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E-ISOLATION : DYNAMIC TESTING FACILITY WITH HIGH-PERFORMANCE FORCE MEASUREMENT SYSTEM

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Abstract: *The dynamic characteristics of seismically isolated bearings are highly dependent on the size effect and rate-of-loading, especially under extreme loading conditions. Therefore, confirming the actual properties and performance of these bearings with full-scale specimens under prescribed dynamic loading protocols is essential. The number of large dynamic testing facilities is still limited and even though the existing falicities in the US, China, Taiwan, Italy, etc. are conducting these tests, the acquired reaction force at their dynamic loading tests are contaminated by friction generated by the large vertical loads and inertial force of the heavy moving platen. To solve this problem, the authors have proposed a high-performance reaction force measurement system that can eliminate the effects of friction and inertia forces even under large vertical load and high-speeds, and a seismic isolation testing facility with the proposed system (E-Isolation) has been completed on March 2023 in Japan. This test facility is designed to conduct not only dynamic loading tests of seismic isolation bearings and dampers but also to perform hybrid simulations of seismically isolated structures. In this paper, design details and the realization of this system into an actual dynamic testing facility are presented and the outcomes are discussed.*

1 Background

Since around 1970, seismic isolation and vibration-controlled structures have been developed and widely implemented to minimize or eliminate damage to the main structural frame during earthquakes. These innovative methods do not dissipate energy during an earthquake by plasticizing structural members, such as columns and beams, but instead by using seismic isolators and energy-dissipating dampers. Seismic isolators and dampers are essential components that determine the seismic response of a structure. Test methods for evaluating the performance of seismic isolation bearings are outlined in both ISO and JIS standards. Specifically, horizontal performance evaluation tests necessitate that the seismic isolation rubber bearing is repeatedly forced to deform to a specified shear strain while under constant vertical pressure. While it is preferable to test seismic isolation bearings at their full-scale and actual velocities, reduced models and static loading are often employed due to the limitation of the capacity of testing equipment. However, static tests using scaled-down specimens can produce results different from full-scale dynamic tests. Among the standard rubber laminates used for seismic isolation bearings, natural rubber bearings (NRB) exhibit a relatively linear load-displacement relationship. In contrast, lead-plugged laminated rubber bearings (LRB) and high-damping rubber bearings (HDRB) with enhanced damping capabilities exhibit more complex behaviors. Additionally, the size of the specimen notably influences the performance of these bearings. Ensuring the stable performance of larger rubber bearings, especially those with diameters exceeding 1 meter, is more challenging than their reduced-size ones. This is primarily because, during the manufacturing process of seismic isolation laminated rubber, achieving a flawless bond over the entire surface of a full-size rubber bearing is more intricate. Additionally, it is recognized that the energy dissipation capacity of seismic isolation bearings can be readily impacted by the heat generated from the lead-plug or high-damping rubber. Therefore, it is crucial to verify the behavior of seismic isolation bearings using a dynamic testing machine with a full-scale specimen.

Seismic isolation bearings, utilized in large structures such as high-rise buildings and long-span bridges, sometimes support vertical loads exceeding 3,000 tons in a single unit. As these seismic isolation structures increase in size, Extrapolating full-scale dynamic results from reduced or static test results reduces reliability. Thus, there has been an increasing demand to verify the performance of seismic isolation bearings via full-scale dynamic testing. Figure 1 shows the typical components of dynamic testing machine, including the Seismic Response Modification Device (SRMD) testing facility (Benzoni et al. 1998) at The University of California, San Diego. The moving platen, which induces a shear force on the test specimen, is dynamically moved in the horizontal direction while subjected to large vertical loads. However, the inertial force of the moving platen and the frictional force due to the large vertical loads are mixed into the measured reaction force from the load cell of the horizontal dynamic jacks. It is not easy to extract accurate reaction force of test specimens in real time because the friction forces in the measured force vary depending on the pressure, velocity, and temperature.

To solve these problems, the authors proposed a high-performance reaction force measurement system that can eliminate the effects of friction and inertia forces, and a seismic isolation test facility (E-isolation) equipped with the proposed system was completed in Japan in March 2023. The purpose of this test facility is not only to perform dynamic loading tests of seismic isolation bearings and dampers but also to perform hybrid simulations of seismic isolation structures. This paper presents the design details of this system and its realization in an actual dynamic test facility and discusses the results.

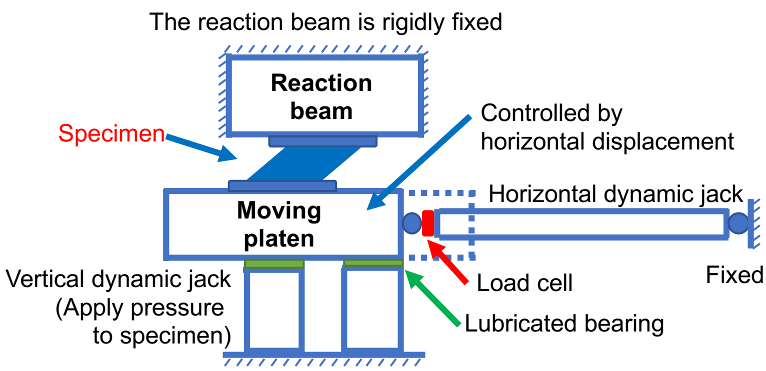

Figure 1. Typical components and conventional force measurement system in dynamic testing machine.

2 Technical issues in dynamic testing machines under large vertical loads

Most seismic isolators utilized in civil and architectural structures are designed to support extremely large vertical loads. While there is a desire to conduct dynamic loading tests with large deformations at high speeds under these conditions, conventional techniques often have problems, especially with accurate measurements. To achieve horizontal deformation of a specimen under a vertical load, several external forces (Figure 2) must be applied. Consequently, the moving platen, on which the test specimen is mounted, is subjected to the following forces (Figure 2):

- Vertical loads applied by vertical jacks (in the vertical direction)
- Self-weight of the moving platen itself (in the vertical direction)
- Friction force between the moving platen and the vertical jacks (in the horizontal direction)
- Inertia force from the moving platen during high-speed horizontal vibrations (in the horizontal direction)

- Shear force due to the deformation of the specimen (in the horizontal direction)
  *This is the primary measurement target.
- Bending moment at the base of the specimen

Specifically, the friction force, influenced by velocity and vertical loads, acts horizontally. It is challenging to remove this force from the measured horizontal reaction force. In large dynamic testing facilities, the friction force is measured by tests in the absence of a test specimen, and remove the effect of the friction force from the measured reaction force after the tests. However, the detailed methodology for modeling these frictional characteristics has not been disclosed to the public. Furthermore, in full-scale tests, the size of the moving platen needs to be increased, leading to a correspondingly greater inertia force. Consequently, load cells of the horizontal dynamic jacks that drive the moving platen are unable to measure the shear force of the specimen in real-time, presenting a considerable technical issue.

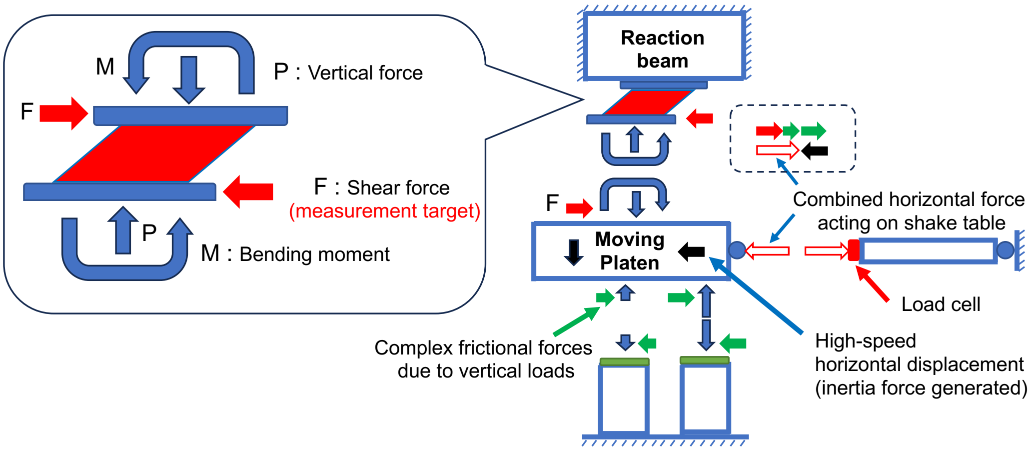

Figure 2. Force acting on moving platen by horizontally deformed seismic isolation bearing.

3 Proposed reaction force measurement system under large vertical loads

This paper proposed a new horizontal reaction force measurement system. In the proposed system, the load cell of the horizontal dynamic jacks is used solely to control the moving platen. The horizontal reaction force of the specimen is measured by a new force measurement system (V-shaped measurement link) attached to the strong reaction beam on the side opposite the moving platen, as illustrated in Figure 3 (right). This system enables the direct measurement of horizontal reaction force of the specimen, excluding inertial and frictional forces. While similar measurement mechanisms have been employed in past experiments with non-significant large vertical loads (Kasai *et al.* (2005)), the primary objective of our development is to realize this horizontal reaction force measurement system under immense vertical loads exceeding 10,000 tons.

In this study, a new reaction beam support was proposed (Figure 3, left). This support incorporates laminated rubber bearings, which exhibits high linearity even under small deformation, positioned between the reaction beam and a rigid concrete structure and tightened by PC strands. Approximately 99% of the specimen's shear force can be measured directly by the load cells of the V-shaped measurement link, while the remaining 1% was intended to be supported by the reaction beam support. The load carried by this support can be calculated by measuring the horizontal displacement of the laminated rubber bearings. The system's accuracy was validated through pilot tests using small-scaled system at Tokyo Institute of Technology (Takeuchi *et al.* (2023)). Following this, a testing machine capable of bearing a vertical load of 3,000 tons was constructed with the proposed reaction beam support mechanism integrated into it.

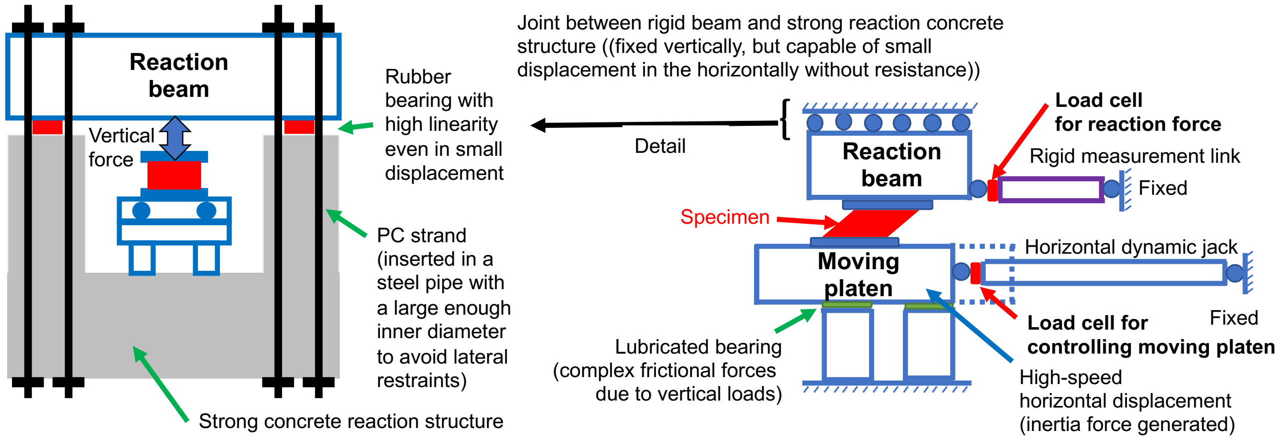

Figure 3. Reaction force measurement system (measurement link and reaction beam support).

4 E-Isolation

E-isolation (Figure 4) is capable of uniaxial dynamic excitation with a maximum vertical load of 3,000 tons (dynamic), a maximum horizontal displacement of ±1.2 m, and a velocity of up to 0.8 m/s. One of its most distinguishing features is the integration of a high-performance force measurement system (Figure 5), which was developed in this study. This system employs a V-shaped measurement link mounted on the reaction beam to directly measure the specimen's reaction force in real-time, unaffected by frictional or inertial forces generated on the moving platen.

To validate the high-performance force measurement system, a test specimen was subjected to a load of up to 100 tons. The measured values from the load cell directly attached to the specimen were then compared with those from the V-shaped measurement link. The results indicated that the two measurements were in extremely close agreement. Furthermore, it was confirmed that at the 100-ton loading level, the force exerted on the reaction beam support was minimal, rendering it almost negligible (Takahashi *et al.* (2023)).

Moreover, to evaluate the system's performance under the maximum vertical load (dynamic) of 3,000 tons, a full-sized laminated rubber bearing with a shear modulus of 0.29 MPa and 1200 mm in diameter was installed. The dynamic cyclic loading tests were then conducted in the horizontal direction. Figure 6 shows an example of these results. This figure reveals that the force measured by a load cell of the horizontal dynamic jacks, similar to those in conventional testing machines, exhibited a bilinear hysteresis loop due to frictional effects. In addition, this hysteresis loop oscillated because of the inertial forces by the moving platen. However, our newly developed high-performance force measurement system effectively removed the contaminations of friction and inertia, and accurately measured forces on the specimen.

The proposed high-performance force measurement system can effectively remove frictional and inertial forces, even in tests involving extremely large vertical loads. Being able to determine the accurate horizontal force of a specimen in real-time means that accurate results can be immediately available right after tests. When testing machine is employed for product inspections, products can be dispatched right after tests with precise data. This process not only shortens the construction period but also offers societal benefits and significant advantages in industrial applications. Furthermore, E-Isolation can conduct real-time hybrid simulations where force testing and numerical analysis are concurrently integrated. The subsequent chapter provides an example of such a real-time hybrid simulation utilizing E-Isolation.

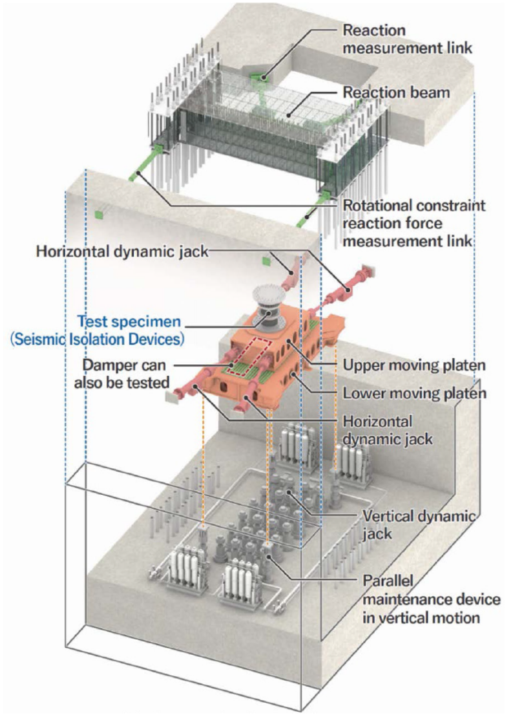

Figure 4. Configuration of E-Isolation.

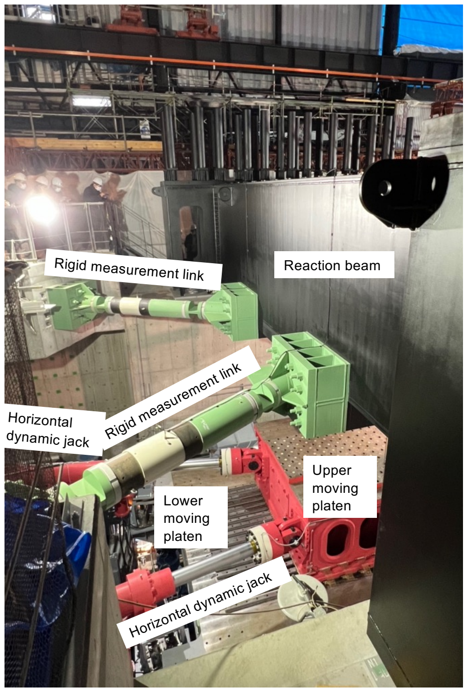

Figure 5. High-performance force measurement system in E-Isolation.

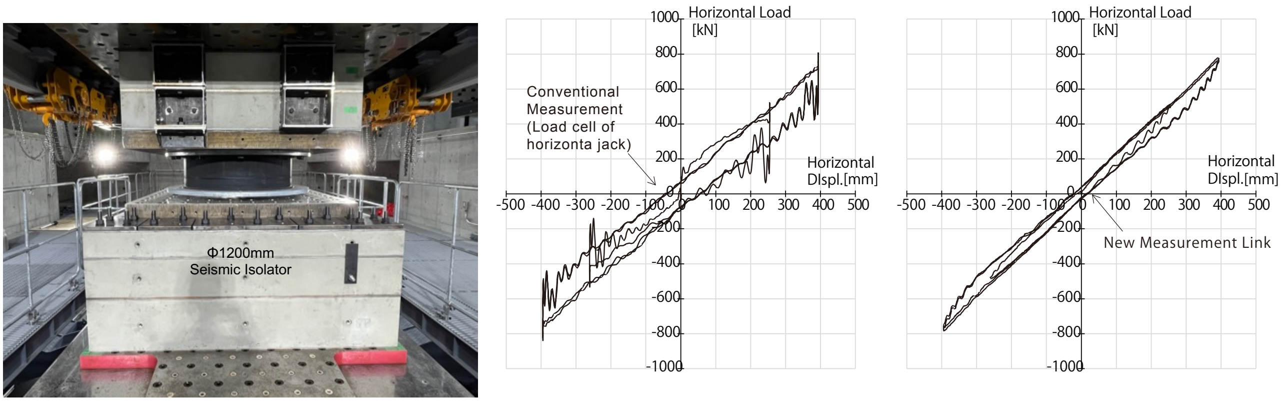

Figure 6. Force – displacement hysteresis loops of seismic isolator (vertical load 16929kN, 2.5Hz sine loading).

5 Hybrid simulation

The hybrid simulation (Hakuno et al., 1969, Nakashima et al., 2020) was proposed in Japan and is now widely used in the world to simulate the seismic response of large-scale structures. It is an experimental method that is used to deform a structural specimen as if it were responding to an earthquake ground motion using an online computer-controlled simulation of dynamic response. In hybrid simulation, one member or part of a structural system is built experimentally while the remaining parts are modeled using a computational model and the equation of motion for the structural system is solved by time integration schemes. The restoring force characteristics of the experimental part are obtained by data acquisition from the force sensor of the physical test run in parallel to the analysis. Since E-Isolation has the high-performance force measurement system eliminating the effects of friction and inertia forces, the precision of hybrid simulation can be substantially improved. The servo-controller in this facility has a hybrid simulation mode to communicate with computational kernels (ex. OpenSees) in real-time by OpenFresco (Takahashi *et al.*, (2006), Schellenberg *et al.* (2009)), which provides a high-speed, low latency data communication between the servo-controller and the analytical computer by reflective memory (GE Intelligent Platforms 5565PIORC product family).

Pseudo-dynamic simulations and real-time hybrid simulations were conducted. For the pseudo-dynamic hybrid simulation, results were compared between the cases: one using measurements from the load cell on the dynamic jack and the other using measurements from a high-performance force measurement system. The test specimen used in the pseudo-dynamic simulation was an 800 mm-diameter laminated natural rubber bearing. The test specimen for the real-time hybrid simulation was a 1200 mm-diameter laminated natural rubber bearing. An actual two-story seismically isolated building, as shown in Figure 7, was assumed as the model building for the hybrid simulations. The numerical model employed was a shear spring model with three masses, also illustrated in Figure 7; its parameters can be found in the same figure. The building was supported by 20 bearings of 800 mm-diameter, or by 10 bearings of 1200 mm-diameter. In the hybrid simulations, only one bearing was tested at E-Isolation, and the number of bearings was multiplied against the measured reaction force for the simulation. Since the hysteresis of the bearings are almost linear, hybrid simulations and pure numerical analysis can be compared with high accuracy.

The results of the pseudo-dynamic simulation are shown in Figure 8. Figure 8 reveals that the results using the load cell of the horizontal dynamic jacks differ significantly from the pure numerical analysis results due to the frictional forces mixed into the measured reaction forces. Conversely, the results using the high-performance force measurement system align closely with the results of the analysis. The real-time hybrid simulation also calculated the accurate response of the building (Figure 9).

Therefore, the high-performance force measurement system of E-isolation allows for real-time accurate measurements of forces on the test specimen. This capability facilitates the evaluation of the entire structure's dynamic response through hybrid simulation.

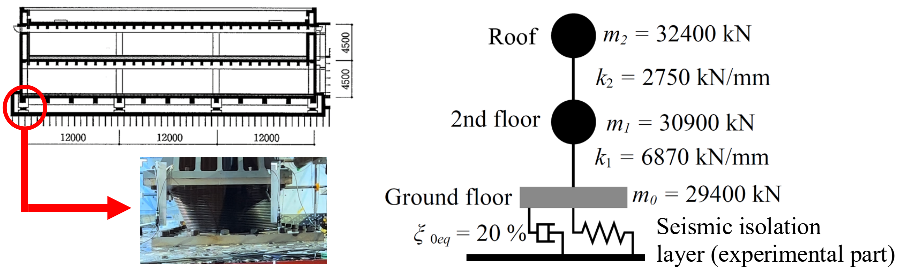

Figure 7. The objective 2-story building and numerical model.

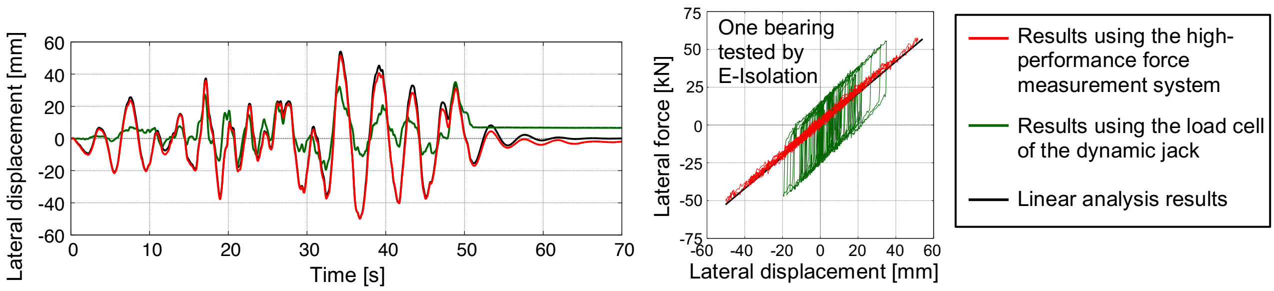

Figure 8. Results of the pseudo-dynamic simulation using 800mm-diameter seismic isolator.

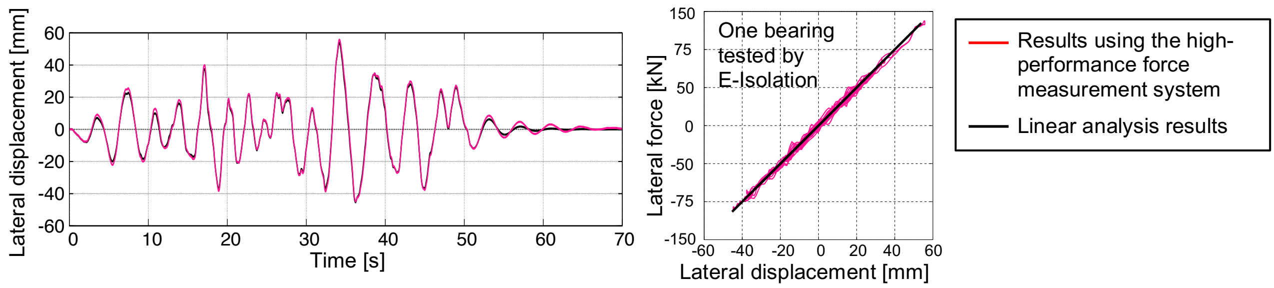

Figure 9. Results of the real-time hybrid simulation using 1200mm-diameter seismic isolator.

6 Conclusions

Full operation of E-Isolation began in June 2023, marking the beginning of the accumulation of high-quality data on the dynamic behavior of full-scale seismic isolation bearings and energy-dissipating dampers. With this development, Japan is now on par with nations like the United States, China, and Taiwan, which have pioneered the development of full-scale seismic isolation testing machines. Furthermore, we believe that Japan has been able to stay one step ahead of other countries through innovations in measurement technology.

E-isolation, serving as a third-party organization, will certify the performance of commercial seismic isolations and vibration control components. The certification is expected to assist Japan in not only preserving but also enhancing its position in the field of seismic isolation and vibration control technologies. In addition, if the world's largest three-dimensional shaking table, E-Defense, were paired with E-Isolation (to be located adjacent to E-Defense) and complemented by a supercomputer, such a comprehensive setup would be expected to bolster forefront role in earthquake engineering education and research in the world.

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8 References

Takahashi Y., Takeuchi T., Kishiki S., Yoneda M., Wada A. (2023) E-Isolation–High-performance dynamic testing installation for seismic isolation bearings and damping devices, *International Journal of High-rise buildings*, 12(1), 1-13.

Takeuchi T, Takahashi Y., Umemura Y., Terazawa Y., Uemura K., Ueda T. (2023): Scaled dynamic loading tests on seismic isolation bearing excluding the contamination of friction and inertia forces, *Engineering Structures*, (296), 116844.

Benzoni, G., Seible, F. (1998). Design of the Caltrans seismic response modification device (SRMD) test facility, Research co-ordination meeting of the IAEA's co-ordinated research programme on intercomparison of analysis methods for seismically isolated nuclear structures, pp. 101-115.

Kasai, K., Sakata, H., Komehana, S., Miyashita, Y. (2004). Experimental study on dynamic behavior of timber frame with viscoelastic damper (in Japanese), *Journal of Structural Engineering (AIJ)*, 50B, pp. 349-360.

Hakuno, M., Shidawara, M., Hara, T. (1969). Dynamic destructive test of a cantilever beam controlled by an analog computer (in Japanese). *Journal of JSCE*, No.171, pp.1-9.

Nakashima, M. (2020). Hybrid simulation: An early history, *Earthquake Engineering and Structural Dynamics*, Vol. 49, pp. 949-962.

Takahashi, Y., and Fenves, G.L. (2006). Software framework for distributed experimental-computational simulation of structural systems, *Earthquake Engineering and Structural Dynamics*, Vol. 35, pp. 267-291.

Schellenberg, A., Kim, H. K., Takahashi, Y., Fenves, G. L., Stephen A. Mahin, S. A. (2009), OpenFresco Command LanguageManual (Ver.2.6), <available at https://openfresco.berkeley.edu/>.