Performance Evaluation of Seismic Isolators by Means of Hybrid Simulations

S. Strano, M. Terzo

***Abstract*—In this paper, the implementation and validation of hybrid tests for base-isolated structures are presented. Hybrid testing is a technique that combines physical testing and numerical simulation. In this study, two different types of seismic isolators have been considered: fiber reinforced bearings and high damping rubber bearings. The seismic bearings constitute the physical models and the structure is simulated by a numerical model. The experimental results demonstrate the feasibility of the proposed procedure in order to evaluate the performance of the considered seismic bearings.**

***Index Terms*— Hybrid testing, seismic isolation, High Damping Rubber Bearing, Fiber Reinforced Bearings.**

I. Introduction

Base Isolation is technology that consists in inserting a devices, flexible in shear, at a given level of the structure. In this way, there is a modification of the building dynamic properties and, with a proper design, base isolation prevents the ground motion amplification that would damage the construction in its fixed base configuration [1].

Within this context, shaking table test is a well established method used to evaluate the seismic performances of base-isolated structures. This testing technique is able to simulate conditions very close to what would occur in reality during a particular event. For shaking table tests a complete structural system is required and the specimens need to be carefully designed with the rules of dynamic similitude. The main disadvantages of this testing technology are: (i) high costs, (ii) limits on the size and weight of the specimen due to limited capacity of most shaking tables available worldwide.

Due to high costs of a shake table test, in this study a hybrid testing procedure is used to investigate the performance of a base-isolated structure.

Real-time hybrid simulation (RTHS), also known as real-time substructure testing, is a real-time extension of conventional hybrid simulations. It consists in dividing a structural system into a physical substructure containing a key region of interest that is experimentally tested and a numerical substructure that contains the rest of the structure, which is numerically simulated [2, 3]. During a RTHS, the experimental and analytical substructures are coupled by maintaining compatibility and equilibrium at the interfaces between these substructures. RTHSs are very effective for the assessment of the dynamic and rate-dependent behaviour of systems subjected to dynamic excitation [4]. Thus, this experimental procedure facilitates the testing of structural components associated with vibration control, including passive (e.g., isolation bearings and dampers), semiactive, and active control devices, which are typically nonlinear and rate dependent because RTHSs are performed in real-time; therefore, they can account for velocity-dependent phenomena, such as strain-rate effects and viscous damping forces. This characteristic is one of the most interesting features of the method. Special attention has been recently directed toward the application of this technique to the evaluation of the performance of passive control systems for the seismic protection of buildings.

In this study, two different types of seismic isolators have been adopted for RTHS: a fiber reinforced bearing (FRB) and a High Damping Rubber Bearing (HDRB).

FRBs are a low cost product because their production involves a less labor-intensive manufacturing process [5, 6].

A great advantage of using fiber reinforcement is that of giving the possibility to build each isolator simply by cutting pads to the required shape and dimension.

The RTHSs have been performed adopting a suitable test rig characterized by a versatile control algorithm in order to provide stable dynamic tests.

II. Real-Time hybrid simulation system

For RTHSs, the physical substructure interacts with a computational model (numerical substructure) by means of a feedback loop, exchanging information in real time with minimum error between them [7]. In Fig. 1, a scheme for RTHSs is shown, where $\ddot{x}_g$ is the ground acceleration, d is the command displacement obtained by numerical integration of the equations of motion, r is the compensated displacement, u is the control action, y is the measured displacement, e is the control error and F is the reaction force of the specimen that is used as the input of the numerical integration scheme.

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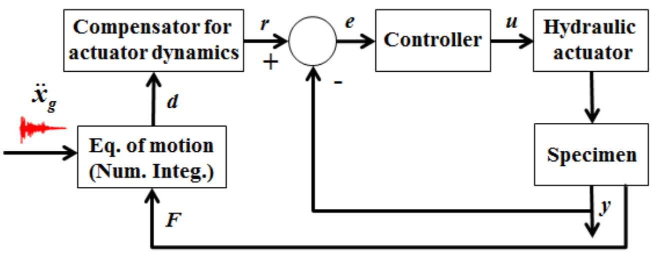

Fig. 1. Schematic of a RTHS.

The displacement at the degree of freedom of interest is calculated using a numerical model and is passed to the delay compensator, which, in turn, sends the reference signal to the controller of the hydraulic actuation system.

III. Test Rig Description

The experimental setup used for RTHSs was designed to perform shear tests on seismic isolators [8-11]. The machine mainly consists of a sliding table (1.8 m x 1.59 m) driven by a hydraulic cylinder that allows shear testing of isolators, while a vertical actuator imposes constant vertical loads on the devices under test [12]. The table motion is constrained to a single horizontal axis by means of recirculating ball-bearing linear guides. Fig. 2 shows that the isolators being tested are placed between a sliding table and a vertical slide that moves into suitable guides integrated in the reaction frame.

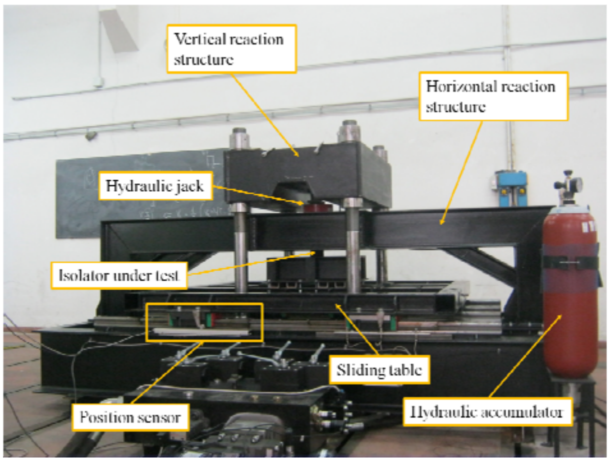

Fig. 2. Test rig components.

A hydraulic accumulator is used to keep the vertical load constant during testing.

The test rig is instrumented to measure the table position using a magnetostrictive position sensor. The sensor is placed between the sliding table and the fixed base (see Fig. 2 for reference).

The actuator force is measured using a strain gauge load cell [13, 14]. It is placed between the hydraulic cylinder and the sliding mass (see Fig. 3 for reference).

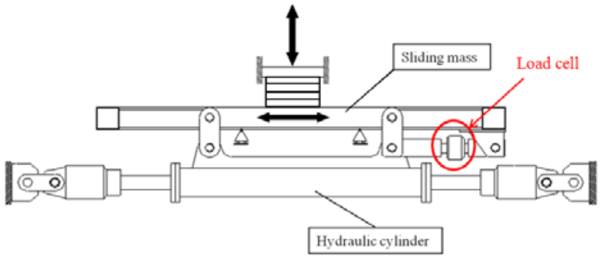

Fig. 3. Schematic of the RTHS test set-up.

The hydraulic power unit of the horizontal actuator consists of a variable displacement pump powered by a 75 kW AC electric motor. The maximum horizontal force is 190 kN, with a maximum speed of 2,2 m/s and a maximum stroke equal to 0,4 m (± 0,2 m).

Moreover, removing the reaction structure allows the testing equipment to be used as a shaking table [15, 16]. The Fig. 3 depicts a device placed between the horizontal sliding table and the vertical actuator. As previously mentioned, a horizontal displacement was imposed on the bearing by means of the hydraulic actuator. Then, the measured reaction force was fed back to the numerical model for the solution of the equation of motion. From this procedure, a command for the following time step was derived. The inertia force of the sliding mass, obtained from the measured horizontal acceleration of the table and its mass, was subtracted from the force measured by the load cell.

A computer with a dSPACE DS1103 controller board was used for solving the equations of motion and for providing real-time control.

IV. Seismic Isolators Under Tests

HDRBs are commonly employed in seismic isolation, they consist of alternate layers of steel and elastomer connected by curing. Fig. 4 shows a photo of the HDRB adopted in this study.

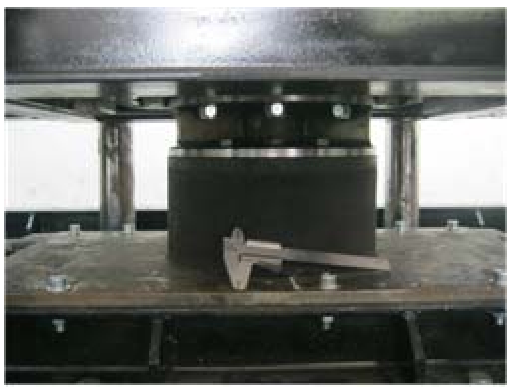

Fig. 4. Photo of the HDRB for RTHS.

The FRBs are multilayer elastomeric bearings where the reinforcing elements, normally steel plates, are replaced by fiber reinforcement. The fiber reinforcement, in contrast to the steel reinforcement (which is assumed to be rigid both in extension and flexure), is assumed to be flexible in extension, but completely without flexural rigidity. Calabrese et al. [17] studied the influence of fiber flexibility on the mechanical properties of the fiber reinforced isolator, such as vertical and horizontal stiffness. The authors showed that it is possible to produce a fiber reinforced isolator that matches the behavior of steel reinforced isolator. FRBs are significantly lighter and can lead to a much less labor intensive manufacturing process.

As shown in Fig. 5, no external reinforcing layers were used. This condition was necessary to have a steel-rubber contact interface.

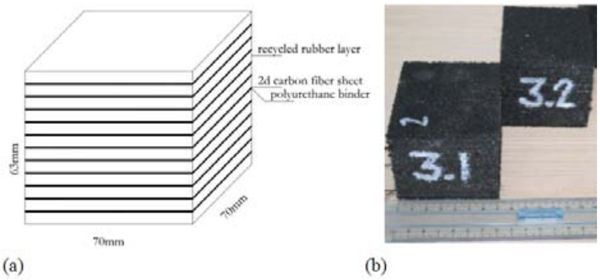

Fig. 5. Sketch of the tested recycled rubber FRBs (a) and picture of two of the tested devices (b).

The manufacturing of the bearings was very simple. The whole process took only few hours for the curing of the binder. Each bearing was shaped by a table cutting machine dividing a long pad of large dimensions. The design vertical pressure on the bearings was approximately 3.85 MPa. This is a realistic value for most base isolated frame structures.

V. RTHS WITH A FRB

In this section, the description of the RTHS adopting the FRB and the main results are reported. The simulated structure is a representation of a real model that is going to be tested on a shaking table at Department of Structures for Engineering and Architecture of the University of Naples Federico II (DiSt), Italy [18]. The base mass considered for the hybrid simulation is the mass of a rigid floor that can be bolted to the upper structure in order to have an adjunctive mass and a rigid constrain for the deformation of the columns. The building will result with a shear type configuration at the base floor, while the top mass can be considered pinned at the columns. This configuration gives a fixed base period of 0.30 s, this is in the range of periods for which base isolation can be significantly effective in reducing the seismic demand on a structure.

The selected input acceleration is shown in Fig. 6.

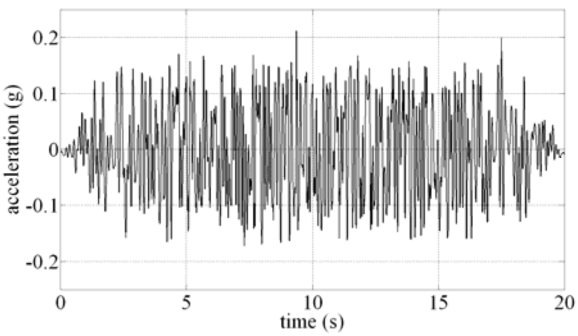

Fig. 6. Selected input acceleration.

The structure dynamic response has been calculated numerically using numerical integration of the equations of motion with a time-step of 0.001 s.

One bearing, placed between the horizontal sliding table and the vertical slide (Fig. 3), has been chosen as the physical model. The relative displacement of the isolation system (i.e. the algebraic difference of the base and the ground displacements) has been calculated and physically imposed to the bearing at each step by means of the hydraulic actuator. Then, the measured reaction force has been fed back to the algorithm for next step. Simultaneously, a constant vertical load of 18.4 kN (a quarter of the total mass) has been applied to the bearing.

In hybrid testing, inevitable time lag exists when the displacement is commanded and when the actuator reaches the commanded position [2]. For this reason, the main objective of the control system is to make the measured displacement as close as possible to the desired displacement, minimizing phase lag and providing accurate tracking of the reference signal.

To this end, suitable tracking nonlinear controller must be developed [19, 20]. The adopted control approach consists in a feedforward action integrated with a feedback one. The feedforward control has been developed on the nonlinear inverse model of the system. The feedback control has been adopted to compensate for tracking errors due to model uncertainties and unknown reaction force of the device under test [21].

The relative displacement response of the base is illustrated in Fig. 7.

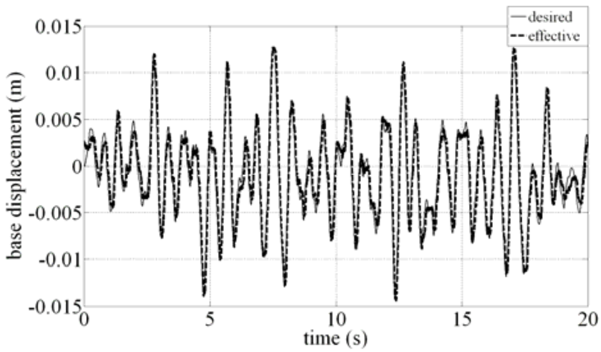

Fig. 7. Base displacement.

It is possible to see the very good tracking performance of the controller. Indeed, the relative displacement between the ground and the base, provided by the numerical model (the desired displacement), is very close to the measured one, which is imposed to the seismic bearing through the hydraulic actuation system and the sliding table.

A photograph depicting the deformed state of the bearing during the test is presented in Fig 8.

Fig. 8. Zoom on FRB deformed under hybrid simulation at peak horizontal displacement.

In Fig. 9, the comparison between the superstructure displacement, in the cases of fixed base and isolated hybrid model, is reported. The result shows a substantial reduction of the relative displacement for the isolated building.

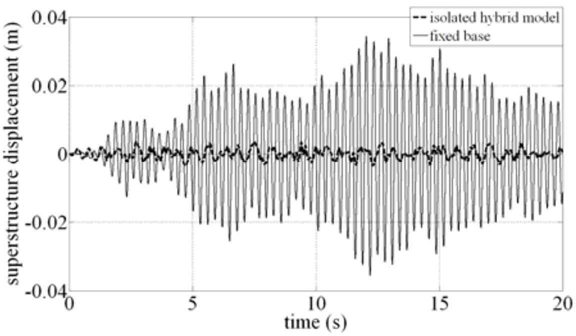

Fig. 9. Superstructure relative displacement.

The comparison in terms of superstructure acceleration, for the fixed base and the isolated hybrid model, is reported in Fig. 10.

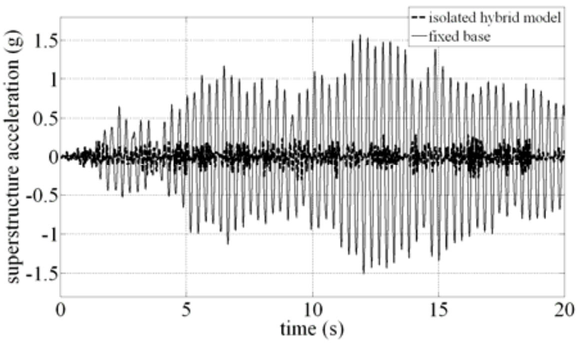

Fig. 10. Superstructure acceleration.

The effectiveness of the FRB-based isolation system is demonstrated by a substantial reduction of the peak acceleration respect the same structure fixed at the base.

VI. RTHS WITH A HDRB

The RTHS descripted in this section has been implemented to verify the applicability of the proposed testing procedure for the evaluation of seismic performance of base-isolated building equipped with HDRB. A SDOF base-isolated structure has been used with a base-isolated undamped period of 1 s. The structure has a fixed-base natural period of 0.4 s and a damping ratio of 2%. The base isolation frequency has been obtained by defining the structure mass and taking into account an equivalent horizontal stiffness of the seismic isolator $K_{h,eq}$=800 kN/m, even if the reaction force of the isolator is nonlinear due hysteresis phenomenon [22].

The system is divided into two parts: (1) the physical substructure, consisting of the seismic isolator anchored between the sliding table and the reaction structure (see Fig. 3 for reference), and (2) the numerical substructure, consisting of an elastic SDOF structure. In this way, it possible to obtain a virtual testing system suitable for the experimental analysis. This is an innovative procedure applicable in other cases of interest.The overall test setup is shown in Fig. 11.

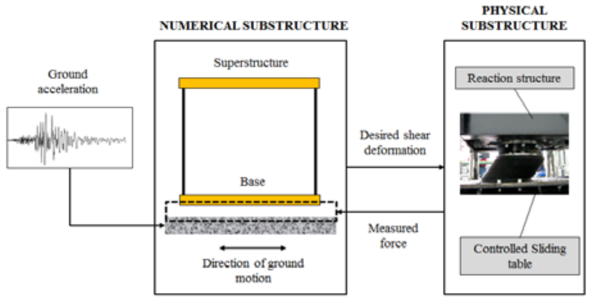

Fig. 11. RTHS test setup for an isolated structure with HDRBs.

The Friuli Earthquake (1976, Italy) has been chosen as the input ground motion. The duration of the earthquake record used is 10 s. The central difference method has been used for the integration of the equation of motion, with a time step Δt = 0.1ms. This time step has been adequate to accurately integrate the equation of motion for the natural frequencies considered in the experiments.

Fig. 12 shows the comparison between the ground acceleration and the base one.

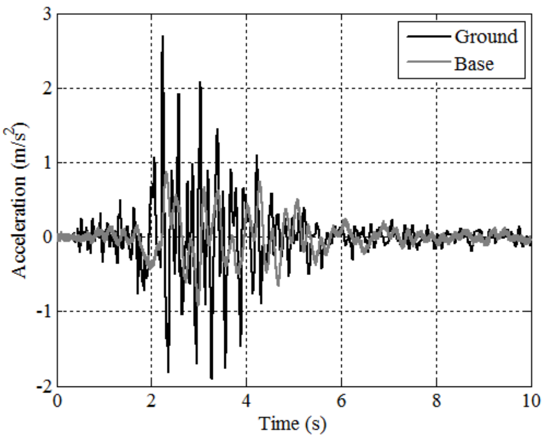

Fig. 12. Comparison between ground and base accelerations.

The acceleration diagrams of Fig. 12 show a substantial reduction of peak acceleration, this result demonstrates the effectiveness of the base-isolation system and confirms the possibility of evaluating the performance of the seismic isolator in RTHS.

The comparison between the measured displacement and the commanded one is shown in Fig. 13, the diagrams are practically superimposed as demonstration of the goodness of the compensation method.

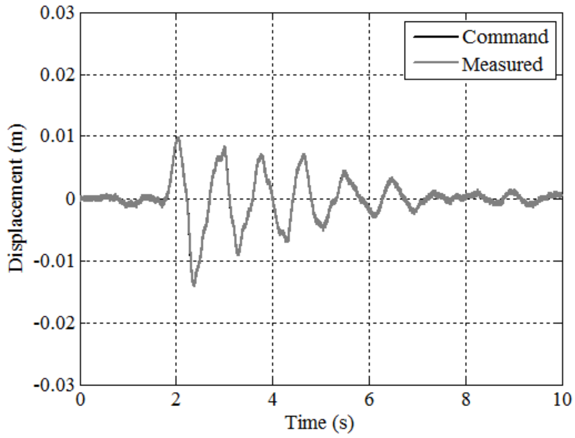

Fig. 13. Time histories of the commanded and measured displacements.

Another test has been conducted by considering a structure with a base-isolated undamped period of 2 s. The ground and the base accelerations for the second test are shown in Fig. 14.

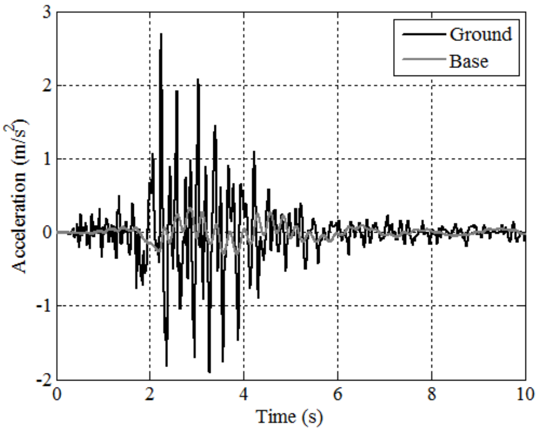

Fig. 14. Comparison between ground and base accelerations (base-isolated structure natural period of 2 s).

The higher value of the base-isolated structure natural period determines a higher reduction of the acceleration transmitted to the structure.

The measured displacement and the commanded one are shown in Fig. 15.

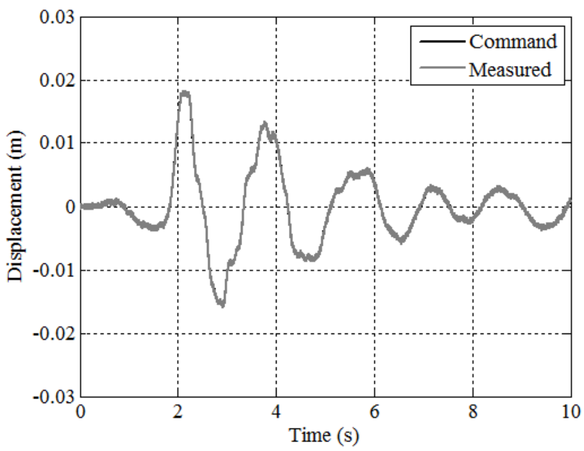

Fig. 15. Time histories of the commanded and measured displacements (base-isolated structure natural period of 2 s).

A higher value of the base-isolated natural period involves higher base displacements and lower transmitted acceleration. The results confirm the reliability of the proposed method for testing base-isolated structures in hybrid simulations.

VII. Conclusion

In this study, real-time hybrid tests have been proposed in order to have a prediction of the behavior of a base-isolated building equipped with different base isolation systems.

The real-time hybrid simulations have been performed adopting a suitable test rig characterized by a versatile control algorithm that ensures stable experiments. The results highlight good performance of the procedure and, at the same time, they demonstrate the applicability of the considered seismic devices for base isolation. Indeed, the output of the numerical model, in terms of acceleration and displacement, shows the reduction of the accelerations transmitted to the structure with acceptable shear deformations of the seismic isolators.

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