E-Isolation: Large-scale seismic isolation test facility in Japan with high-fidelity measurement system

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Abstract

Seismic isolation has been gaining popularity since the 1990s by proving its performance in many earthquakes, and the number of applications of such techniques in Japan alone will continue to increase to more than 5,500 buildings by 2023. However, no facility in Japan has long been able to dynamically test full-scale bearings larger than 800 mm in diameter. In March 2023, the "E-Isolation" full-scale test facility for seismic isolation bearings and energy dissipation devices was completed and testing of various devices began. Although the configuration of the system is similar to that of conventional test facilities, this new facility introduces an advanced reaction force measurement system that can eliminate the contamination of friction and inertial force of loading system, which is essential for real-time hybrid simulation experiments. This report describes the outline of the high-fidelity testing machine and its performance.

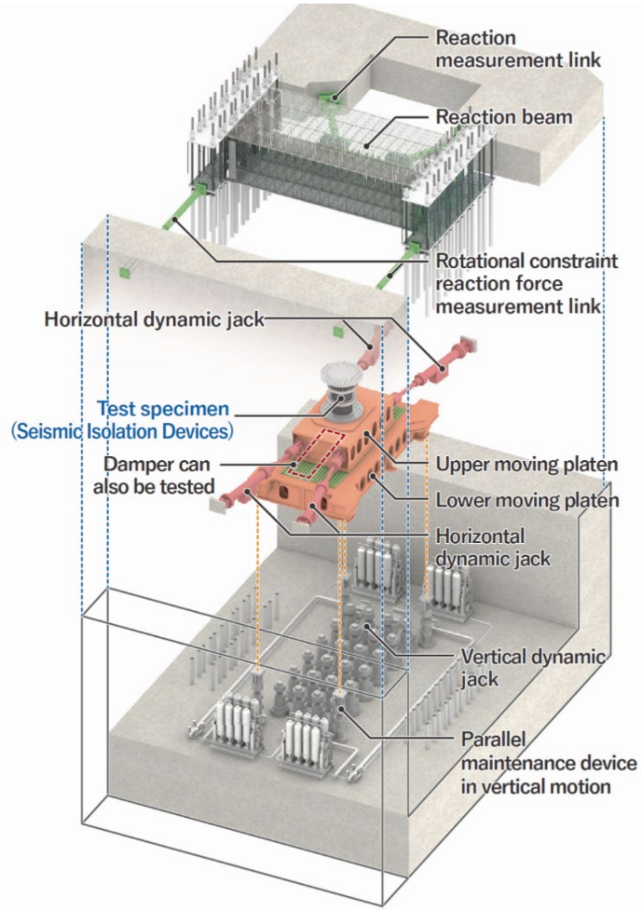
Keywords

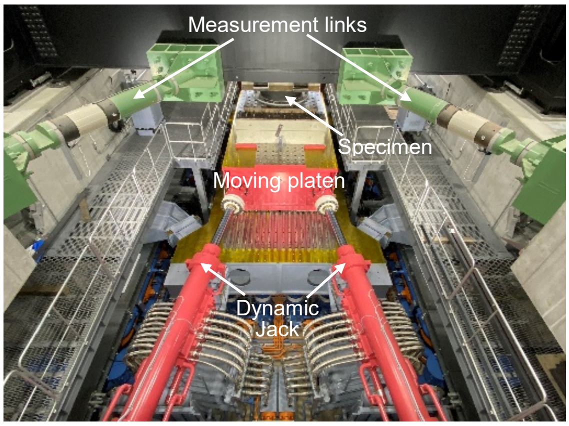
Seismic Isolation, Bearing, Dynamic test, Friction, Inertia force, Real size specimen, E-Isolation

1. Introduction

Seismically isolated buildings with seismic isolation bearings can significantly reduce the response of structures to earthquakes, and the number of applications of such techniques in Japan alone will continue to grow to more than 5,500 buildings by 2023. They are beginning to be used not only in high-rise buildings, but also in large bridges. The numerical modeling of these bearings is complicated due to their size, frequency and velocity, vertical force, and temperature dependence. Therefore, it is very important to verify the behavior of seismic isolation bearings using full-scale dynamic test facilities. However, for a long time, no facility in Japan has been able to dynamically test full-scale bearings larger than 800 mm in diameter, and such performance tests have been relied upon at testing facilities outside Japan, such as in the United States and China.

In March 2023, the "E-Isolation" full-scale test facility for seismic isolation bearings and energy dissipation devices was completed, and testing of various devices has begun. Although the configuration of the system is similar to conventional test facilities such as SRMD at UCSD (San Diego) or BATS at NCREE (Taipei), this new facility introduces an advanced response measurement system that can physically eliminate the frictions and inertial forces, which is essential for real-time hybrid simulation experiments. This report describes the outline of this precise testing facility and its performance.





(a) View of the test machine

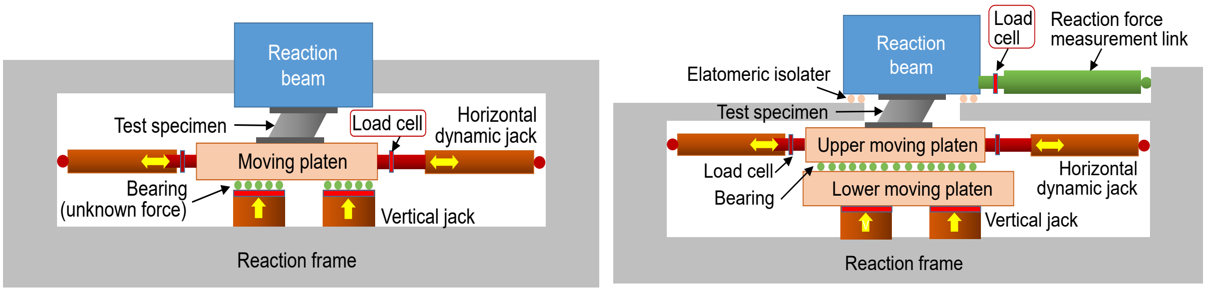
(a) Configuration of the test machine (c) External view of the testing laboratory

Figure 1 Configuration of E-Isolation testing facility

2. Outline of the testing facility

The new testing facility, E-isolation, constructed in Japan, Hyogo, Miki besides E-defense facility (Figure 1) has a vertical load capacity of 36,000kN (static), 30,000kN (dynamic), stroke limit of 250mm and velocity capacity of 70mm/sec. In the horizontal direction, dynamic single directional loading capacity is 6,500kN (static), 5,100kN (dynamic) with ±1,300mm stroke limit and the max velocity is 800mm/sec.

Figure 2(a) shows the configuration of the testing facilities employed in conventional testing facilities as SRMD at UCSD, or BATS in NCREE . The moving platen that shears the specimen is moved dynamically in the horizontal direction while being subjected to large vertical forces of more than tens of thousands of kilonewtons.

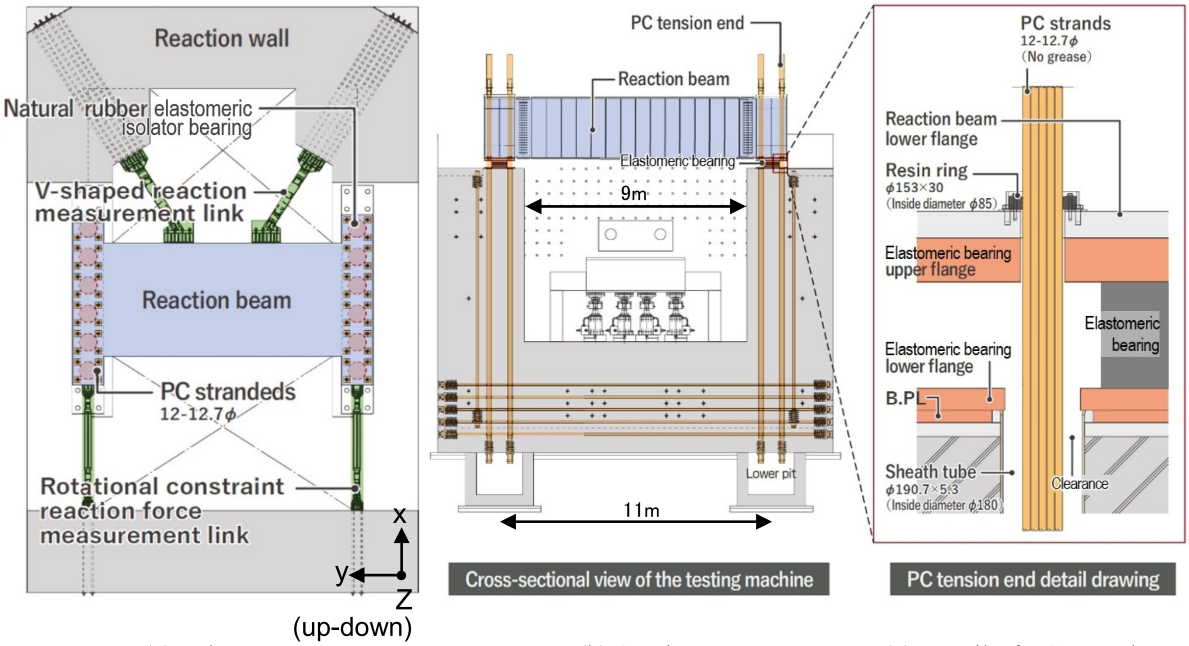


(b) Conventional measurement system (b) Measurement system in E-isolation

Figure 2 Conventional and improved measurement system

The horizontal reaction force can be obtained from the load cells at the horizontal dynamic jacks, however, the frictional forces owing to the large vertical force and inertial force of the heavy platen are mixed into the measured reaction force of the load cell. Efforts have been made [1] for constructing an accurate friction model for the frictional force, however, it is not easy to accurately reproduce a complex friction model that depends on the pressure, velocity, frequency, and temperature, and the time delay involved in the calculation is a challenge when the test result is utilized for real-time hybrid simulation experiments.

In E-isolation testing facility, a new type of reaction force measurement system as shown in Figure 1(b) are introduced where a reaction beam was placed on top of the specimen, which was elastically supported with very low linear stiffness in the horizontal direction and almost rigid in the vertical direction, and the relatively stiff reaction force measurement links were connected between the reaction beam and rigid reaction prestressed concrete wall in the horizontal direction [2],[3]. Most of the horizontal reaction force was measured in real-time using the four force measurement links, and because the reaction beam hardly moved, almost no inertial force was generated. Furthermore, by supporting the reaction beam with elastomeric isolators, which are soft in the horizontal direction and rigid in the vertical direction, only around 1% of the horizontal force transferred through these elastomeric isolators can be accurately supplemented by measuring the deformation. The another method of removing frictional and inertial forces by simultaneously measuring compressive and shear forces inserting 3D load-cells between the reaction beam and specimen has already been introduced in several reports [4], [5]. However, to withstand vertical forces of several thousand tones, dozens of 3D load-cells must be arranged and the axial and shear forces calculated from the combined forces, which not only requires handling a large amount of data but also introduces errors due to the correlation between axial and shear forces. The required shear force is roughly 1% to 10% of vertical load in typical seismic isolation testing systems, therefore, shear strain on a stiff load cell that can withstand high axial force will be minute, especially smaller specimens, making it difficult to ensure accuracy. In the method proposed by authors, the horizontal and vertical reaction forces are separated, a small numbers of large-capacity load cells with single axis are placed in each direction, thereby simplifying and increasing the reliability of the data handled. While similar measurement mechanisms have been employed in past experiments with no significant large vertical loads [6], the primary objective of our development was to realize this horizontal reaction force measurement system under immense vertical loads exceeding 10,000 tons.



(a) Plan (b) Section (c) Detail of PC strands anchoring reaction beam

Figure 3 Plan and section of real-size dynamic testing facility in Japan

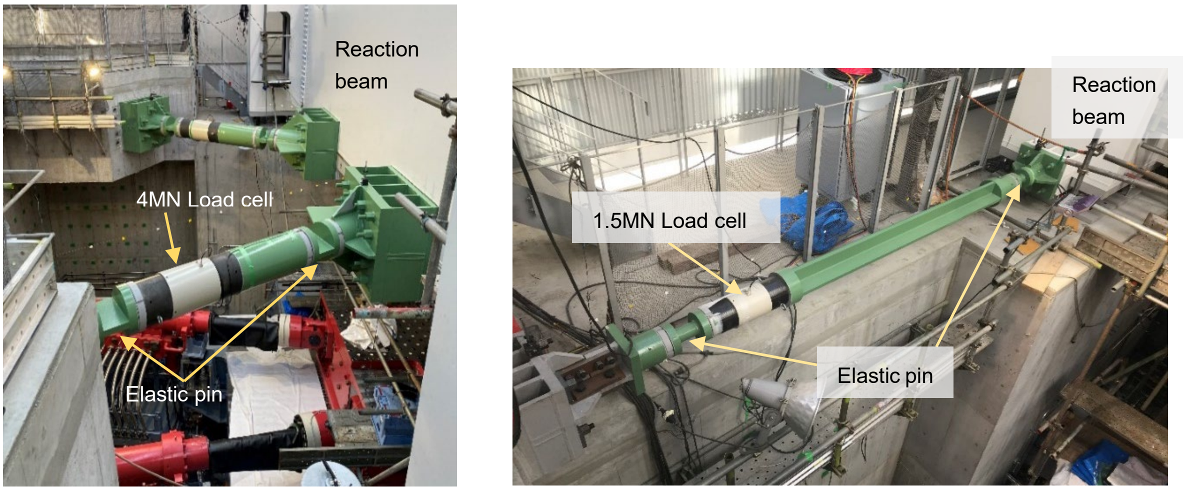
3. New horizontal force measuring system

Figure 3 shows the plan and cross-sectional views of the constructed experimental set-up. 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 in the vertical z-axis 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 of 14.6m length between bottom and top anchors that apply 50,000 kNs 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, 99% of the horizontal force is measured through the reaction measurement link, where the ratio of horizontal force transferred through the laminated rubber bearings is less than 1%. Due to the reliable elastic characteristics of the laminated natural rubber bearings and geometrical stiffness of the PC strands, horizontal forces can be accurately included in the resultant reaction forces by using their horizontal deformation.

The reaction beam consists of four steel box beams with section of 2.5 m height, 1.2 m wide, 9.1m long, 22 mm to 30 mm in thickness and 20 tons weight on each, and two more box-shaped beams of 1.25 m wide, 7.2 m long and 22 tons weight on each end transverse beams connected in an H-shaped plan, as shown in Figure 3(a). The six beams were installed individually and assembled at the construction site by friction bolt connections. In addition, large plates of 30mm of 4.8m width and 8.4m length are bolted on the top and bottom of the connected boxes for integration. The expected vertical deformation was 7.6mm (1/1450), and the torsional angle was 1/759 under vertical load of 30,000kN and horizontal load of 6,000kN.

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 of 4.8m wide and a couple of rotational constraint measurement links, as shown in Figure 4. The 4MN and the 1.5MN load cells are mounted on the V-shaped links and the rotational constraint links, respectively. V-shaped measurement links restrain the displacement of the reaction beam in the x 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. 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 prestressed concrete 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.

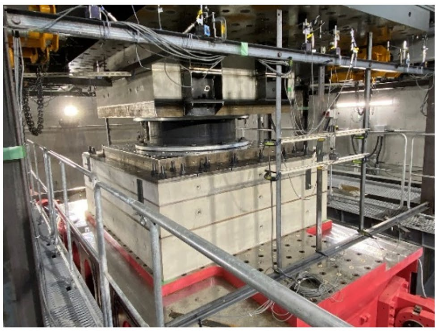
Both links should be able to keep up with the vertical displacement of the center of the reaction beam under a vertical force of 30,000 kN within the elastic range, and the shear force and bending moment applied to the load cell must be controlled within the allowable range. For this reason, joints with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



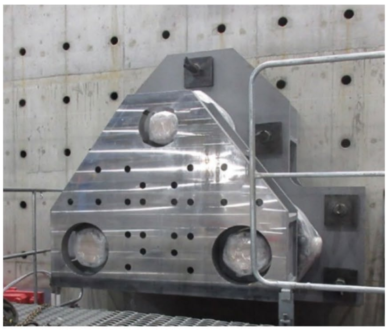
(a) V-shaped measurement link (b) Rotational constraint link

Figure 4 Reaction-force measurement link

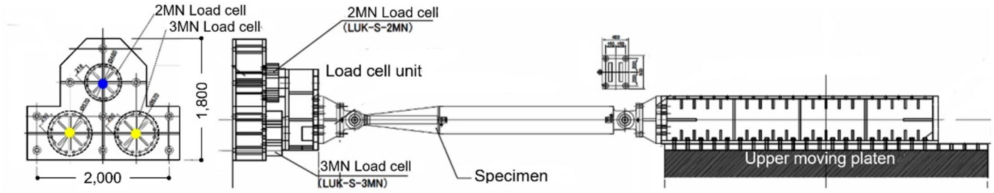
Testing jig for seismic isolation bearings and energy-dissipation devices are shown in Figure 5. Not only seismic isolation bearings but short column specimens up to 2.1m height can also be assessed by this testing device. For energy-dissipation devices, an additional load-cell unit consisting of three 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 forces will be directly measured eliminating the effects of friction and inertia forces similar to the measurement link system.



(a) Test jig for seismic isolation bearings



(b) Test jig for energy-dissipation devices



(c) Set-up for energy-dissipation devices

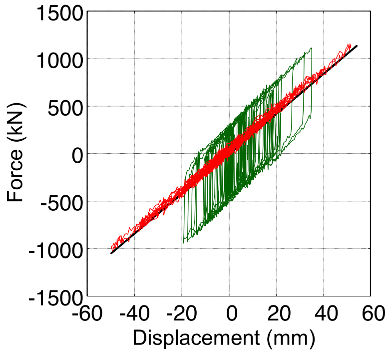
Figure 5 Test jig for seismic isolation bearings and energy-dissipation devices

4. Hybrid simulation capability

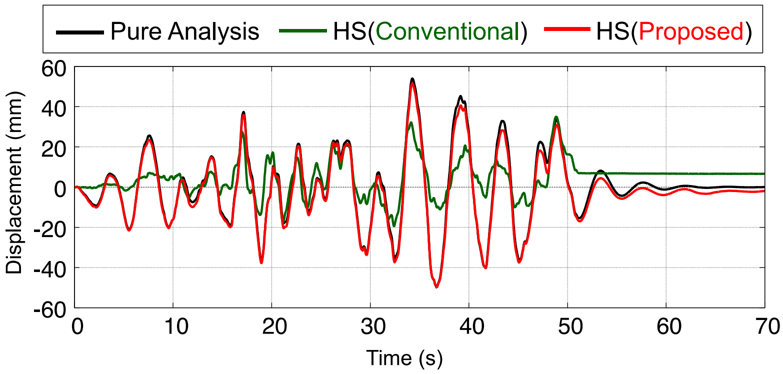
The hybrid simulation is an experimental method that is used to deform a structural specimen as if it were responding to an earthquake ground motion using an online computer-controlled simulation of dynamic response. In hybrid simulation, one member or part of a structural system is built experimentally 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. 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 [7], [8], which provides a high-speed, low latency data communication between the servo-controller and the analytical computer by reflective memory.

Figure 6 shows the result of hybrid simulation experiment for simulating the response of two-story seismically isolated building model with a real natural rubber bearing. In Figure 6(a), the green line from the load cell attached to the horizontal jack includes the effects of friction force, while the red line from the proposed measurement link correctly shows the reaction hysteresis without the effects of friction force. Due to the contamination of the friction forces, the obtained time history of the building model from (the green line in Figure 6(b)) has large error to the simulation (the black line), while the hybrid simulation with the proposed links (the red line) provides almost the same as the simulation.



(a) Hysteresis at isolation layer



(b) Time history obtained by hybrid simulation

Figure 6 Comparison of conventional and proposed measurement system with hybrid simulation

5. Conclusive remarks

In this article, a recently constructed dynamic testing facility for seismic isolation bearing in Japan, E-isolation, eliminating the effects of friction and inertia forces of loading system was introduced. All the researchers in the world on seismic isolation or energy-dissipation devices are welcomed utilizing this facility.

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