Council on Tall Buildings and Urban Habitat Korea
International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

International Journal of High-Rise Buildings
March 2023, Vol 12, No 1, 93-105
https://doi.org/10.21022/IJHRB.2023.12.1.93

E-Isolation : High-performance Dynamic Testing Installation for Seismic Isolation Bearings and Damping Devices

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Abstract Seismic isolation and vibration control techniques have been developed and put into practical use by challenging researchers and engineers worldwide since the latter half of the 20th century, and after more than 40 years, they are now used in thousands of buildings, private residences, highways in many seismic areas in the world. Seismic isolation and vibration control structures can keep the structures undamaged even in a major earthquake and realize continuous occupancy. This performance has come to be recognized not only by engineers but also by ordinary people, becoming indispensable for the formation of a resilient society. However, the dynamic characteristics of seismically isolated bearings, the key elements, 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 testing facilities with such capacity is still limited and even though the existing labs in the US, China, Taiwan, Italy, etc. are conducting these tests, their dynamic loading test setups are subjected to friction generated by the large vertical loads and inertial force of the heavy table which affect the accuracy of measured forces. To solve this problem, the authors have proposed a direct reaction force measuring system that can eliminate the effects of friction and inertia forces, and a seismic isolation testing facility with the proposed system (E-isolation) will be 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.

Keywords Seismic Isolation, Bearing, Dynamic test, Friction, Inertia force, Scale effect, E-Isolation

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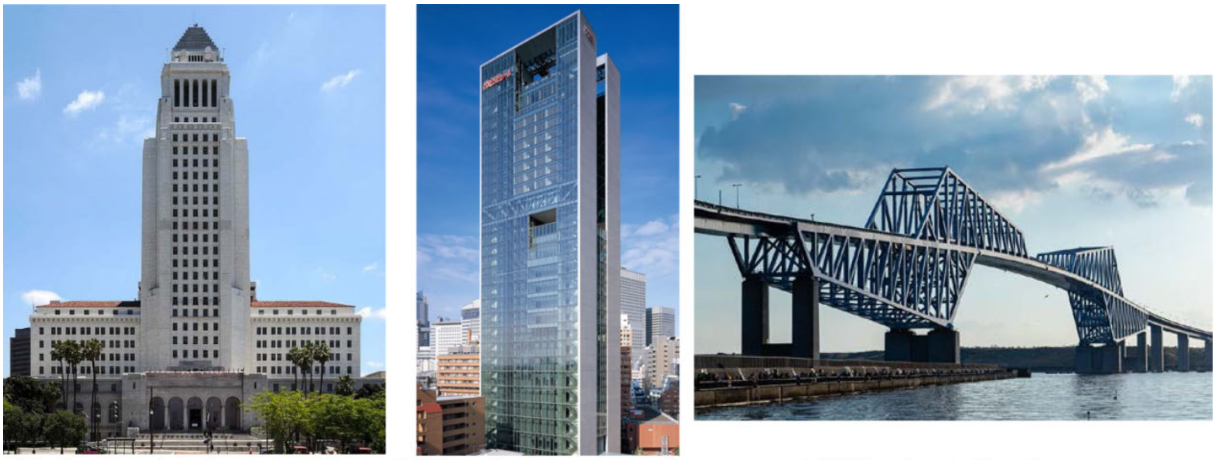
1. Introduction

Looking back on the development of earthquake-resistant structures, there are two main concepts: First, the strength-based structures, which resist strong earthquakes elastically, and second, ductile structures which give the structural members the ability to deform plastically. The former can be applied to low-rise buildings, but cannot be applied to mid-rise or higher buildings. Ductile-frame has been recommended for buildings of all heights and bridges not only in Japan but also in the U.S., China, Italy, and other seismic-prone countries. Both reinforced concrete and steel structures have been actively studied to provide ductile behavior and frames with stable plastic deformation capacity, and many textbooks and design guidelines in various countries carefully describe these methods. However, the recommended ductility here is actually obtained by observable structure damage. Following the ductile structure concept, even if human lives are secured during a major earthquake, damaged houses, hospitals, factories,



(a) Los Angeles city center, US (b) Yoyogi seminar tower, Japan (c) Tokyo bay bridge, Japan

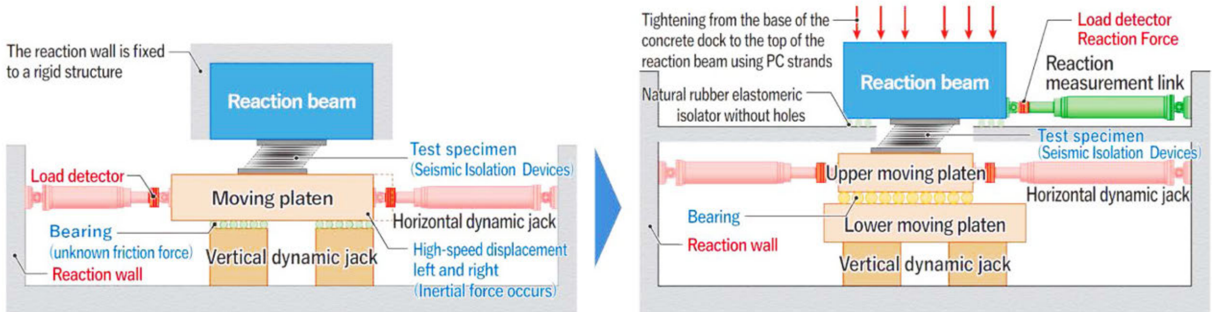
Figure 1. High-rise building and large bridge incorporating seismic isolation.

offices, schools, bridges, etc. cannot be used in most cases, will lose their functions, and in some instances, they should be demolished and rebuilt. Since around 1970, seismic isolated and vibration-controlled structures have been developed and put into practical use as structural methods that minimize or entirely eliminate the damages in the main structural frame during earthquakes. These innovative structural methods canalize the plastic energy on seismic isolation members and energy dissipating dampers during an earthquake, rather than on structural members such as columns and beams. This way, the main structural members remain intact after the earthquake, and all building functions or occupation will be uninterrupted. These techniques have already been widely applied to numerous high-rise buildings and large bridges, as shown in Figure 1.

Needless to say, seismic isolation devices and dampers are critical components that govern the seismic response of a structure, and it is necessary to comprehensively understand their behavior under a major earthquake before the design stage and construction. Therefore, it is important to conduct dynamic tests on full-scale isolation devices that closely represent the realistic seismic behavior, simulating all conditions when an actual earthquake strikes a seismically isolated structure. A certain amount of structural damage is expected according to strength and ductility based design which has been confirmed during earthquakes in the last 70 years. On the contrary, the users are expecting a damage-free performance from seismically isolated structures even under a severe earthquake. Public understanding is crucial to promote the spread of seismically isolated structures, and the synergic effect of these initiatives will help build a more resilient society.

Among the typical laminated rubber bearings used for seismic isolation, natural rubber-based laminated rubber bearings (NRB) have a relatively linear force-displacement relationship, while lead-plugged laminated rubber bearings (LRB) and high-damping rubber bearings (HDRB) with added damping capacity are known to exhibit complex behavior under high vertical forces and large dynamic horizontal deformation and where the performance is also highly dependent on the member size. Especially, large rubber bearings of over 1m diameter require longer production time for vulcanization adhesion and have a higher risk of defects. Therefore, it is very important to verify the behavior of such seismic isolation bearings using dynamic testing machines on full-scale specimens. However, there are no facilities in Japan that can dynamically test full-scale laminated rubber bearings over 400 mm in diameter, such as those used for large buildings and bridges. Until now, such tests have been conducted on testing facilities outside Japan e.g. in the U.S., Taiwan, etc. Figure 2(a) shows the Seismic Response Modification Device (SRMD) testing facility (Benzoni et al.,1998) at UCSD. The moving platen, which induces shear force on the test specimen, is dynamically moved in the horizontal direction while being subjected to high vertical forces of tens of thousands of kNs. However, the frictional reaction at the supporting bearings due to the large vertical force and the inertial force of the heavy table is mixed into the measured reaction force of the load cell attached to the horizontal actuators. Alireza et al. (2019) realized a real-time hybrid experiment by correcting inertial forces by measuring acceleration and constructing an accurate friction model for friction forces. However, it is not easy to accurately reproduce a complex friction model that depends on pressure, velocity, phase, and temperature, and the time delay associated with the calculation also poses a challenge for real-time hybrid experiments.

To solve these problems, the authors are proposing a direct measurement system, as shown in Figure 2(b), a substantially large reaction beam is placed on the upper side of the specimen supported by special bearings (laminated natural rubber isolators) with very low stiffness in the horizontal direction while almost rigid in the vertical direction ($K_h < K_v / 3000$). Unlike regular seismic isolators,



(a) Conventional force measurement system (b) Proposed force measurement system

Figure 2. Comparison of conventional and proposed reaction force measurement system.

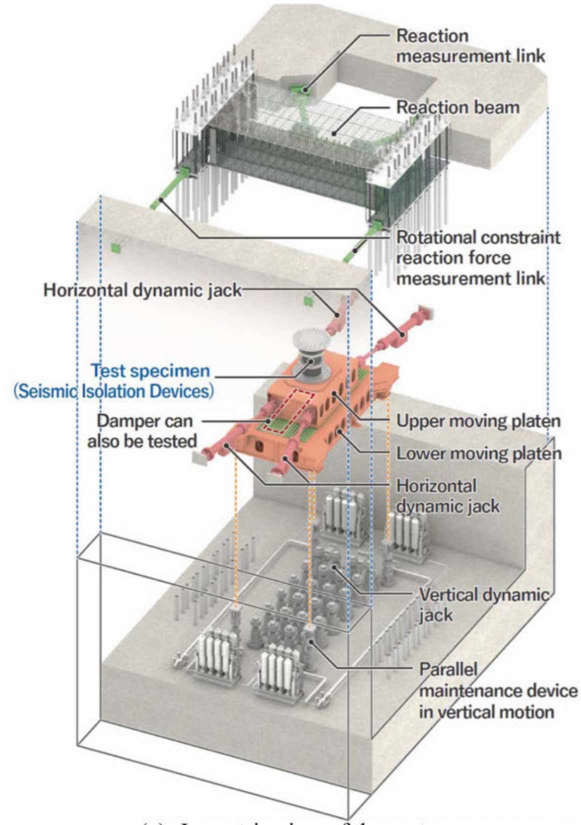
these elastomeric bearings don't have a hole in their center which enables them to act like a solid rubber ball sustaining large vertical force. As the layered steel plates inside the bearing composition don't have holes either, rubber expansion is restrained and stress concentrations are prevented effectively. Reaction force measurement links are horizontally connected between the reaction beam and the rigid RC reaction wall. Majority of the horizontal reaction force is measured in real-time through these force-measurement links, and since the reaction beam moves minimally, almost no inertia force is generated. Furthermore, by supporting the reaction beam with elastomeric bearings, only 1-2% horizontal force is transmitted through the support layer. Since laminated natural rubber isolator bearings are expected to exhibit linear properties, even under small horizontal deformations of a few mm and large vertical loads, these horizontal forces transmitted through the bearings can also be accurately captured. To keep the bearings under compression, pre-tensioned PC strands are provided, while the horizontal stiffness with their P-D effects can also accurately be captured because their tension forces are unchanged.

Although this concept of eliminating the effects of friction by measuring the reaction force on the reaction side has been used in frame testing in the past, there are few precedents for the use of this approach in full-scale dynamic testing machines by arranging multiple load cells between a test piece and a reaction beam (Shimoda, 1990s, Zayas, 2023). But our design concept of the system follows the "design axiom" proposed by MIT Professor Nam P. Suh (Suh, 1990). In any design, there are a set of functional requirements (FRs) and a set of design parameters (DPs) to be determined by the design. The relationship between them is expressed by a design matrix (A) as "FRs = A*DPs". The design matrix A is a very complex, but it can be simplified by organizing the problem and incorporating new ideas. The design matrix A for a force data acquisition system to insert many load cells between the test machine and the specimen is complicated, and it is difficult to improve the accuracy of horizontal load measurement because the load cells, which are subjected to large compressive forces, must measure a horizontal force of about 10% of the vertical load. In this proposed method, the design matrix A can be made into a simple diagonal matrix because the reaction beam is supported flexibly in the horizontal direction and the horizontal load is measured by four horizontal links that are free in the vertical direction. As a result, the accuracy of horizontal force data acquisition can be improved. With the collaborations with a group of researchers, the author team is currently constructing Japan's largest full-scale seismic isolation bearing test facility incorporating this proposed system (Figure 3).

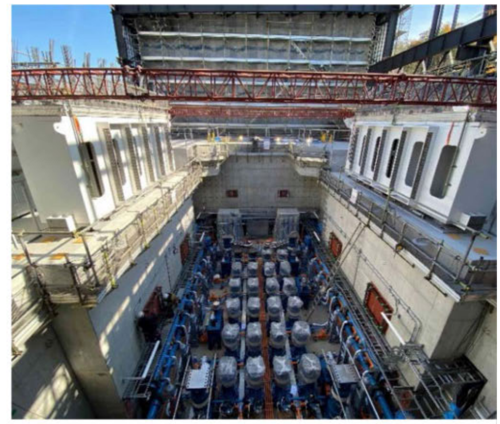
In this paper, detailed design for incorporating this proposed measurement system into an actual large dynamic testing facility is introduced and discussed. The process of integrating a new idea into a real device requires a vast amount of research and iterations, and these processes are presented and discussed along with the details of the design for each component.

2. Proposed horizontal force measuring system

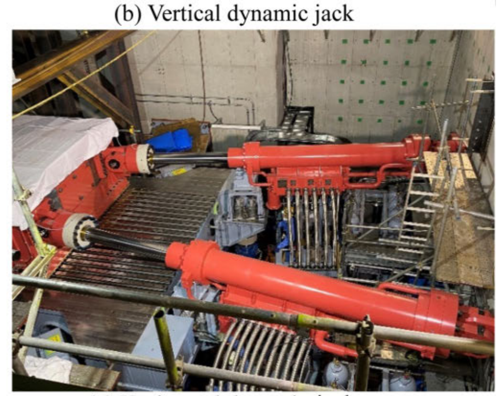
At first, reaction force measuring systems in existing dynamic testing machines are outlined and frequently observed shortcomings of those systems are clarified. In the commonly implemented reaction force measurement system shown in Figure 2(a), the top plate of the seismic isolation bearing specimen is fixed to a large steel beam (e.g. SRMD in UCSD, Benzoni et al.,1998) or a concrete frame (e.g. MATS in NCREE, Lin et al., 2017). Meanwhile, the bottom plate of the specimen is connected to a moving platen on horizontal bearings with vertical loading capability to conduct performance verification tests by applying a prescribed dynamic horizontal deformation protocol. The horizontal reaction force of the tested seismic isolator specimen is measured by a load cell serially connected to a horizontal dynamic actuator. However, during the dynamic loading of the seismic isolation bearing subjected to high level axial forces, the frictional forces in the horizontal bearing of the moving platen and the inertial forces generated by the mass of the platen itself are merged into the measured horizontal reaction force values. The inertia force can be estimated by measuring



(a) Isometric view of the system



(b) Vertical dynamic jack



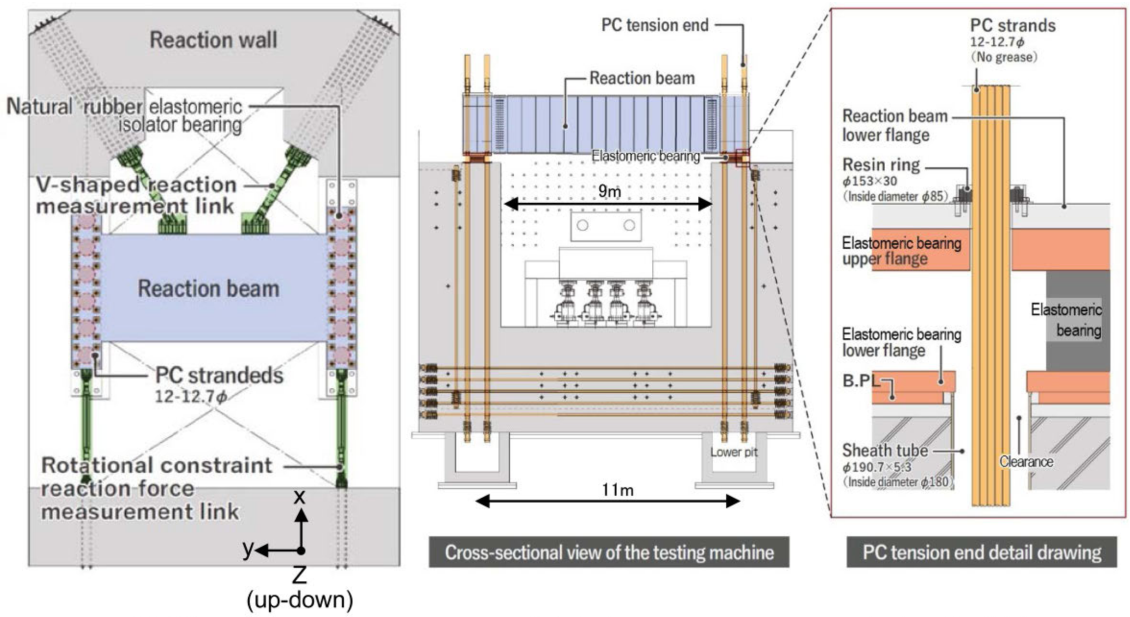
(c) Horizontal dynamic jack

Figure 3. Real-size dynamic testing facility under construction.

the acceleration and multiplying it with the mass of the moving platen but calculating and eliminating the effects of the friction force is quite challenging because friction depends not only on the constantly changing vertical forces but also on velocity, phase, temperature, and other parameters. In Alireza et al. (2019), a sophisticated friction model is proposed, and a real-time hybrid simulation is attempted, however, the friction force has not been entirely eliminated.

The reaction force measurement system proposed in this paper is outlined in Figure 2(b) and Figure 3 which shows the plan and cross-sectional views of the proposed experimental set-up. The new testing facility just constructed in Japan, Hyogo, Miki besides E-defense facility (Figure 4) has a vertical load capacity of 36,000 kN (static), 30,000 kN (dynamic), stroke limit of 250mm and velocity capacity of 70 mm/sec. In the horizontal direction, dynamic single directional loading capacity is 6,500 kN (static), 5,100 kN (dynamic) with ±1,300 mm stroke limit and the max velocity is 800 mm/sec. In this testing system, a big steel reaction beam is placed above the specimen similar to the SRMD facility in UCSD, but this time it is supported by laminated natural rubber bearings with low horizontal stiffness and high vertical stiffness, instead of being fixed to the RC reaction walls. The reaction beam is connected to a horizontally rigid RC reaction wall by a V-shaped measurement link with built-in load cells and a couple of rotational-constraint measurement links with built-in load cells also. The two transverse beams at both sides of the reaction beam are pulled down with horizontally-free PC strands (steel strands for precast concrete) of 14.6 m length between bottom and top anchors that apply compressive force to the laminated rubber bearings so that the compression force on these bearings is not lost even when the reaction beams are subjected to lift-up effects during the experiments. Because of the low horizontal stiffness of the rubber bearings supporting the reaction beam, majority of the horizontal force is measured through the reaction measurement link, where the ratio of horizontal force transmitted through the laminated rubber bearings is less than 1%. Due to the reliable elastic characteristics of the laminated natural rubber bearings, horizontal forces in these bearings can be accurately included in the resultant reaction forces by using their horizontal deformation. Since the horizontal displacement of the reaction beam is expected to be in the vicinity of 1-2 mm and acceleration is at a negligible level, in principle, the measured forces should not be affected by the frictional or inertial forces, which have been an issue in existing facilities.

Design details of each component realizing this system are discussed in the following sections.



(a) Plan (b) Section (c) Detail of PC strands

Figure 4. Plan and section of real-size dynamic testing facility in Japan.

3. Design and construction of RC reaction wall

A part of the detailed design drawings of RC reaction wall is shown in Figure 5. For a future extension to 50,000 kN vertical loading capacity with a two-dimensional horizontal moving platen, the RC reaction wall has been designed to withstand these conditions with 9.90-11.00 m clear span. The thickness of the reaction walls is 3.50 m and the foundation thickness is 4.5 m. Prestressing is implemented in the foundation and walls, for preventing cracks in these concrete walls.

The reaction beam is placed on the RC reaction walls supported through twelve laminated natural rubber bearings with 650 mm diameter. PC strand sets consisting of 12 × φ12.7 mm strands are connecting the reaction beam onto the RC reaction walls. Four of these PC strand sets are provided for each bearing with a design pre-stress level of 1050 kN on each (1240 kN in construction, considering future relaxation). Pre-stressing forces are designed to keep the support rubber bearings under compression even under the most severe testing conditions.

To allow the expected horizontal movement of the reaction beam, PC strands have been placed in sheath tubes with 190.7 mm diameter. 5.3 mm thickness, allowing 47 mm clearance in the design stage around the PC strands. The 11.52 m tall sheath tubes are precisely

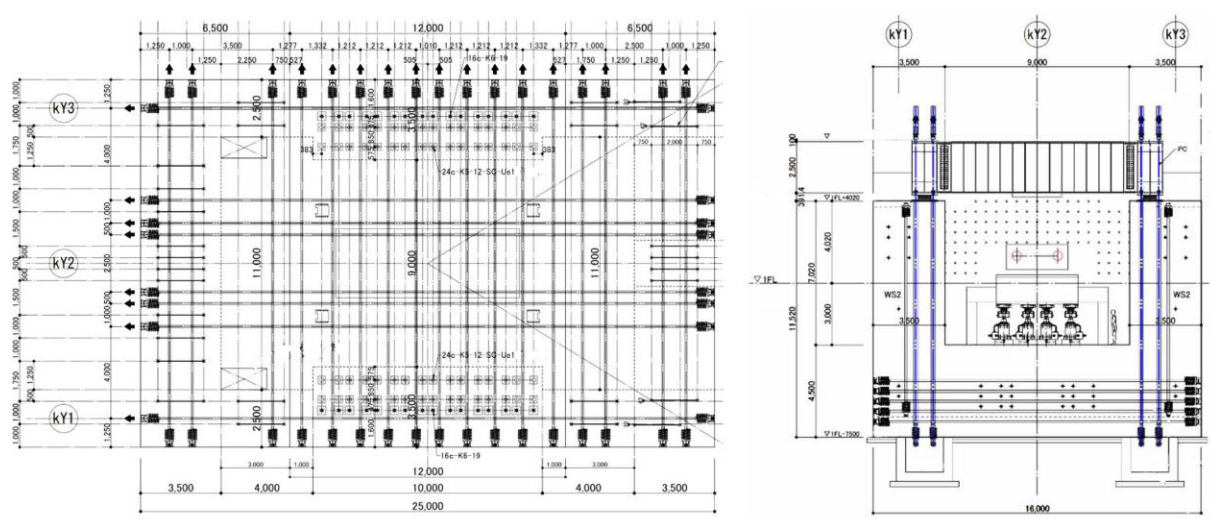
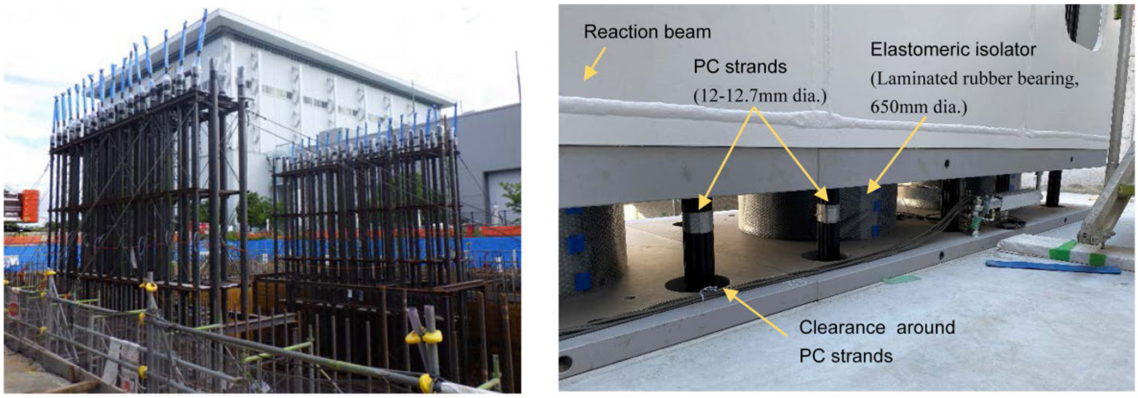


Figure 5. Plan and section of RC reaction wall with PC strand arrangement (Courtesy of Kurosawa Construction)



(a) Template framework for sheath tube (b) PC strands and elastomeric bearing supporting reaction beam

Figure 6. PC strands construction anchoring the reaction beam.

installed into the RC reaction walls within 1/650 error margin, using template frameworks as shown in Figure 6 (a). As result, 30mm clearance around the PC strands is secured (Figure 6(b)).

4. Design and fabrication of steel reaction beam

The reaction beam consists of four steel box beams with section of 2.5 m height, 1.2 m wide, 9.1 m long, 22 mm to 30 mm in thickness and 20 tons weight, and two more box-shaped beams of 1.25 m wide, 7.2 m long and 26 tons weight on each end connected in an H-shaped plan, as shown in Figure 7. The six beams are transported individually and assembled at the construction site by friction bolt connections. In addition, large plates of 30 mm of 4.8 m width and 8.4 m length are bolted on the top and bottom of the connected boxes for integration. Design of the reaction beam was carried out starting with simple calculations followed by sophisticated finite element analysis, and it was confirmed that each component was kept below the allowable stress level for the steel material and slip load of the bolts, where the design vertical deformation was 7.6 mm (1/1450), and the torsional angle was 1/759 under vertical load of 30,000 kN and horizontal load of 6,000 kN.

To ensure the quality of each friction bolt connection, comprehensive tolerance controls were conducted during the fabrication of the reaction beam. During the assembly, the warping caused by welding was minimized and the

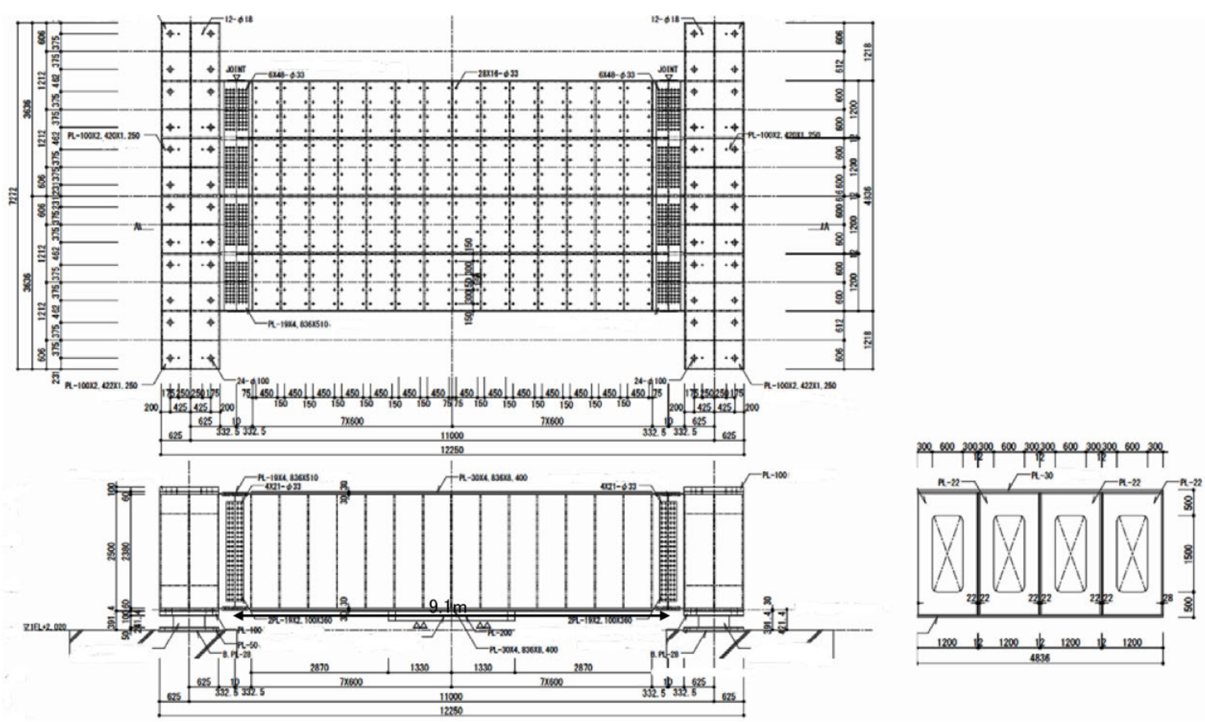
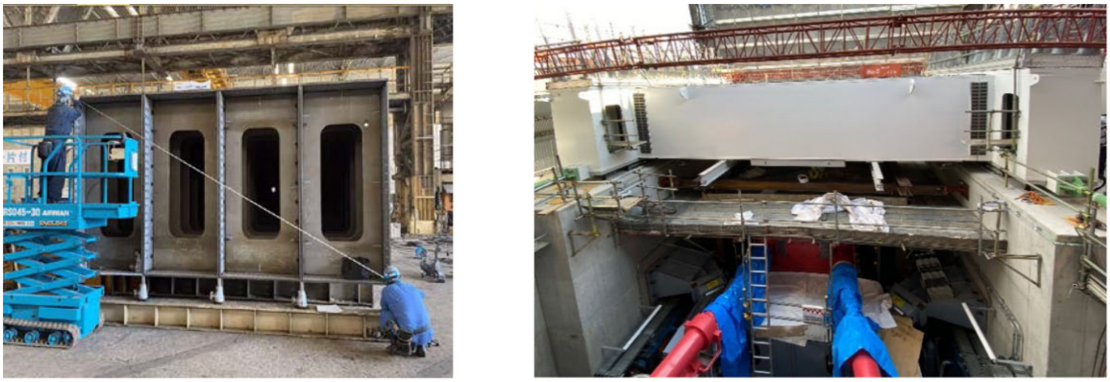


Figure 7. Plan and section of reaction beam. (Courtesy of Nippon Steel Engineering and Dr. Hidemoto Mukai)



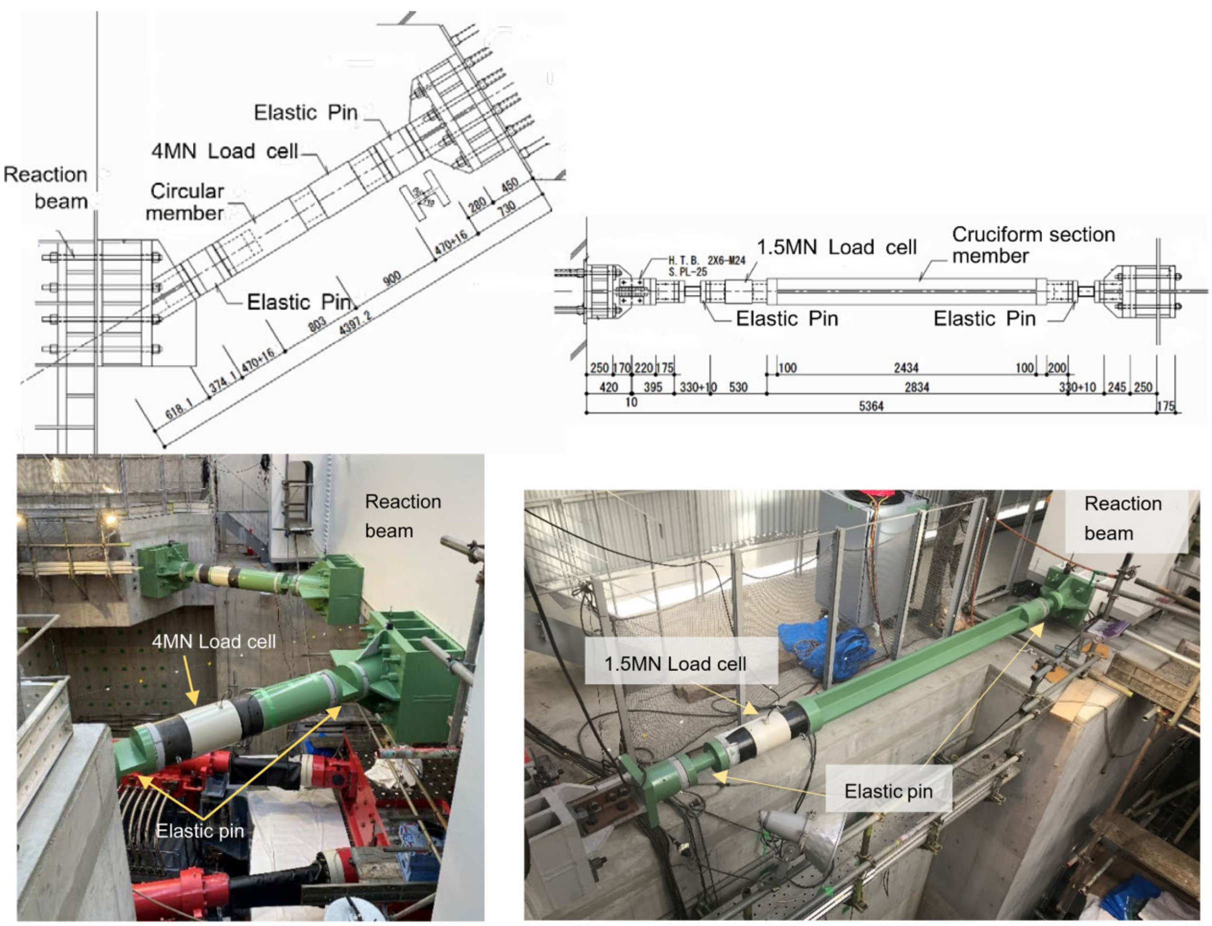
(a) Fabrication of reaction beam (b) Installed reaction beam on elastomeric isolator bearings

Figure 8. Fabrication and installation of reaction beam.

tolerance of the friction joint was successfully obtained to be less than 1 mm (Figure 8).

5. Design and fabrication of force measurement links

The key component of the proposed system, the reaction force measurement link, consists of a V-shaped measurement link intersecting the center of the reaction beam and a couple of rotational constraint measurement links, as shown in Figure 4(a). 4MN and 1.5MN load cells are mounted on the V-shaped link, and the rotational constraint link, respectively. V-shaped measurement links restrain the displacement of the reaction beam in the x



(a) V-shaped measurement link (b) Rotational constraint link

Figure 9. Reaction-force measurement link.

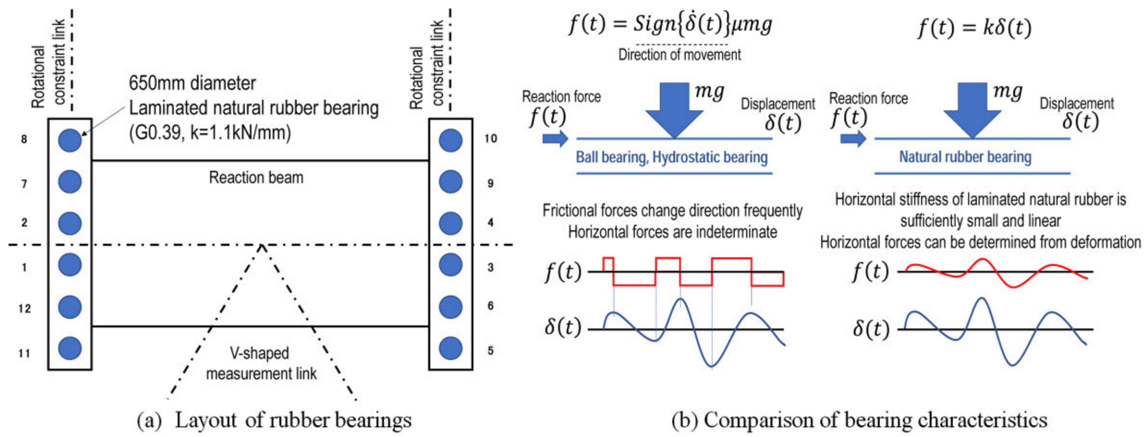


Figure 10. Elastomeric isolator supporting the reaction beam.

and y directions, and the individual reaction forces along x and y directions can be obtained by multiplying cosine and sine components on axial forces respectively. Hereafter, x-axis is defined as the main loading direction and y-axis is defined as the orthogonal direction in plan, where z-axis is the vertical direction as shown in Figure 4(a). To restrain the rotation of the reaction beam about the z-axis, a couple of rotational constraint links are added between both wings of the reaction beam and the RC reaction wall. Conducted analyses indicate that up to 75% of the major reaction forces will be resisted by the V-shaped measurement links and the remaining by the rotational constraint links. The additional reaction forces measured by these links are expected to be 99%.

V-shaped link should be able to keep up with the vertical displacement of the center of the reaction beam under a vertical force of 30,000 kN within the elastic range, and the shear force and bending moment applied to the load cell must be controlled within the allowable range. For this reason, joints with reduced bending stiffness at both ends are used for these links. This method effectively reduces shear forces and bending moment as shown in Figure 9. This joint is hereafter referred to as an 'elastic pin'.

6. Elastomeric isolator supporting reaction beam

Twelve 650-mm-diameter natural rubber laminated bearings (rubber shear modulus $G = 0.39$ N/mm^2, horizontal stiffness for small amplitudes $k = 1.1$ kN/mm, total stiffness of 12 bearings is 13.2 kN/mm) were employed for supporting the reaction beam as shown in Figure 10(a). As indicated in Figure 10 (b), sliding bearings such as ball bearings or hydrostatic bearings generate frictional reaction forces, which fluctuate instantaneously and frequently depending on the phase of motion, making it difficult to determine the friction forces by using displacement data. Conversely, natural rubber isolator bearings exhibit relatively low horizontal stiffness, and as long as linear behavior is ensured, the reaction force can be accurately determined from the very small displacement. Micro-deformation experiments were conducted on candidate laminated rubber bearings during the design stage to confirm the stability of their linear behavior.

Besides, 48 PC strands of 12 m × 5/6 (fixed ends)-

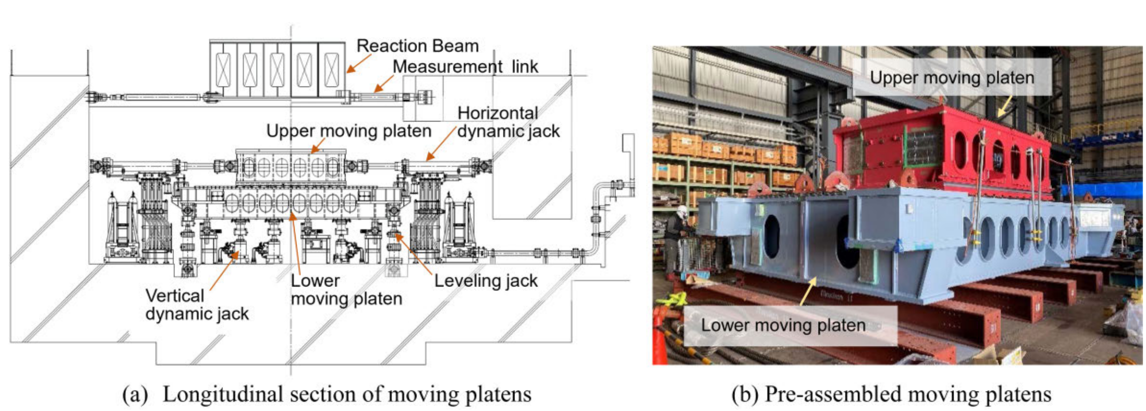
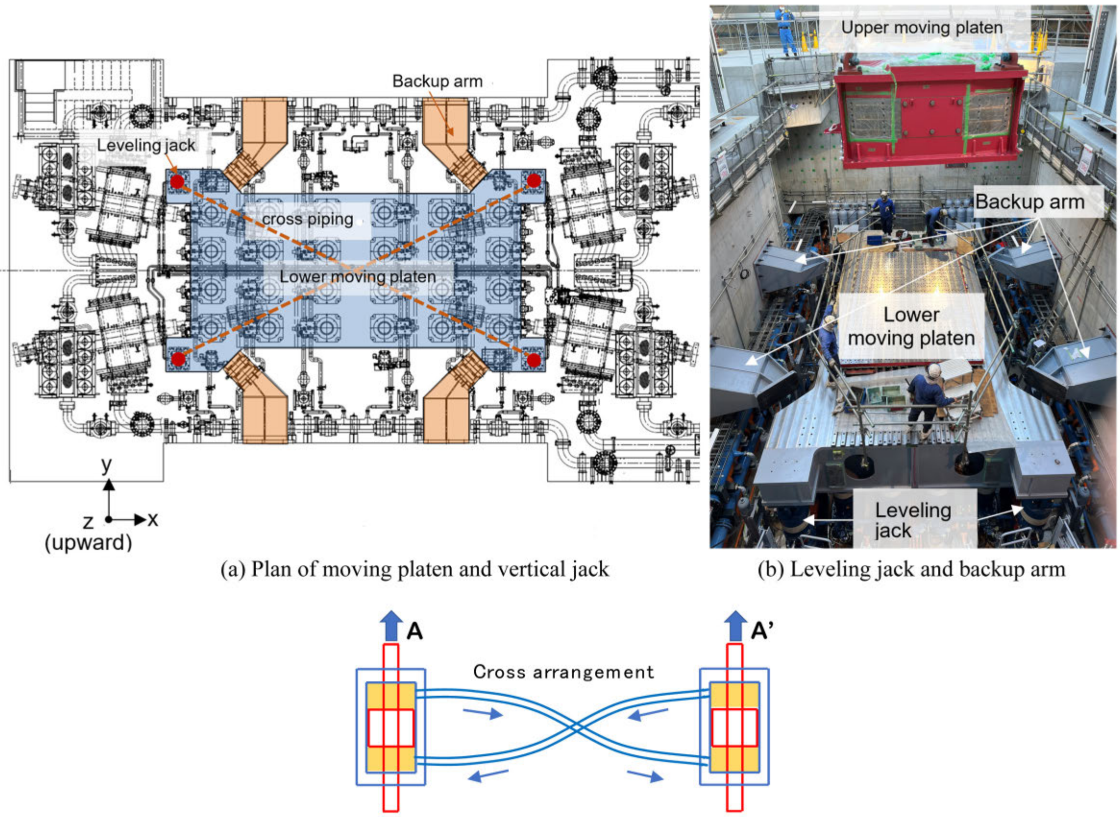


Figure 11. Configuration of moving platen (Courtesy to Mitsubishi Heavy Industries Machinery Systems)



(a) Plan of moving platen and vertical jack

(b) Leveling jack and backup arm

(c) Mechanism of leveling jacks

Figure 12. Restraint systems for moving platen. (Courtesy to Mitsubishi Heavy Industries Machinery Systems)

effective length (4 strands per support) between the bottom of the reaction beam and the bottom of RC wall with 1240 kN of tension force each exhibit a horizontal stiffness of 6.0 kN/mm in total due to their PΔ effect. As result, total horizontal stiffness at supporting bearings is expected to be approximately 19 kN/mm only. Therefore, the horizontal forces induced by these bearings are expected to be substantially small relative to the measurement links, namely less than 1%, and can be accurately evaluated by measuring the horizontal displacement of the reaction beam, which is approximately 1-2 mm under maximum force 6,000 kN.

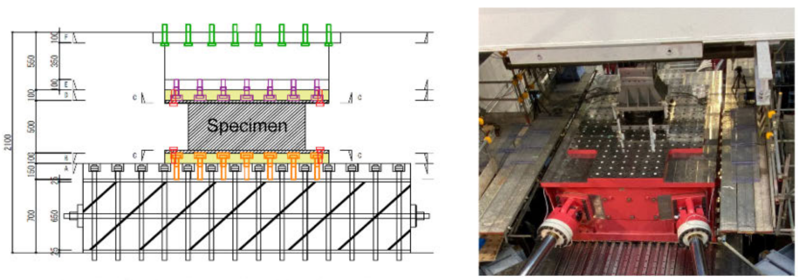
7. Configuration of the moving platen

As shown in Figure 11, the moving platen consists of a lower layer that moves vertically and an upper layer that moves horizontally in the x-direction. The lower platen is controlled by 24 vertical dynamic jacks while the upper platen is supported on the lower layer by linear sliders with 18 rails and 14 sliders on each rail (total number of the sliders of 252), moves in the x-direction by 4 horizontal dynamic jacks.

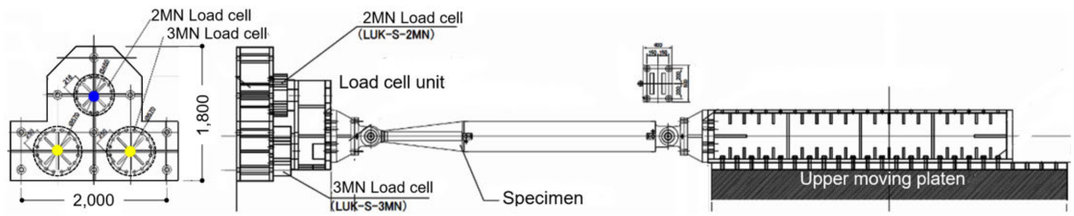
As the vertical jacks are simply supporting the moving platens, there is no restraining measure against partial uplift as a result of the rotation about y-axis and x-axis. Also, they don't resist against z-axis rotation or y-axis displacements. Therefore, 4 leveling jacks restrain x-axis and y-axis rotations, and 4 backup arms are provided to limit z-axis rotation and movement in the y-axis. Furthermore, 4 horizontal dynamic jacks are angled slightly (10° from x-axis) to control y-axis movement and z-axis rotations (Figure 12). The leveling jacks are linked with cross-connected oil chambers which stabilize the horizontal level without obstructing the vertical movement of the mechanism as shown in Figure 12 (c). Total 28 numbers of vertical load cells are provided on the vertical jacks and leveling jacks, and total vertical reaction force (F_z), rotational moment around x-axis (M_x) and rotational moment around y-axis (M_y) can be obtained from these values.

8. Test jigs for various specimens

Testing jig images for seismic isolation bearings and energy-dissipation devices are shown in Figure 13. Not only seismic isolation bearings but short column specimens up to 2.1 m height can also be assessed by this testing device. For energy-dissipation devices, an additional load-cell unit consisting of three flat load-cells is attached on the RC reaction wall, and by setting the specimen between this load-cell unit and upper moving platen, reaction



(a) Jig for laminated rubber bearings (b) Temporary set-up



(c) Jig for energy-dissipation devices

Figure 13. Testing jigs for various specimens.

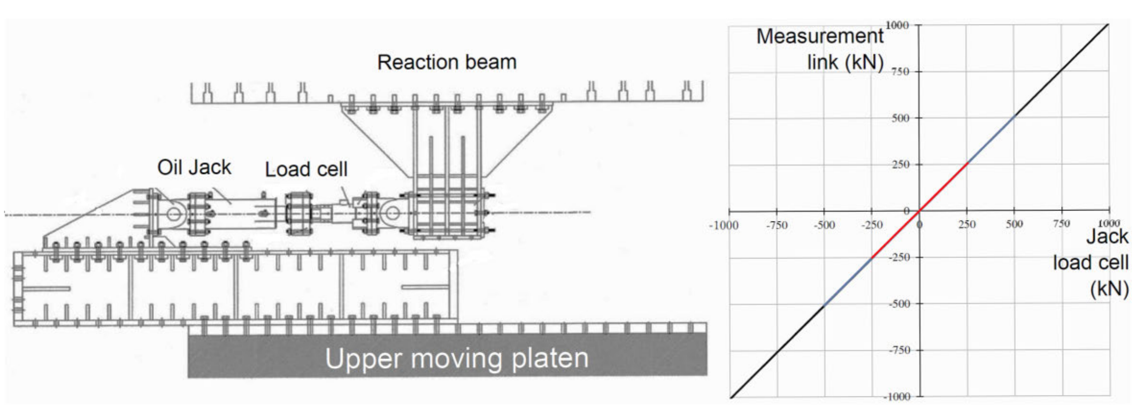
forces will be directly measured eliminating the effects of friction and inertia forces similar to the measurement link system.

9. Preliminary test for measurement link

Prior to the completion of the facility, preliminary experiments were conducted to confirm the accuracy of the proposed reaction force measurement link. Specifically, an oil jack and load cell were installed in serial between the upper moving platen and the bottom of the reaction beam as shown in Figure 14(a), and a horizontal load of up to 1000 kN was applied by the oil jack, while the load cell readings were compared with those of the reaction force measurement link system. Part of the results are shown in Figure 14(b). The sum of reaction force measured by the measurement link and forces transferred through 12 rubber bearings with P-D effect of the 48 PC strands are parallelly captured by the load cell with an error of less than 1%, which is considered to be a closer agreement when the reaction force of the bearing supporting the reaction beam is also taken into account.

10. Hybrid simulation capability

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



(a) Setup for preliminary test (b) Test result

Figure 14. Preliminary test for measurement link.

the force sensor of the physical test run in parallel to the analysis. Especially, real-time hybrid simulation (RTHS) is an efficient method to evaluate the dynamic response of structural systems with rate-dependent devices.

Since the proposed facility has a direct reaction 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), 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).

11. Conclusive remarks

In this article, a just-constructed dynamic testing facility in Japan, specifically designed for seismic isolation bearing tests, eliminating the effects of friction and inertia forces was introduced. Presented discussions are summarized as follows.

1) A method was proposed to determine the frictional and inertial forces mixing into the measured reaction forces in the dynamic testing systems, by using a direct measurement link that measures the reaction force was proposed.
2) Design of a fully pre-stressed RC reaction structure that can withstand 30,000 kN vertical force was presented, including the details of the reaction beam connected by PC strands allowing horizontal displacement.
3) Design and fabrication of steel reaction beam consists of six steel box sections spanning 11 m was presented. Special fabrication and assembly were conducted to prevent distortion caused by welding and ensure required tolerances.
4) Reaction force measurement link system consisting of two V-shaped links and two rotational constraint links is proposed. These links are expected to capture majority of the reaction forces without the effects of friction and inertia forces which was unavoidable in conventional facilities. An elastic pin connection was proposed to obtain accurate measure-ment following the vertical movement.
5) Laminated natural rubber bearings are chosen for supporting the reaction beam due to their low horizontal stiffness and elastic behavior that allows to clearly identify the reaction forces.
6) Moving platen configuration including various stability systems was presented.
7) Test setup configurations eliminating the effects of friction and inertia forces are introduced not only for seismic isolation bearing tests but also for energy-dissipation devices/dampers.

Preliminary experiments were conducted to confirm the accuracy of the proposed reaction force measurement link, and it was confirmed that the error margin is less than 1%.

The ability to accurately measure the specimen reaction force in real-time is expected to be a significant advantage for real-time hybrid simulations using this system.

Dr. M. Yoneda proposed and we have agreed to call this new facility “E-Isolation” after it’s neighbor and sibling facility “E-Defense” which was established in

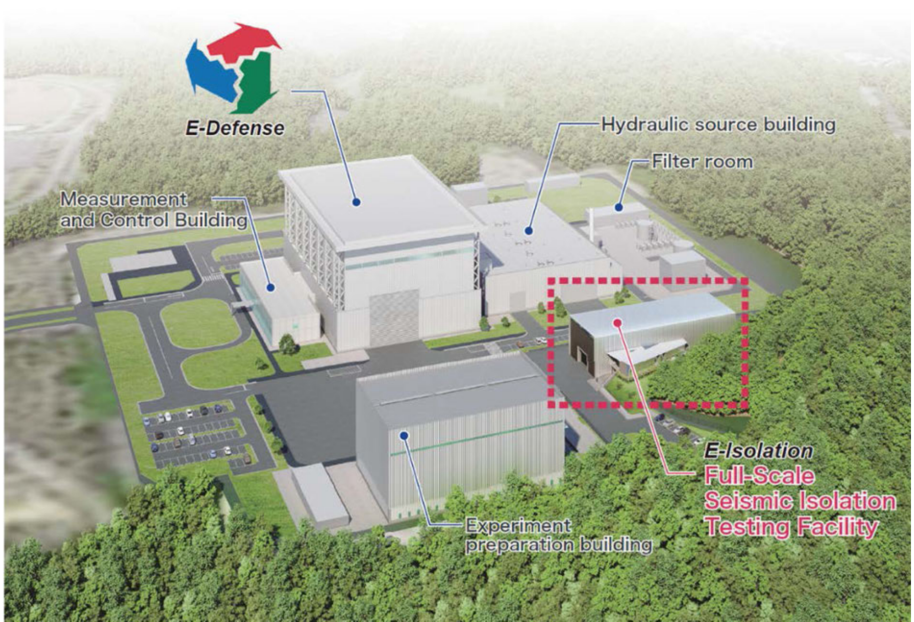


Figure 15. E-Defense and E-Isolation in Hyogo, Japan.

2005 (Figure 15). We are hoping this location is bound to become one of the main centers of earthquake engineering in the world.

Acknowledgment

This work was supported by Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), Enhancement of National Resilience against Natural Disasters (Funding agency: National Institute for Earth Science and Disaster Resilience). The authors would like to express their deepest gratitude to all those who contributed to this research project including Cabinet office, Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan and National Research Institute for Earth Science and Disaster Resilience (NIED). First, we appreciate those who strongly encourage and support us to construct the new facility, Governor Tomohiko Saito, Hyogo Prefecture, Mayor Kazuhiko Nakata, Miki City, and President Kazuya Masu, Tokyo Institute of Technology. In particular, we would like to thank to Dr. Yoshiaki Nakano, Mr. Takahito Inoue, Ms. Tomoko Sakaguchi from NIED, Dr. Keita Uemura, Mr. Tomoya Ueda from Kyoto University, Dr. Yuki Terazawa, Dr. Miku Kurosawa, Mr. Ichiro Hirano, Mr. Sachio Umemura, Mr. Kazushi Sakai, Ms. Maho Kobayashi from Tokyo Tech.

We also deeply appreciate the project team who proceeded the design, fabrication, construction, and assembly in an extremely short period of time, including Taisei Corporation, Kozo Keikaku Engineering Inc. (KKE), Mitsubishi Heavy Industries Machinery Systems Ltd., Nippon Steel Engineering Co., Ltd., Fuso Kiko, Kurashiki Kako Co., Ltd., Kurosawa Construction Co., Ltd., Mukai Structural Design Office, Koizumi I. W. Inc., Kanden Plant Corporation, Japan Society of Seismic Isolation (JSSI), Japan Seismic Isolation Laboratory (JSIL).

Especially we thank to Dr. Ichiro Nagashima, Dr. Tsutomu Komuro, Dr. Ryota Maseki, Mr. Kyohei Ueda, Ms. Yukimi Sahoda, Mr. Ko Endo, Mr. Wataru Mimura, Mr. Takahiro Nakajima, Mr. Masayoshi Takazawa, Mr. Yusuke Noguchi, Mr. Shinnosuke Okayama, Mr. Taisuke Masuno, Ms. Ayumi Suzuki, Mr. Yasuhiro Ueno, Mr. Yuki Kobayashi, Mr. Takumi Koike, Mr. Yutaka Saito, Mr. Kohji Yoshida from Taisei Corporation, Chairperson Shota Hattori, Dr. Guo Xianqun, Mr. Naoya Goto from KKE, Mr. Masayuki Shimizu, Mr. Masayuki Suetsugu Mr. Shohei Ikari from Mitsubishi Heavy Industries Machinery Systems Ltd., Dr. Hidemoto Mukai and Mr. Manabu Koizumi, and Dr. Yasushi Ichikawa, Mr. Atsushi Watanabe, Mr. Mitsuharu Sakai from Nippon Steel Engineering, Mr. Masayuki Gurita, Mr. Kohji Higashiyama from Kurashiki Kako, President Masaaki Watase, Mr. Shuji Murasaki, Mr. Kazuaki Aso from Fuso Kiko, Dr. Ryotaro Kurosawa, Mr. Tsukasa Kashiwazaki from Kurosawa Construction, Mr. Hiroshi Morikawa from Kanden Plant, President Akinobu Nakazawa, Mr. Nagahide Kani, Mr. Yoshihisa Kitamura from JSSI, Mr. Takaaki Miyabara, Mr. Kazuo Ebihara, Dr. Shoji Hayasi, Dr. Kazuo Tamura, Mr. Kenji Sawada from JSIL, Mr. Hidemi Niinai, Mr. Yuichi Kojima, Mr. Masanobu Hayashizaki who support experiments and operation, and Dr. Andreea Dutu from Technical University of Civil Engineering of Bucharest, Dr. Fatih Sutcu from Istanbul Technical University for their advises.

This project was realized by the support of many people involved in research, design, and construction related to seismic isolated and vibration controlled structures in Japan. We would like to mention a few names here to express our gratitude. In fact, the project is being carried out with the support of vast time contribution of this group of engineers.

Distinguished Professors;

Dr. Tsuneo Okada, Dr. Masao Saitoh, Dr. Toshio Nishi, Dr. Katsuki Takiguchi, Dr. Hirokazu Iemura, Dr. Katsunori Kaneda, Dr. Teruhiko Yoda, Dr. Yozo Fujino, Dr. Haruyuki Kitamura, Dr. Masayoshi Nakashima, Dr. Toshiharu Kanebako, Dr. Toshimi Kabeyasawa, Dr. Masaru Kikuchi, Dr. Hiroyasu Sakata, Dr. Hideo Fujitani, Dr. Mineo Takayama, Dr. Mitsuyosi Akiyama

Outstanding structural engineers in general contractors, other companies and organizations;

Mr. Tadashi Hayashi, Mr. Kazushi Ishizaki, Dr. Kunio Ukai, Mr. Osamu Hosozawa, Mr. Tominari Miwa, Mr. Masayuki Yamanaka, Dr. Hideo Katsumata, Dr. Tuyoshi Sano, Mr. Tsutomu Arai, Mr. Takayuki Sakakima, Dr. Akira Fukukita, Mr. Kazuo Kojima, Mr. Yasushi Kurokawa, Dr. Akihiko Kondo, Dr. Masahiko Higashino, Mr. Hiroyuki Ueda, Dr. Masashi Yamamoto, Mr. Hirotaka Sekido, Mr. Toru Tuchihashi, Mr. Takahiro Kido, Mr. Hideo Kobayashi, Mr. Shigeki Sugiura

Distinguished material engineers in rubber bearing supplier;

Dr. Nobuo Murota, Dr. Masahiro Nakamura, Mr. Naoki Kato, Mr. Mitsuru Miyazaki

Disclosure

The authors have no conflicts of interest to declare.

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