Analysis, Testing and Application of the 3D BCS Base Control Isolation System with 3D Viscodampers

Victor Kostarev(✉), Alexander Kultsep, and Petr Vasilyev

CVS (CKTI-Vibroseism) Co. Ltd., Saint Petersburg, Russia
`victor.kostarev@gmail.com`

Abstract. The February 6, 2023 Magnitude 7.8–7.5 earthquake in Turkey has shown and confirm an efficiency of seismic isolation for protection of buildings and structures against seismic motion. However, there is no enough information regarding behavior of the seismic isolated structures and hospitals subjected to the peak ground acceleration over 0.5 g. At the same time recent investigations during Tohoku Earthquake 2011 and at the world's biggest E-Defence 1500 tons shaking table in Japan have demonstrated inconsistent results for conventional isolation systems with an essential seismic amplification in the vertical direction and limited overall efficiency. This contribution presents results of analysis, natural scale testing and application cases of the passive Base Control System (BCS) consists of the spatial (3D) coil spring isolators and separately located 3D viscodampers. According to the performed investigations the BCS is able to provide an optimal stiffness, frequencies and damping close to the optimal values for the current site seismic data and structure's features in the range of 0.5–2.0 Hz in the horizontal direction and 1.5–3.0 Hz in the vertical direction with system's damping over 20%. The efficiency of the BCS system were confirmed by natural scale testing at the unique 3 000 metric tons test rig. A comparative analytical study has confirmed an advantage of the BCS system against other isolation systems providing isolation efficiency in all directions of structures' seismic response.

Keywords: Spatial 3D Base Isolation · Natural Scale Testing · Analysis

1 Experimental Data on BI Behavior Under Severe Earthquakes and Natural Scale Shaking Table Tests

Recent experimental studies on the behavior of the most widely used base or seismic isolation systems (BI/SIS), such as LRB and TPB, during the Tohoku 2011 Great East Japan Earthquake and full-scale tests on the world's largest earthquake shaking table, E-Defence in Japan, have dramatically changed the general understanding of the actual effectiveness of these types of seismic isolation [1, 2].

As an example, Table 1, developed by M.Iiba and T.Saito [1, 2], presents data on the three-component motion recorded in eight buildings with seismic isolation systems of different types during the Tohoku 2011 earthquake.

B. Sadan et al. (Eds.): WCSI 2023, LNCE 533, pp. 240–251, 2024.
https://doi.org/10.1007/978-3-031-66888-3_20

Table 1. Behavior of the BI buildings under Tohoku 2011 Great East Japan Earthquake

	Site	Usage	Structure Type	Floor	Δ (km)	Main isolator and damper	Location of Sensors	ACC. (cm/s^2)			Disp. of SI (cm)
								X	Y	Z	
KA	Sendai	Office	SRC	B2F 9F	172	HRB	under SI above SI top floor	289 121 142	251 144 170	235 374 524	15.7
KB	Fukushima	Office	RC	2F	178	NRB, LRB, OD	under SI above SI top floor	582 176 155	758 213 185	446 516 621	24.6
KC	Fukushima	Office	RC	3F	184	Unknown	under SI above SI top floor	411 184 154	334 226 157	324 463 581	5.8
KD	Tsukuba	Office	PcaPc	7F	334	NRB, LRB, SD	under SI above SI top floor	327 92 126	233 76 91	122 198 243	6.8
KE	Tokyo	Museum	RC	B1F 3F	382	HRB	under SI above SI top floor	100 76 100	79 89 77	84 87 90	4.2
KF	Tokyo	Office	RC	B2F 12F	386	NRB, LRB	under SI above SI top floor	104 55 94	91 41 82	58 62 104	5.1
KG	Kawasaki	Residence	PcaPc	6F	401	NRB, LRB	under SI above SI top floor	86 58 63	104 65 68	34 49 55	5.22
KH	Odawara	Office	RC	6F	457	NRB, LRB	under SI above SI top floor	136 58 63	120 134 67	47 47 48	25.2

The overall conclusion based on building inspections with seismic isolation systems after primary ground motion shocks and aftershocks confirms a sufficient effectiveness in reducing horizontal seismic loads on the structural components, as their integrity was preserved in all cases. However, the vertical component of the seismic ground motion consistently increased by 2–2.5 factor on the upper floors of the buildings, thus the combined action of weakened horizontal and amplified vertical structures' seismic response compromises an overall effectiveness of the observed seismic isolation systems.

Significant complements to the aforementioned field data from the Tohoku 2011 earthquake are the results of shaking table tests on full-scale multi store buildings with different seismic isolation systems conducted at the E-Defense test facility in Japan in the frame of USA and Japan 2010–2017 collaborative test program, K.L. Ryan, et/al, [3–5]. This 3D shaking table with the 1 500 tons capacity allows an actual testing of the seismic resistance and evaluation of a seismic capacity of large-scale structures and components under conditions that reproduce high-intensity multi-component seismic loads. Various types of typical 4-, 5-, and 10-story buildings with different types of seismic isolation systems were tested on the E-Defense shaking table. Despite the practical limitations of the experimental setup (mass and size of the specimen and seismic displacements), a large and valuable experimental data was obtained. The tests also included the simulation of idealized one or two-component seismic horizontal loading before final test with 3D seismic motion, (see Fig. 1).

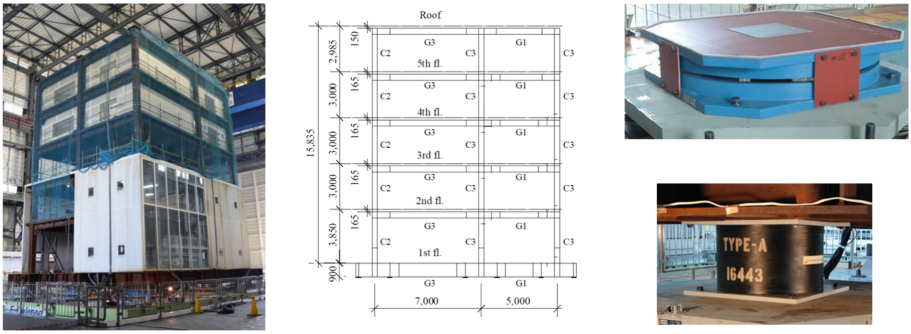

Fig. 1. 5th floors building at the E-Defense shaking table, its dimensions and TPB and LRB isolators subjected to testing, [3–5].

As a result of methodically organized tests, a comparative study of the seismic response of each building mode with and without a seismic isolation system (Rigid mode), revealed several significant deviations towards a substantial deterioration in the performance of all horizontal isolation systems (TPB and modified LRB/CLB) compared to the design specifications when subjected to strong or even moderate vertical seismic components in the shaking table input. The isolation effect under 3D excitation was dramatically reduced even in horizontal plane, while the vertical response of the structure increased significantly, (see Fig. 2).

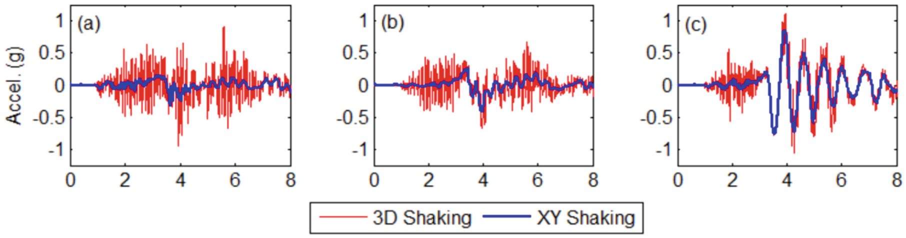

Fig. 2. Horizontal seismic response (Y) of the 5th floor of the structure under horizontal X.Y (2D) excitation (blue lines) and X, Y, Z (3D) excitation (red lines). a) TPB; b) LRB/CLB; c) Fixed (Rigid) base configurations, [3–5].

Overall, the materials of surveys and analysis of seismic resistance of buildings and structures with BI subjected to real earthquakes, as well as the data from full-scale testing of buildings with BI on the E-Defense seismic platform indicate objectively existing limitations on the effectiveness of "horizontal" types BI subjected to real three-component earthquake excitation. These limitations and peculiarities of behavior of horizontal seismic isolation, regardless of the type of isolating supports, were neglected for years before and should be definitely considered in future BI designs.

The question arises: what causes such a significant discrepancy between analytical and experimental results in evaluating the effectiveness of BI? The answer lies in the widespread use of simplified approaches for seismic analysis of BI, even at the level of construction standards, codes and recommendations, including national and international standards. The routine approach typically involves:

- considering only one horizontal or, at most, two horizontal components of an earthquake excitation;
- ignoring the vertical component of seismic excitation;
- neglecting the real vertical structural stiffness of the seismic isolation elements;
- simplified assessment of soil conditions and SSI;
- not considering the coupling between vertical and horizontal characteristics of the seismic isolation elements.

As a result, the essential effects that tune the isolated structure to the dominant vertical frequencies of seismic ground motion and thus reduce the actual effectiveness of the BI are not considered in the analysis provide idealized positive and sometime wrong picture of horizontal BI systems behavior and efficiency.

The way out of this situation is the development of a multi-component 3D BI that would be effective during real earthquakes, without increasing the vertical response of the structure and thereby restoring confidence in the application of seismic isolation systems, which has been compromised by the experience of past earthquakes and the results of full-scale shaking table testing of horizontal types of seismic isolation.

2 BCS Seismic Base Isolation System

According to our knowledge among all of the existing spatial passive 3D developments of isolation devices, the most effective and reliable system seems to be the Base Control System (BCS): seismic displacements control of structures, [6–8].

The BCS consists from separately installed 3D helical spring units and 3D viscous dampers provides to the isolated structure necessary BI flexibility in horizontal directions and amortization in the vertical direction with a close to the optimal BI damping reduces umbilical effects to an appropriate relatively small range, (see Fig. 3).

In Table 2 are shown typical properties of the BCS isolation system provide the most efficient seismic isolation for structures in all spatial directions. Specific parameters of the BCS should be chosen considering peculiarities of input seismic motion, soil conditions, SSI effects and dynamic properties of the structure to be seismically isolated.

Comprehensive full-scale experimental studies of spring supports and 3D dampers have allowed for the development of refined non-linear analytical models of the BCS system, which have been used for the analysis of many structures, (see Fig. 4).

Fig. 3. BCS high capacities spring unit and 3D damper installed between sub and superstructure (left). Installation of the BCS spring units for isolation of multistore building (right).

Table 2. Typical properties (range) of the BCS seismic isolation system

Typical BCS Characteristics	Parameter	Comment
Conditional BCS Structure's Vertical Frequency [Hz]	1.5 – 3.0	Provides mitigation of structures' seismic response in vertical direction
Conditional BCS Structure's Horizontal Frequency [Hz]	0.5 – 2.0	Very efficient reduction of seismic demands in horizontal direction
Damping Ratio [%]	> 10/20	Upgrading of isolation and dramatic mitigation of umbilical displacements

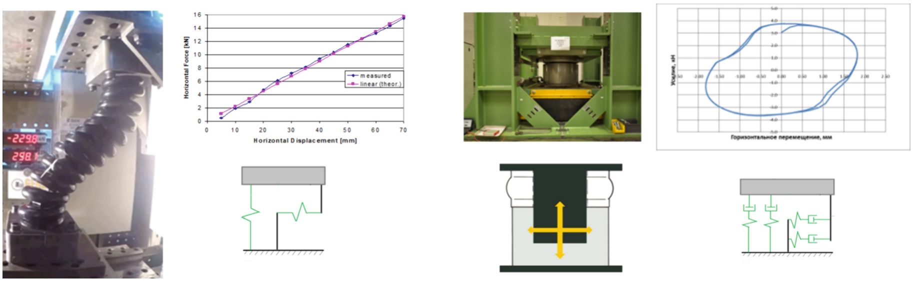

Fig. 4. BCS testing and non-linear analytical models of spring unit (left) and 3D damper (right).

3 BI Systems Comparative Study

Analytical studies have been conducted on the behavior of typical nuclear power plant reactor buildings with various types of seismic isolation devices under intense seismic excitation, [9–11], (see Fig. 5).

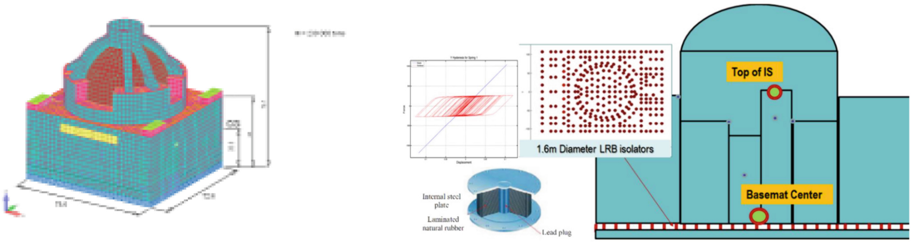

Fig. 5. NPPs' reactor buildings subjected to comparative BI study, [9–11].

The Fig. 6 shows the analysis results of the very massive NPP VVER-1200 Reactor Building with a height over 60 m, installed on the BCS system, for a seismic ground motion with PGA 0.4g, [12]. The spectra of the seismic response of the structure for the horizontal and vertical directions (Y, Z) are given for an elevation equal to about half the height of the building. The upper curves refer to the variant of the rigidly supported building and all other curves to the BCS with different damping.

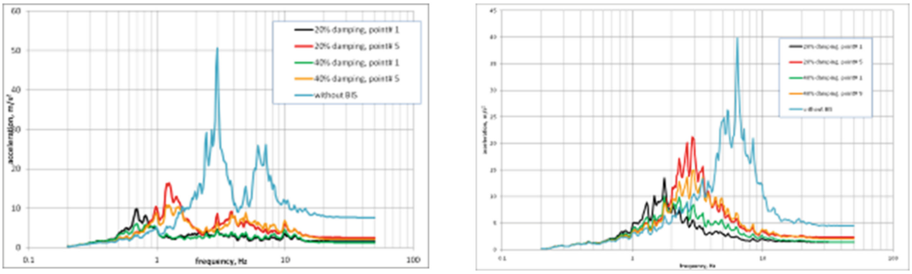

Fig. 6. In-Structure Response Spectra for horizontal (left) and vertical (right) directions with different range of SIS system's damping (20–40%)

Obviously, the use of BCS allows not only to provide good isolation parameters in the horizontal plane, but also to reduce the amplification of the seismic response of the building in the vertical direction, which is not achievable for the most common types of seismic isolation.

This effect was also confirmed by independent researchers who conducted comparative analyzes of the effectiveness of different types of seismic isolation LRB, TPB and BCS for the same type of structures and for the same seismic conditions, performed in accordance with ASCE requirements, [9–11].

As an example, Fig. 6 presents the results of a probabilistic comparative study of the LRB and BCS seismic isolation systems effectiveness, considering the coherence and incoherence of the seismic impact and the influence of soil conditions for the NPP reactor building, shown in Fig. 5 (right), [9].

The results presented show that the BCS system is better than LRB in terms of efficiency not only in the vertical direction, as proven by previous studies, but also in the horizontal direction, providing significantly better overall seismic isolation of the

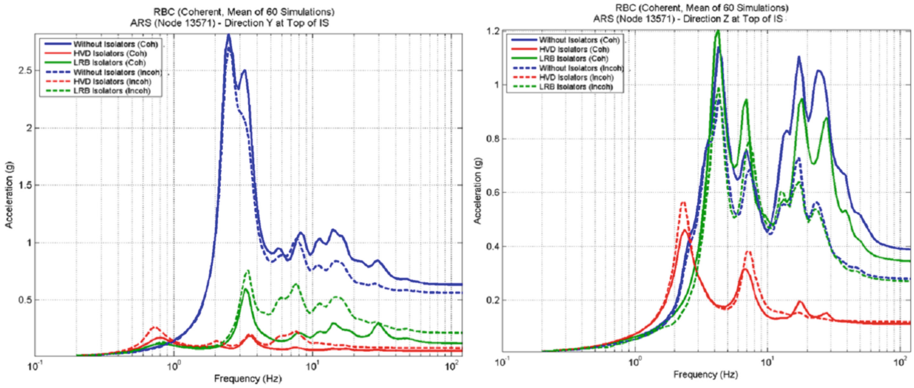

Fig. 7. In-Structure Response Spectra (coherent) for horizontal Y direction (left) and vertical Z direction (right). Without BI (blue curves), LRB (green), BCS (red), [9].

building. This positive result is achieved due to the high damping in the BCS system Fig. 7.

Another proof of the BCS effectiveness was performed by LRB, TPB, BCS comparative analysis of a typical industrial building, (see Fig. 8). Two types of seismic analysis with PGA 0.4g of this building were performed - deterministic with a rock soil property and probabilistic, considering the medium soil conditions and the incoherence of the seismic motion.

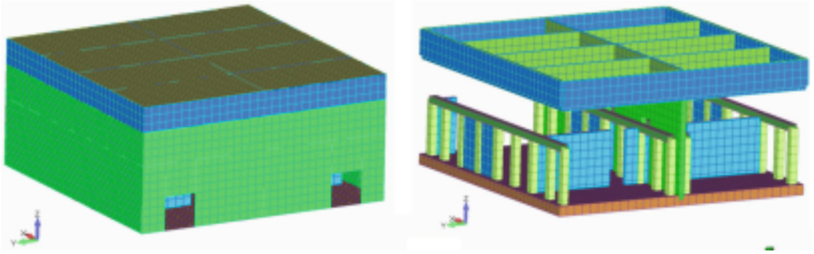

Fig. 8. Industrial building for the comparative seismic analysis without BI and with three types of BI (LRB, TPB and BCS).

In the Fig. 9 are shown the results of a deterministic analysis of a building located at a rock site with rigid anchoring (Rigid) without isolation and with three cases of seismic isolation systems as LRB, TPB and BCS. It should be noted that analytical models for isolators were developed on the basis of available test data of these devices. On the left are the In-Structure Response Spectra for the horizontal Y direction, and on the right for the vertical Z direction, [11].

In this study, BCS demonstrated the best seismic isolation performance in both horizontal and vertical directions. Noteworthy is the large amplification of the vertical response for the LRB and TPB systems compared to the "Rigid" case. This analytical result confirms the data of field experimental studies discussed above, [1, 2].

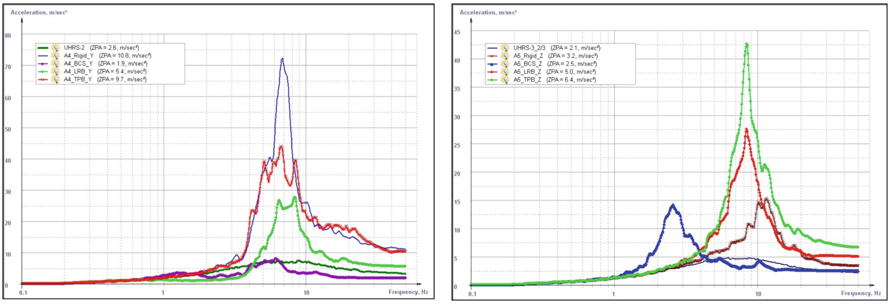

Fig. 9. Comparison of In-Structure Response Spectra for 4 cases of structure placed at the rock site. Left picture horizontal Y direction: Blue curve without BI, Red TPB, Green LRB. Purple BCS, Dark green UHRS. Right picture vertical Z direction: Green TPB, Red LRB, Brown without BI, Blue BCS, Black UHRS.

The results of a comparative study of the seismic response of the same industrial building (Fig. 8) placed at the average soil conditions in deterministic and probabilistic formulations are presented in the Fig. 10, [11]. Four cases of building support were under investigation: Rigid support (without BI) and BI with LRB, BCS and TPB. An improved non-linear analytical model for the LRB system was used. The Y and Z spectra in the Fig. 10 are built for the top elevation of the building.

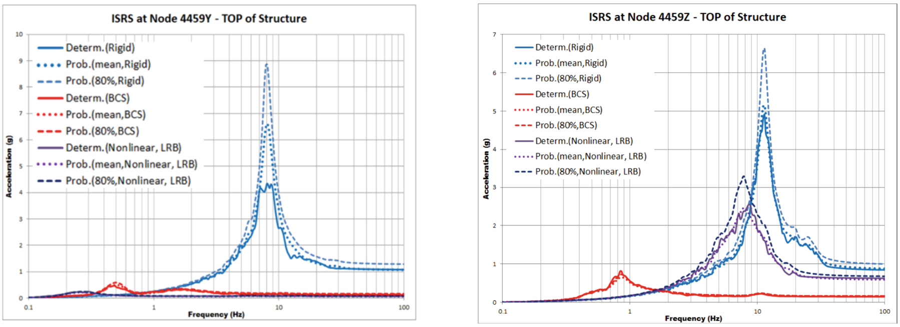

Fig. 10. Comparison of deterministic and probabilistic In-Structure Response Spectra for rigid base structure without BI and with BI. Blue curves Rigid, Purple LRB, Red BCS.

The analysis performed showed approximately the same efficiency of the LRB and BCS systems for the horizontal Y direction and higher efficiency of the BCS isolation system for the Z direction, as in all previous studies mentioned above.

4 BI Natural Scale Testing

It should be noted that the improved analytical model of the BCS system was developed and confirmed on the basis of full-scale tests carried out on a number of test rigs in a spatial 3D approach, (see Fig. 4). Beside individual BI components testing the BCS system was subjected for testing at a special inverse test rig SIST developed and erected in Saint-Petersburg, Russia for testing natural scale isolators and dampers.

SIST inverse approach means that the substructure is not shaking like in shaking table approach but the superstructure is shaking at its natural frequencies providing BI elements with a full scope of loads equal to a full gravity and dynamics of superstructure and their deformations correspond to a very severe earthquake. SIST superstructure has variable mass from 400 t to 3000 t, mounted on four to eight experimental test BI specimens (isolators, dampers, snubbers, etc.). SIST hyudraulic system has pushing capacity over 1100 tons with a fast release system and displacements range over 300 mm, (see Fig. 11).

Fig. 11. Upper row: BCS natural scale testing at the Inverse SIST test rig. General View with the variable Superstructure 2 000 tons (left). 3D BCS system with spring units and 3D Viscodamper (middle). Spring Unit under Beyond Design Earthquake Loading (right). Lower row: LRB natural scale testing at the Inverse SIST test rig. General View with the variable Superstructure 400 tons (left). LRBs under full dead weight loading (middle). LRB under seismic displacements (right).

At the SIST it is possible to test any types of seismic isolators, snubbers and dampers subjected to a full dead load capacity and real seismic displacements by shaking the superstructure at its natural frequencies and modes of vibration, (see Figs. 11 and 12).

5 BCS Efficiency. Confirmation Under Real Earthquake

The efficiency of the BCS was confirmed by its behavior under real earthquake with PGA 0.12g when two similar buildings in Mendoza University, Argentina, one with BCS and the other without BCS (rigid based), were subjected to the seismic motion (Stuardi 2008), [13]. The views of the buildings tested by earthquake and the location of spring units and VD dampers are shown in Fig. 13.

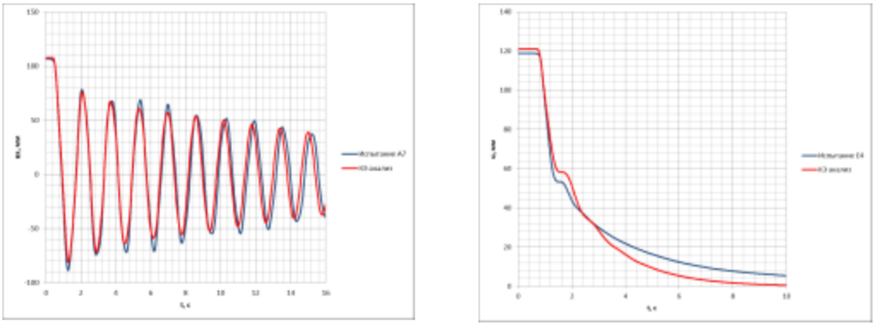

Fig. 12. BCS SIST test without and with dampers. Low system's damping of spring units (left). High BCS damping over critical value for the main modes of vibration with dampers (right).

Fig. 13. Two similar structures subjected to earthquake. Isolated by BCS and non-isolated rigid based buildings (left) and location of spring units and viscodampers in the space between sub structure and super structure of the BCS isolated building (right)

The buildings were equiped with acceleration sensors and gauges to perform strain and stress comparative measurements in the structures. Figure 8 shows the time histories of accelerations at the top of these two buildings subjected to the earthquake 5.7 magnitude (Fig. 14).

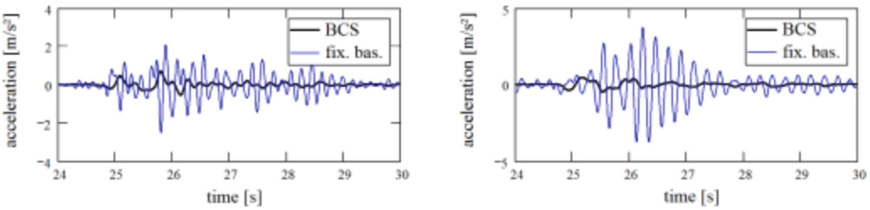

Fig. 14. Accelerations at the top of two buildings, BCS isolated and non-isolated, subjected to the earthquake in the X (left) and Y (right) directions

The measurement performed for the isolated (i) and non-isolated (ni) buildings have shown that the distortion in spring elements and viscodampers are very small (around

3.0 mm). At the same time, it was observed that there is a constant acceleration distribution along the isolated building height. Comparative acceleration measurements at the roofs of non-isolated (ni) and isolated (i) buildings and observation of the buildings state after earthquake have shown the following relative parameters:

- Acceleration along X, Y and Z axes: Xni/i = 0.25/0.05g; Yni/i = 0.4/0.06g; Zni/i = 0.06/0.07g. Roof 3D acceleration reduction achieved is more than 75%.
- In the vertical direction an amplification of accelerations was not observed in spite of non-optimal parameters of the spring units stiffness and damping that could be simply upgraded.
- No structural damage was observed in both buildings.
- Comparative behavior of the (ni) and (i) similar structures in % according to performed measurements during earthquake:

Axial forces reduction: $>$ 60%. Shear force reduction: $>$ 75%. Bend Moment reduction: $>$ 90%. Story Drift reduction: $>$ 80%.

Thus, the BCS has demonstrated its outstanding isolation capability with very limited relative (umbilical) displacements of super and substructures under real earthquake conditions confirming pioneer's IHI shaking table test results performed in Japan in late 80's last century, Y. Ochi, et al., 1990, [15, 15].

6 Conclusions

1. Both deterministic structural analysis and probabilistic safety assessment have shown that the BCS base isolation approach based on using of the 3D coil spring isolators and 3D viscodampers is feasible and highly efficient providing 3D spatial seismic isolation.
2. The effectiveness of the BCS was confirmed by comprehensive natural scale tests and BCS behavior under real earthquake.

References

1. Iiba, M., et al.: Behavior of seismically isolated buildings based on observed motion records during the 2011 great East Japan earthquake. In: Proceedings of the 13th WCSI Sendai (Japan), pp. 24–27 (2013).
2. Saito, T.: Behavior of response controlled and seismically isolated buildings during severe earthquakes in Japan, Energia, Ambiente e Innovazione (2015). https://doi.org/10.12910/EAI2015-078.
3. Ryan, K.L., et al.: NEES/E-defense base-isolation tests: interaction of horizontal and vertical response. In: Proceedings of 15 WCCE, Lisboa (2012)
4. Furukawa, S., et al.: Comparison of vertical dynamic response characteristics of two base-isolated buildings based on full-scale shaking table test. In: Proceedings of 15WCEE, Lisbon, Portugal (2012)
5. Sasaki, T., et al. : NEES/E-Defense base-isolation tests: effectiveness of friction pendulum and lead-rubber bearings systems. In: Proceedings of the 15 WCEE Conference Lisboa (Portugal) (2012)

6. Nawrotzki, P., et al.: 3-D Base control systems for the seismic protection of structures. In: Proceedings of the 16WCSI World Conference on Seismic Isolation, 1–6 July 2019, Saint Petersburg, Russia (2019)
7. Sollogoub, P.: Editor in Chief (2020), Seismic Isolation Systems for Nuclear Installations. International Atomic Energy Agency (IAEA). Technical Report 1905, Vienna, Austria
8. Siepe, D., Nawrotzki, P.: Horizontal and vertical isolation of seismic and aircraft impact. In: Proceedings of the 14th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures, 9–11 September 2015, San Diego, USA (2015)
9. Nawrotzki, P., et al.: 3D seismic isolation systems for the nuclear industry layout, design & qualification, Transactions, SMiRT-26 Berlin/Potsdam, Germany, July 10–15, 2022 Division V (2022)
10. Ghiocel, D.M.: Probabilistic seismic SSI analysis sensitivity studies for base-isolated nuclear structures subjected to coherent and incoherent motions. In: the SMiRT25 Conference Proceedings, Division III, Charlotte, NC, August 4–9 (2019)
11. Kultsep, A., et al.: Numerical simulation of non-linear effects in seismic isolation systems. LRB, TPB and BCS BI systems comparative study. Transactions, SMiRT 26, 10 – 15 July 2022, Berlin/Potsdam, Germany Special Session: Seismic Isolation (2022)
12. Dan, M. Ghiocel., et al.: A study on seismic SSI analysis of a base-isolated storage structure founded on firm soil. Transactions, SMiRT 26, 10–15 July 2022, Berlin/Potsdam, Germany Special Session: Seismic Isolation (2022)
13. Vasilyev, P.: Methods for calculation of the reactor building with seismic isolation system under dynamic loads, Transactions, SMiRT-22, San Francisco, USA (2013).
14. Stuardi, J., et al.: Comparative seismic performance of a base control system based on measured and calculated responses. In: Proceedings of 14WCEE, Beijing, China (2008)
15. Ochi, Y., et al.: Application of high viscous damper on piping system and isolation floor system. In: Proceedings of the 9th European Conference on Earthquake Engineering, Moscow (1990)
16. Belyaev, V., et al.: Modern methods of seismic protection of structures considering the spatial nature of seismic impact. J. Nat. Man-made Hazards. Safety of Structures. **4** (65), (2023) Moscow ISSN 2221–5638