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Investigation of the Seismic Performances of an FRBs Base Isolated Steel Frame through Hybrid Testing

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***Abstract*— Hybrid testing is a technique that combines physical testing and numerical simulation. In this paper, the results of a hybrid test are presented in order to describe the seismic behavior of a steel frame isolated using Fiber Reinforced Bearings (FRBs). FRBs tested in this study are made by recycled rubber and carbon fiber reinforcement. In the hybrid simulations, the seismic bearings constitute the physical models, and the structure is simulated by a numerical model.**

The test demonstrates the feasibility of an innovative, low cost, seismic isolation technology and the applicability to frame structures.

***Index Terms* — Hybrid testing, seismic isolation, Fiber Reinforced Bearings.**

I. INTRODUCTION

Shaking table test is a well established method used to evaluate the seismic performances of structural systems. 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 hybrid testing is used to investigate the performance of an innovative low cost isolation system applied to a steel structure.

Generally, seismic isolation is applied to large and expensive buildings as computer centers, chip fabrication factories, emergency operation centers, and hospitals.

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To extend this valuable earthquake-resistant strategy to housing and commercial buildings, it is necessary to reduce the cost and weight of the isolators. The primary weight in an isolator is due to the reinforcing steel plates, which are used to provide the vertical stiffness of the rubber steel composite element. A typical rubber isolator has two large endplates (around 20mm thick) and 20 thin reinforcing plates (around 2mm thick).

The high production costs result from the labor involved in preparing the steel plates and the assembly of the rubber sheets and steel plates for vulcanization bonding in a mold. The steel plates are cut, sandblasted, acid cleaned, and then coated with bonding compound.

Next, rubber sheets and steel layers are superimposed and cooked under pressure in a mold. FRBs are a low cost product because their production involves a less labor-intensive manufacturing process.

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. Currently, all isolators are manufactured as either circular or square in the mistaken belief that if the isolation system for a building is to be isotropic, it needs to be made of symmetrically shaped isolators. But, rectangular isolators in the form of long strips would have distinct advantages over square or circular isolators when applied to buildings where the lateral resistance is provided by walls since they could be used directly under the resisting elements without the need of using any transfer beam, reducing significantly the realization costs. In FRBs, the vertical stiffness is given by the fiber reinforcement. The mechanical behavior of FRBs of different shapes is given by Calabrese et al. [1] where the influence of the stretching of the reinforcement and the compressibility of the rubber is discussed. A surprising result of the theoretical models proposed by the authors is that the mathematical structure of the theory is the same for the apparently unrelated effects of stretching of the reinforcement and compressibility in the elastomer.

An unexpected advantage in the use of a fibers reinforcement appears when an FRB is displaced in shear. The FRBs plane cross sections, in an unbonded application, can curve. The tension in the fiber bundle (which acts on the curvature of the reinforcing sheet caused by the shear) produces a frictional damping that is due to individual strands in the fiber bundle slipping against each other. This energy dissipation in the reinforcement adds to that of the

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elastomer. Therefore, when designing a fiber reinforced isolator for which a specified level of damping is required, it is not necessary to use any elaborate compound to provide dissipation.

FRBs seem to be a smart technology to mitigate seismic risk especially in developing countries where the easy production process and the low costs involved could represent a plus for their wide scale use.

The behavior of FRBs in compression and shear has been widely investigated Calabrese et al. [1] but only few experimental tests on shaking table are available in the literature.

The hybrid tests proposed in this study where performed in order to have a prediction on the response of a prototype steel building, that is going to be tested on a shaking table, to an EC8 compliant seismic event.
The comparison of the Hybrid test results and the shaking table results will constitute a companion work to this paper.

II. Recycled Rubber - Fiber Reinforced Bearings

The adopted isolators 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. [2] 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.

The tested bearings are shown in Fig. 1. They are of square shape 7by7 cm with a total high of 6.3 cm. The bearings are reinforced with 13 bi-directional carbon fiber layers with an equivalent thickness of 0.15mm. The recycled rubber has a shear modulus of approximately 1MPa at 100% deformation, under the applied vertical load.

Fig. 1. Fiber Reinforced Bearings tested in this study.

There are no top and bottom reinforcing fibers as studies conducted by Kelly an Calabrese show that, for the design vertical pressure of 3.45MPa and a frictional coefficient μ=0.9, the top and bottom surfaces do not slide and the external layers are effectively confined, with no need of further reinforcement. Moreover, the rubber-steel friction coefficient interface is higher than that at the carbon fiber-steel interface that would result in an usual configuration with the external reinforcing layers.

III. Structural model

The structure considered for the simulation is a 2 DOFs system with a total mass of 7.7 ton. The base mass is 3.5 ton, while the top mass is 4.2 ton. 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. Fig. 2 shows the real superstructure for the shake table tests. 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.

Fig. 2. The prototype superstructure.

For the shake table tests, as for the hybrid simulation, the building will be isolated on four Fiber Reinforced Bearings, one under each column. The isolation system is designed so to have a period of 1.15 s. The design displacement is 0.035m and the desired equivalent viscous damping is 10%. The bearings are designed in accordance with the criteria proposed by Calabrese at al. [1].

IV. Hybrid testing

The aim of the proposed hybrid testing consists in evaluating the response of the isolated structure due to an earthquake input. In the following the experimental setup and the main results of the hybrid testing are reported.

A. *Experimental setup*

The experimental setup has been designed to perform shear tests on seismic isolators. The machine mainly consists of a sliding table (1.8 m x 1.59 m) driven by a hydraulic cylinder that allows to impose periodic deformations to the isolator under test, simultaneously loaded with a constant vertical compression [3]. The table motion is constrained to a single horizontal axis by means of

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recirculating ball-bearing linear guides. With reference to Fig. 3, the isolator under test is placed between a sliding table and a vertical slide (in Fig. 3 the vertical slide is hidden by the horizontal reaction structure). This one is fixed to the upper side of the isolator and moves vertically by means of suitable vertical guides integrated in the horizontal reaction structure.

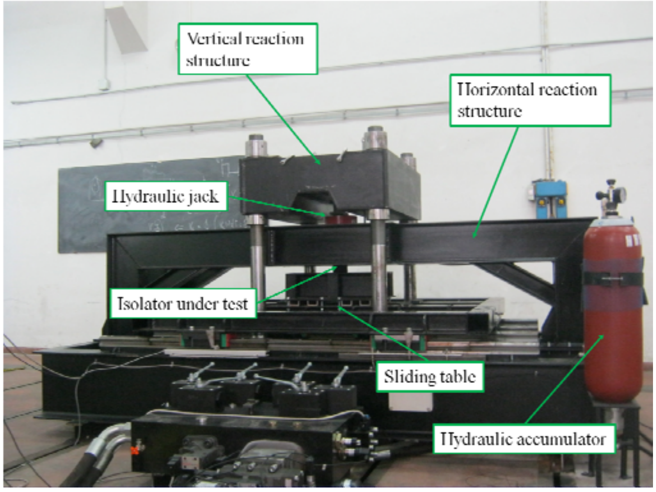

Fig. 3. Test rig showing components.

The hydraulic jack allows the isolator under test to be vertically loaded (max 850 kN) while a suitable hydraulic accumulator maintains the load constant. The jack load is balanced by the vertical reaction structure while the isolator reaction force and the correspondent overturning moment are balanced by the horizontal reaction structure.

The hydraulic power unit consists of a variable displacement pump powered by a 75 kW AC electric motor. The maximum horizontal force is 190 kN, the maximum speed is 2.2 m/s and the maximum stroke is 0.4 m (± 0.2 m).

The test rig is instrumented to detect the measurements of the table position, the actuation horizontal force and the vertical load.

The removal of the reaction structures allows the testing machine to be used as a shaking table [4].

A computer with a dSPACE DS1103 controller board has been used to solve the equations of motion and for providing a real time control.

B. *Hybrid testing results*

In this section the hybrid testing procedure and the main results are reported.

The earthquake input used for the hybrid testing is an artificial record generated using Seismo Artif [5]. The target Spectra for the record is representative of the site response of Naples (14.2767, 40.863), on a rock soil (soil class A), with a Topographic Category equal to 1, for the 949yrs return period event [6].

Records are generated trough a physical simulation of earthquake process and are qualified with regard to the seismogenetic features of the source and the soil conditions appropriate to the site [7].

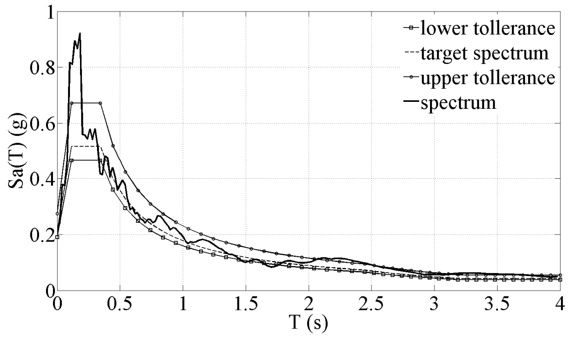

Fig. 4. Acceleration spectra of the selected record and EC8 limits.

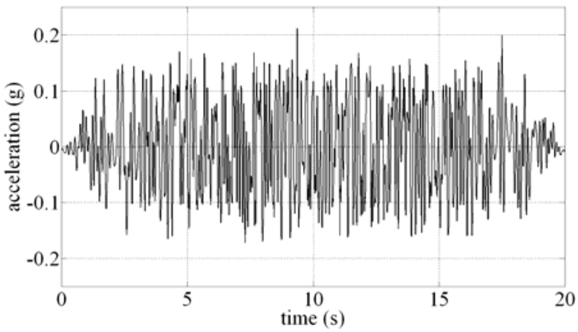

Fig. 5. Selected input record.

The main condition to be satisfied by the chosen ground motion was that the elastic spectrum did not underestimate the spectra, with a 10% tolerance, in a wide range of periods namely 0.3-4 s.

Taking advantage of the symmetry of the prototype structure, described in Section III, each isolator supports a quarter of the total weight and the structure that is modelled as a two degree of freedom system (base + superstructure). The first degree of freedom corresponds to the horizontal displacement of the base and the second degree of freedom corresponds to the horizontal displacement of the superstructure.

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 [8]. 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 [9, 10, 11]. The adopted control approach

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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.

The relative displacement response of the base is illustrated in Fig. 6.

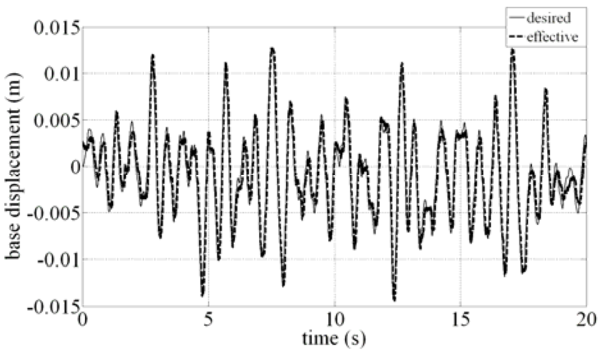

Fig. 6. Base displacement.

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 7.

Fig. 7. Zoom on FRB deformed under hybrid simulation at peak horizontal displacement.

The real time bearing measured force vs. deformation cycles (for a single bearing) is presented in Fig. 8.

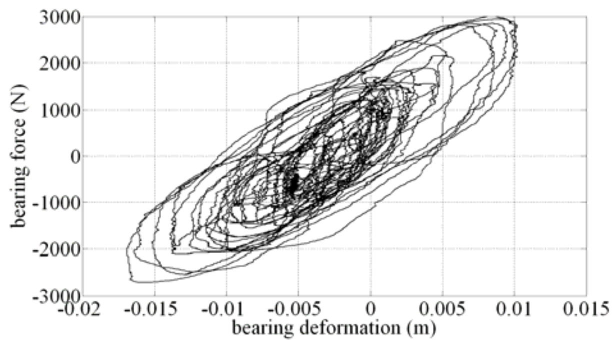

Fig. 8. Bearing force vs bearing deformation.

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.

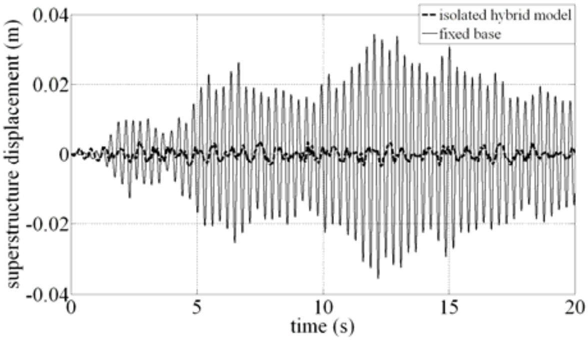

Fig. 9. Superstructure relative displacement.

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

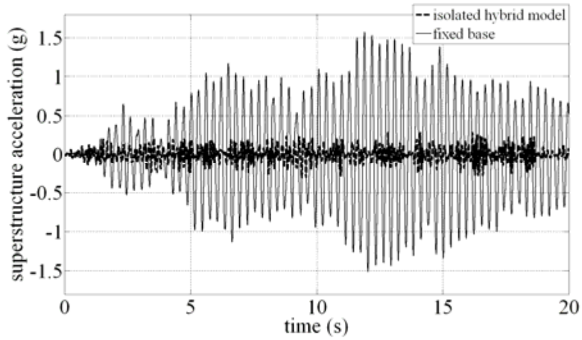

Fig. 10. Superstructure acceleration.

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

V. Conclusion

In this study, hybrid tests have been proposed in order to have a prediction of the behavior of an FRBs isolated building that is going to be tested on a shaking table at DiSt, Italy.

This work gives information about the real performances of a new low cost seismic isolation technology.

As seen by the tests, FRBs perform well as seismic isolators even when applied to light frame structures as local devices. This finding is particularly important for the development of this new and low cost technology.

In addition, shaking table tests on the prototype structure will allow a better understanding of the FRBs performances and will offer a benchmark to the prediction of the behavior of the structure to the shaking table tests.

The comparison of the Hybrid test results and the shaking table results will constitute a companion work to this paper.

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