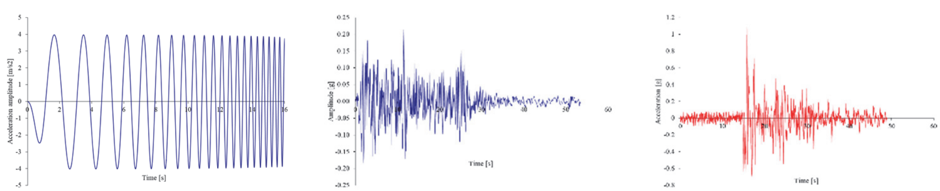


Figure 1. Hardell Type structures to be tested on the shake table [16]



Sine-sweep El Centro (EW component) Vrancea (EW component)

Figure 2. Seismic motions [16]

The obtained data were post-processed and the dynamic characteristics of the model were determined after each seismic motion. The results showed a 29 % increase in the fundamental period of vibration at the end of the sine-sweep loading scenarios which meant that the model suffered some damages. They were confirmed by visual inspection and a detailed presentation can be seen in [16].

3 Hybrid structural system with mineral matrix

The hybrid structure consisted of a modulated system of 60 cm wide and 3.00 m tall cast-in-place panels. The resulted structural model is shown in Fig. 3. The experiment on the shaking table started from a set of diagnostic low-level tests on intact specimen including impulse loading and white noise excitation. The base motion records were applied to the building progressively. The loading scenarios taken into consideration were two sine-beat motions (SB) of different frequencies and duration as well as two earthquake records for Vrancea 1986 earthquake and El Centro 1940 earthquake, presented in Fig. 2b and Fig. 2c.

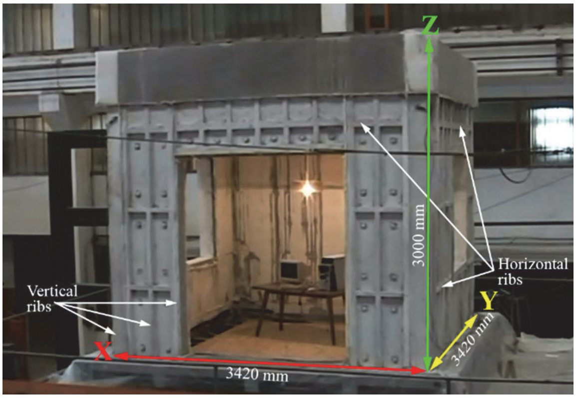


Figure 3. Hybrid structural system with mineral matrix [18]

The obtained data suggest that even though several shaking motions with different amplitudes were considered, the model behaved very well with very small degradations. Another advantage was the light weightiness of the structure compared to an equivalent model made of traditional concrete.

4 Unreinforced masonry structure

The model designed for the experimental program aims at the most accurate replication of the structural typology, using masonry made of solid ceramic bricks and weak mortars based on lime and local aggregates. The structural model proposed for testing is a building made of unreinforced brick masonry, ground-floor only, with a flexible ceiling supported by wooden beams and a classic roof, as shown in Fig. 4.

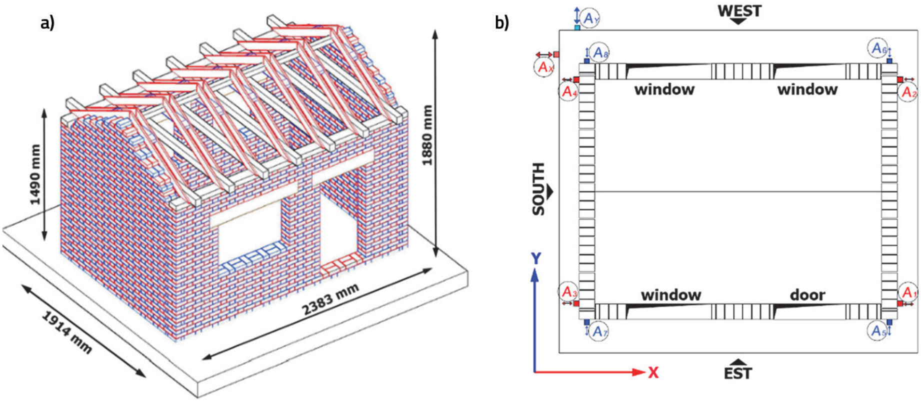


Figure 4. a) Building perspective view b) plan view of the model [26]

The damage to the corner area of the walls occurred because of two factors: the first was the connection between the floor and the structural walls (lack of shear transfer connections can lead to lateral forces acting perpendicular to the wall plane) and the second factor was determined by the existence of window and door gaps in the immediate vicinity of the corner area. The latter is produced due to the in-plane motion of the longitudinal walls leading to the occurrence of a rocking moment at the joints that connect the parapet and the lintel related to the gap.

5 Base isolated structure with multi-stage system

The model was a one-bay one-span steel frame structure with the in-plane dimensions of 1.4 m × 1.0 m and a height of 1.5 m, as shown in Fig. 5. The columns and the beams of the structure were made of INP steel profiles [19].

The multi-stage isolation system consisted of three steel frames made of HEB180 steel profiles having the dimensions of 1.5 m × 1.21 m. The base isolation was achieved by means of elastomeric bearings have 100 mm ×100 mm plane dimensions and a thickness 79 mm. The bearings were weakened following a pattern of nine circular holes 20 mm in diameter and the hardness of the elastomer was 60 ShA. The additional mass consisted of three concrete slabs at the top of the structure and four concrete slabs at the base of the structure, each of them weighing 360 kg [19].

Sine-beat actions and an artificial accelerogram were applied in the longitudinal direction of the experimental model (the x direction of the shaking table): Test 1 - a sine-beat action with a frequency of 10 Hz and a maximum acceleration of 0.5g; Test 2 – a sine-beat action with a frequency of 10 Hz and a maximum acceleration of 0.6g; Test 3 – a sinus beat action with a frequency of 10 Hz and a maximum acceleration of 0.8g; and Test 4 – an artificial accelerogram with a maximum acceleration equal to 2.5 g. The response of the model was recorded by means of displacement transducers and accelerometers positioned as shown in Fig. 6.

A comparison of the acceleration amplitudes at the level of the shake table (A0) and at the base of the model (A1) rendered evident the efficiency of the solution for dampening the seismic motions [19], as seen from Fig. 7.

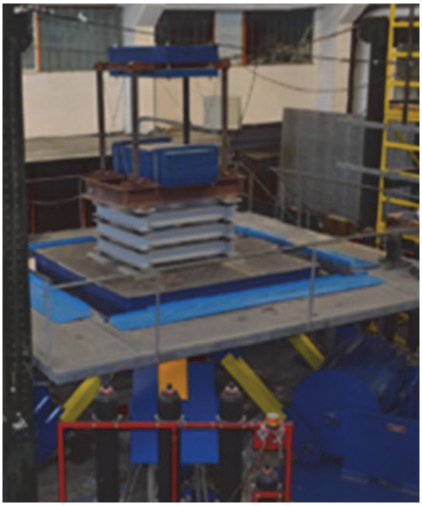


Figure 5. Base isolated structure [19]

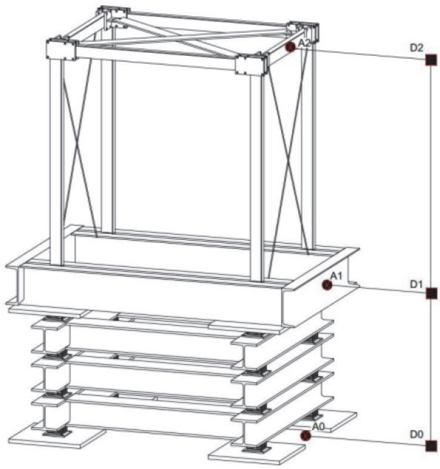


Figure 6. Location of recording equipment [19]

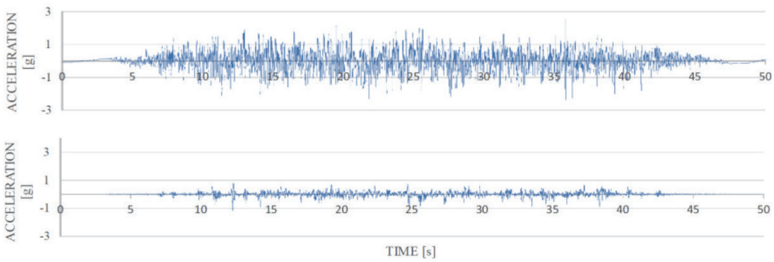


Figure 7. Acceleration amplitudes at the level of the shake table (top) and at the base of the model (bottom) [19]

A significant reduction of the accelerations recorded at the top of the structure was noticed compared to the maximum acceleration recorded at the level of the shake table. The peak acceleration was about three times lower in the case of Test 1, approximately four times lower for Test 2, three times lower for Test 3 and two times lower for Test 4. The experimental model behaved like a rigid body (the displacement values from the top and the bottom of the structure were approximately equal) and the structure did not show any degradations, even during severe action with PGA equal to 2.5g.

6 Steel frame structure with energy dissipation device at the nodes

Steel structures are widespread in seismic areas due to their ductile behaviour and increased energy dissipation capacity. The steel beam-to-column joints must be capable of simultaneously providing the strength and deformation capacity of the structures [27]. The model was a one-bay one-span steel frame structure with energy dissipation devices at the beam-column nodes in the longitudinal direction (direction of the shaking motion) and was stiffened by means of braces in the transversal direction, as shown in Fig. 8. The experimental data was recorded by means of 4 accelerometers and 4 displacement transducers. The latter were positioned in such a way so as to record the relative displacements between the upper end of the column and the end of the beam in order to assess the effectiveness of the adopted seismic energy dissipation solution.

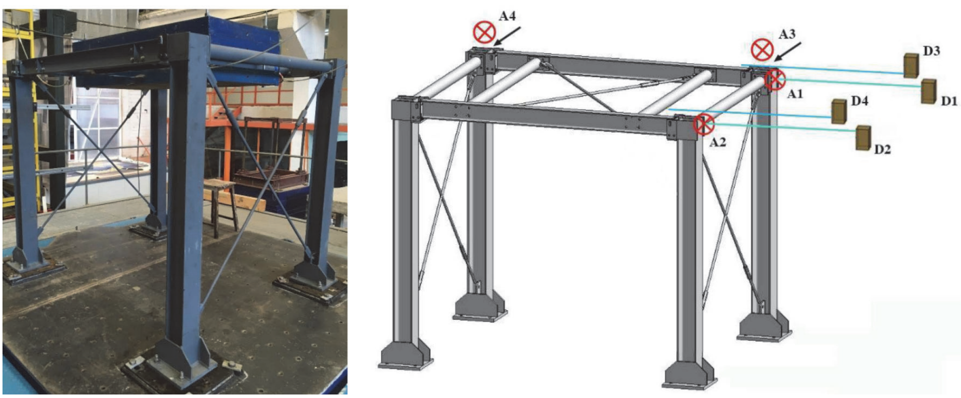


Figure 8. Frame structure on the shake table (left) and the location of the recording equipment (right) [27]

The damping characteristics of the model subjected to different seismic scenarios, both artificially generated and records of real earthquakes, were determined from the free vibrations at the end of each shaking motion, as shown in Fig. 9. The proposed solution for the seismic energy dissipation devices at the nodes proved to be effective in reducing the effects of the shaking motion and a patent application was filed, pending acceptance.

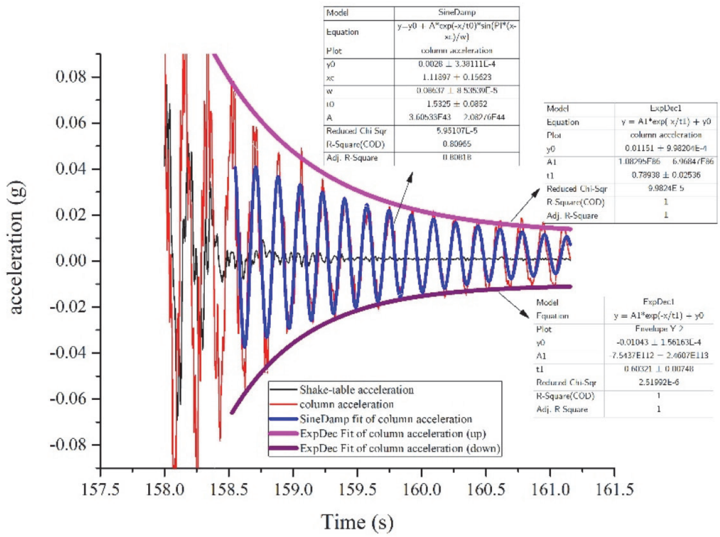


Figure 9. Assessment of the damping ratio from the free vibration decay

7 Reinforced concrete frame structure with short columns

The 1/3-scale symmetric structure was designed according to the specifications of European norms and following the guidelines in the national annex for Romania. The "short column scenario", as seen in Fig. 10, was considered to account for RC frame structures that have partial infill walls. The model was tested as part of the FP7 Anagennisi project. The frame was designed to have shear failure in the short column span, to simulate cases where a column is restrained along its height. The frames were tested using uniaxial shaking, with Peak Ground Accelerations (PGA) starting at 0.14g and incrementally increased depending on the response of the shake table and the strain measurement on the longitudinal rebar in the column [10].

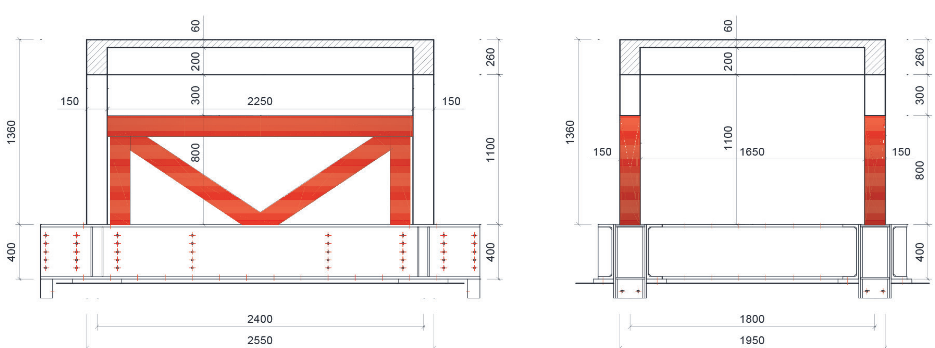


Figure 10. Geometry of the model (steel frame to simulate the partial infill wall is shown in red)

The reduction in the fundamental frequency of the structure with each seismic input was a clear sign of damage accumulation. The structure however, being very stiff took little damage during the first few tests. At 0.41g and 0.81g few hairline shear cracks began to propagate, decreasing the natural frequency by 24 % and 35 %, respectively. During the 1.62g test, the shear cracks opened and closed until cracks extended over the full strut zone and total collapse of the short column occurred. The part of the column below the restraining section remained intact with no visible cracks [10].

8 Conclusions

The paper presents an overview of the experimental investigations on the seismic behaviour of several structural systems by means of shake-table tests conducted at the Technical University "Gheorghe Asachi" of Iasi. The experiments highlighted the importance of such investigation methods in understanding the behaviour of real buildings subjected to earthquake loads. As it can be seen, a wide range of structural typologies were tested on the shake table to assess their behaviour during seismic motions. Each test had its own particularities and the amount of data collected differed from one case to another depending on what was investigated. The shake table tests provide insightful information on the behaviour of the structural models subjected to seismic loads. However, as previously mentioned, such tests require specialized equipment and highly qualified personnel in order to obtain the best results. The research team at the "Gheorghe Asachi" Technical University of Iasi is always giving its best to obtain accurate and meaningful results that can be used to validate observations made in the field during each seismic even or be used as calibration tools for numerical models. Such valuable experience was gathered during the past 15 years by a team of dedicated researchers in the field of civil engineering.

References

[1] Ruiz-Pinilla, J.G, Adam, J.M., Perez-Carcel, M., Yuste, J., Moragues, J.J. (2016): Learning from RC building structures damaged by the earthquake in Lorca, Spain, in 2011, Engineering Failure Analysis, 68, 76-86, https://doi.org/10.1016/j.engfailanal.2016.05.013

[2] Gautam, D., Chaulagain, H. (2016): Structural performance and associated lessons to be learned from world earthquakes in Nepal after 25 April 2015 (MW 7.8) Gorkha earthquake, Engineering Failure Analysis, 68, 222-243, https://doi.org/10.1016/j.engfailanal.2016.06.002

[3] De Martino, G., Di Ludovico, M., Prota, A., Moroni, C., Manfredi, G., Dolce, M. (2017): Estimation of repair costs for RC and masonry residential buildings based on damage data collected by post-earthquake visual inspection, Bulletin of Earthquake Engineering, 15 (4), 1681–1706, https://doi.org/10.1007/s10518-016-0039-9

[4] Toma, I.O., Atanasiu, G.M. (2010): Modern trends in experimental earthquake engineering research, Bulletin of the Polytechnic Institute of Jassy. Construction. Architecture Section, LVI (4), 43-54.

[5] Garcia, R., Pilakoutas, K., Hajirasouliha, I., Guadagnini, M., Kyriakides, N., Ciupala, M.A. (2017): Seismic retrofitting of RC buildings using CFRP and post-tensioned metal straps: shake table tests, Bulletin of Earthquake Engineering, 15, 3321-3347, https://doi.org/10.1007/s10518-015-9800-8

[6] Mazza, F., Mazza, M. (2019): Seismic retrofitting of gravity-loads designed RC framed buildings combining CFRP and hysteretic damped braces, Bulletin of Earthquake Engineering, 17, 3423-3445, https://doi.org/10.1007/s10518-019-00593-5

[7] Ceci, A.M., Contento, A., Fanale, L., Galeota, D., Gattuli, V., Lepidi, M., Potenza, F. (2010): Structural performance of the historic and modern buildings of the University of L'Aquila during the seismic events of April 2009, Engineering Structures, 32 (7), 1899-1924, https://doi.org/10.1016/j.engstruct.2009.12.023

[8] Mimura, N., Yasuhara, K., Kawagoe, S., Yokoki, H., Kazama, S. (2011): Damage from the Great East Japan Earthquake and Tsunami - A quick report, Mitigation and Adaptation Strategies for Global Change, 16, 803-818, https://doi.org/10.1007/s11027-011-9297-7

[9] Wang. D.Y., Wang, Z., Y., Yu, T., Li, H. (2017): Shake table tests of large-scale substandard RC frames retrofitted with CFRP wraps before earthquakes, Journal of Composites for Construction, 21(1), ID. 04016062, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000720

[10] El Khouri, I., Garcia, R., Mihai, P., Budescu, M., Țăranu, N., Toma, I.O., Gudagnini, M., Escolano-Margarit, D., Entuc, I.S., Oprisan, G., Hajirasouliha, I., Pilakoutas, K. (2018): Shake table tests on frames made with normal and FRP-confined rubberised concrete, In: 16th European Conference on Earthquake Engineering (16ECEE), Thessaloniki, Greece.

[11] Rinaldin, G., Fragiacomo, M. (2016): Non-linear simulation of shaking-table tests on 3- and 7-Storey X-Lam timber buildings, Engineering Structures, 113, 133–148, https://doi.org/10.1016/j.engstruct.2016.01.055

[12] Azadi Kakavand, M.R., Neuner, M., Schreter, M., Hofstetter, G. (2018): A 3D continuum FE-model for predicting the nonlinear response and failure modes of RC frames in pushover analyses, Bulletin of Earthquake Engineering, 16 (10), 4893–4917, https://doi.org/10.1007/s10518-018-0388-7

[13] Yenidogan, C., Yokoyama, R., Nagae, T., Tahara, K., Tosauchi, Y., Kajiwara, K., Ghannoum, W. (2018): Shake table test of a full-scale four-story reinforced concrete structure and numerical representation of overall response with modified IMK model, Bulletin of Earthquake Engineering, 16, 2087-2118, https://doi.org/10.1007/s10518-017-0261-0

[14] Malomo, D., Pinho, R., Penna, A. (2020): Numerical modelling of the out-of-plane response of full-scale brick masonry prototypes subjected to incremental dynamic shake-table tests, Engineering Structures, 209, ID. 110298, https://doi.org/10.1016/j.engstruct.2020.110298

[15] Kajiwara, K., Tosauchi, Y., Kang, J.D., Fukuyama, K., Sato, E., Inoue, T., Kabeyasawa, T., Shiohara, H., Nagae, T., Kabeyasawa, T., Fukuyama, H.,Mukai, T. (2021): Shaking-table tests of a full-scale ten-story reinforced-concrete building (FY2015). Phase I: Free-standing system with base sliding and uplifting, Engineering Structures, 233, ID. 111848, https://doi.org/10.1016/j.engstruct.2020.111848

[16] Toma, I.O., Budescu, M., Albu, Gh. (2009): Seismic behaviour of an experimental model made of thin-walled cold formed steel profiles – Hardell structures, Bulletin of the Polytechnic Institute of Jassy. Construction. Architecture Section, LV (1), 67-78.

[17] Konstantinidis, D., Makris, N. (2010): Experimental and analytical studies on the response of 1/4-scale models of freestanding laboratory equipment subjected to strong earthquake shaking, Bulletin of Earthquake Engineering, 8, 1457-1477, https://doi.org/10.1007/s10518-010-9192-8

[18] Gradinariu, I.D., Budescu, M., Hohan, R., Taranu, G. (2012): Seismic behaviour of a hybrid structural system with mineral matrix, Bulletin of the Polytechnic Institute of Jassy. Construction. Architecture Section, LVIII (3), 33-44.

[19] Fediuc, D.O., Budescu, M., Fediuc, V. (2015): Shaking table test of a base isolated structure with multi-stage system, Bulletin of the Polytechnic Institute of Jassy. Construction. Architecture Section, LXI (3), 9-16.

[20] Yang, J., Lu, Z., Li, P. (2020): Large-scale shaking table test on tall buildings with viscous dampers considering pile-soil-structure interaction, Engineering Structures, 220, ID. 110960, https://doi.org/10.1016/j.engstruct.2020.110960

[21] Wang, J., Liu, K., Li, A., Dai, K., Yin, Y., Li, J. (2021): Shaking table test of a 1:10 scale thermal power plant building equipped with passive control systems, Engineering Structures, 232, ID. 111804, https://doi.org/10.1016/j.engstruct.2020.111804

[22] Xia, X., Zhang, X., Wang, J. (2021): Shaking table test of a novel railway bridge pier with replaceable components, Engineering Structures, 232, ID. 111808, https://doi.org/10.1016/j.engstruct.2020.111808

[23] Richard, B., Cherubini, S., Voldoire, F., Charbonnel, P.E., Chaudat, T., Abouri, S., Bonfils, N. (2016): SMART 2013: Experimental and numerical assessment of the dynamic behavior by shaking table tests of an asymmetrical reinforced concrete structure subjected to high intensity ground motions, Engineering Structures, 109, 99-116, http://dx.doi.org/10.1016/j.engstruct.2015.11.029

[24] Di Trapani, F., Bolis, V., Basone, F., Preti, M. (2020): Seismic reliability and loss assessment of RC frame structures with traditional and innovative masonry infills, Engineering Structures, 208, ID. 110306, https://doi.org/10.1016/j.engstruct.2020.110306

[25] Bakalis, A.P., Makarios, T.K. (2021): Seismic enforced-displacement pushover procedure on multistorey R/C buildings, Engineering Structures, 229, ID: 111631, https://doi.org/10.1016/j.engstruct.2020.111631

[26] Plesu, R. (2013): Contributions to rehabilitation techniques applied to unreinforced masonry structures, PhD thesis, The “Gheorghe Asachi” Technical University of Iasi, in Romanian.

[27] Stascov, M., Mihai, P., Venghiac, V.M., Budescu, M., Taranu., N., Scutaru, M.C. (2019): Structural response of a steel structure with dissipative elements under seismic action experimental set-up, Bulletin of the Polytechnic Institute of Jassy. Construction. Architecture Section, 65 (1), 103-110.