Shake-table test assessment of a base-isolation device for the seismic protection of the Goddess of Morgantina statue

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Keywords: Shake-Table Test, Seismic Protection, Experimental Dynamics

Abstract. Monuments and museums contents in the Mediterranean area have revealed a poor dynamic behavior and suffered large damages during past severe seismic events. Their protection deserved great research efforts due to their inestimable values and high cultural significance. From an analytic point of view, art and museum objects, statues and displays are generally modelled as rigid blocks and have been extensively studied in the non-linear dynamic context. On the other hand, only limited experimental researches have been carried out. Base isolation devices have proven to be highly effective in control the dynamic behavior of for statue-like items. This work presents an analytical and experimental study for the dynamical characterization of a bidirectional base-isolation device. The ability of the device in reducing the dynamic response of statue-like objects has been investigated by means of full-scale shaking table tests carried out at L.E.D.A. Research Institute at the “Kore” University of Enna. Experimental results are then used to calibrate an analytical model of the device. The Goddess of Morgantina statue has been selected as case-study due to its significance and since it is equipped with a base-isolating device in its present placement.

Introduction
In the last decades, monuments and historic buildings located in the Mediterranean area have been exposed to several major earthquakes and extensive damages occurred. While the seismic protection of historic buildings is a well investigated research field with a large amount of numerical and experimental activities, also museums contents, artefacts and statues deserves the attention of scholars due to the high cultural significance and the inestimable value of most of them. Museum artefacts and statues are usually modelled as rigid bodies and no specific provisions are indicated in seismic codes, since they are considered as non-structural elements. Generally, they are analyzed in the non-linear dynamics context [1-3], but the experimental works remain limited. Base isolation techniques revealed to be very effective in seismic protection, also due to their small size, simplicity and affordability.

This paper presents a research conducted in the framework of the Research Project eWAS - An Early-Warning System for Cultural Heritage, funded by the MUR (Italian Ministry of University and Research), which aimed to evaluate the natural hazards to which Sicilian monumental and historical heritage are exposed. An extensive analytical and experimental study to characterize the dynamic performance of a bidirectional base-isolation device is presented. The isolator is based on an element patented as KSJ (Kinematic Steel Joint), consisting of a multiple articulated quadrilateral mechanism with crossing rods, entirely made of cut and folded steel sheets, thus reducing production and maintenance costs [4] and extending the applicability of the base-isolation techniques also to non-structural elements or cultural heritage items. Depending on the item to be protected, KSJ elements can be arranged in several configurations. In order to realize a base-isolation device for statue-like items, as illustrated in Fig. 1-a, KSJ elements can be assembled as
to form two double-rail stacked systems attached to a rigid base. In this way, the statue can undergo horizontal bidirectional relative displacements with respect to the ground.

Figure 1. The statue of the Goddess of Morgantina: a) the full scale replica with the isolation device on the shaking tables at L.E.D.A.; b) in its present placement;

The Goddess of Morgantina statue (depicted in Fig.1-b) has been selected as case-study. This 2.24m tall statue, carved in the 5th century BC in Sicily, was illegally excavated from the archaeological site of Morgantina (Sicily) in late 1970s, and exposed at the Paul Getty Museum in for several years. When the statue was finally returned to Italy on 2011, the base-isolating device, designed and realized in California, has been maintained.

Basing on an accurate 3D laser-scanner survey and 3D-printed form-work, a full-scale replica of the Goddess of Morgantina statue has been constructed. A fibre-reinforced cementitious mortar has been selected for its highly fluidity and for its unit mass, in order to reproduce as close as possible the mass and inertial properties of the actual statue. Full scale shaking table tests have been carried out at L.E.D.A. Research Institute of the "Kore" University of Enna [5]. A great amount of experimental data has been collected in order to prove that the design characteristics of the device are adequate to reduce the acceleration transmitted to the statue and to calibrate an analytical model of the isolated base.

Modelling of the dynamical behavior of the isolation device

Due to the kinematic characteristics of KSJ elements, the base-isolation device under study can be classified as a friction pendulum bearing, since it produces vertical upward displacements as it moves away from the central rest position. The protected item is then constrained to have trajectories contained in a double-curved concave surface. However, unlike conventional bearings, this device can resist uplift and provide reactions to the overturning moment but it does not protect against the earthquake vertical component.

In the base-isolation device at hand, the bi-directional behavior results from the composition of two orthogonal motions at each rail level, which depends on only one co-ordinate. The restoring and frictional forces exerted by the isolator and its self-centering capabilities depend on the slope of the trajectories. By considering, the rails in x direction, and by assuming that the surface can be expressed as z(x), it can be shown that the horizontal component of the restoring and frictional forces can me modelled, respectively, as [6]:

\[ F(x) = k(x) \frac{dx}{dt} \]
\[ F(x) = \mu \frac{dx}{dt} \]
\[
F_R(x) = mg \frac{z'(x)}{1 + z'(x)^2}; \quad F_{R,sl}(x, \dot{x}) = -mg \frac{\mu(\dot{x}) \text{sgn}(\dot{x})}{1 + z'(x)^2}
\]  

(1)

being m the mass of the protected item, g the gravity acceleration, z'(x) the first spatial derivative of the trajectory function, \(\text{sgn}(\cdot)\) the signum function. Moreover, a velocity-variable friction coefficient can be set as [7]:

\[
\mu(\dot{x}) = \mu_{\text{max}} - (\mu_{\text{max}} - \mu_{\text{min}}) \exp(-\alpha |\dot{x}|)
\]  

(2)

where \(\mu_{\text{min}}\) and \(\mu_{\text{max}}\) are the minimum and maximum mobilized coefficient of friction, respectively, \(\alpha\) is a parameter that control the friction coefficient variation rate and the over dot means time differentiation. Classical models of friction-based systems comprise two cases, sliding and sticking. In the sliding case the relative velocity \(\dot{x}\) is non-zero and the friction force is expressed as in Eq. 1. In the sticking phase, the relative velocity is equal to zero and the friction force assumes, for equilibrium conditions, the following expression:

\[
F_{F,sl}(x, \dot{x}) = -\min\left(\left|F_{F,sl}(x, \dot{x})\right|, \left|F_{eq}\right|\right) \text{sgn}(F_{eq})
\]  

(3)

where \(F_{eq}\) is the sum of all other forces acting on the protected object in the direction tangential to the trajectory. Similar equations apply also for the rails acting in y direction and, finally, the equation of motion of the bi-directional base isolation device subjected to a seismic loading can be written in state-space form as

\[
\dot{Z} = DZ - G(Z, \dot{Z}) - \tau \ddot{u}(t), \quad Z^T = [x \quad y \quad \dot{x} \quad \dot{y}]
\]  

(4)

where \(\ddot{u}(t)\) collects the ground acceleration components and \(\tau^T = [0_{(2x2)} \quad I_{(2x2)}]\) is the load location matrix. In Eq. 4, the system matrix \(D\) and the non-linear force vector \(G\) are expressed as:

\[
D = \begin{bmatrix} 0_{(2x2)} & I_{(2x2)} \\ 0_{(2x2)} & -M^{-1}C \end{bmatrix}; \quad G(Z, \dot{Z}) = \begin{bmatrix} 0_{(2x1)} \\ M^{-1}(F_R + F_F) \end{bmatrix}
\]  

(5)

being \(M\) and \(C\) diagonal matrices containing the mass and damping parameters in x and y direction respectively, whereas \(F_R\) and \(F_F\) are \((2x1)\) vectors collecting the components in x and y direction of the restoring forces and friction force, respectively, as defined in the previous equations.

Eq. 4 can be easily solved in a step-by-step integration scheme. In the following applications, a fourth-order Runge-Kutta algorithm has been used in which, at the beginning of each step, the sliding and sticking conditions are separately assessed for each direction.

**Results of shaking table tests**

Several dynamic shaking table tests have been conducted to characterize the dynamical behavior of the device and to assess the seismic protection level [8]. In a first set of tests, broadband random noise acceleration time-histories have been imposed to measure the Frequency Response Function (FRF) between an accelerometer mounted on the shaking table (R1, input) and one on the rigid base (A1, output) of the device, under four increasing load conditions (from C0 to C3) realized by fixing heavy steel plates to the upper rigid base of the device. In the highest load level (C3), the same mass of the full-scale replica of the Goddess of Morgantina statue (about 900 kg) is applied.

Fig. 2 reports the FRFs amplitude plots for each load level, for each direction and for an input intensity of 1.0 m/s² RMS. Results show that the device is able to strongly reduce the horizontal accelerations for each load level. In particular, it is to be noted that the load level C0 (no added
masses) does not represent the normal operating configuration of the device. Moreover, a narrow magnification frequency range between 1.0 Hz and 1.15 Hz has been observed.

![Figure 2. FRF computed for random noise tests: a) x direction; b) y direction](image)

A second set of shaking table tests has been executed by applying the horizontal components of four natural historical earthquakes acceleration time-histories (Kobe, Irpinia, Norcia and L'Aquila), selected for their different frequency content, impulsive behavior, duration and intensity. Firstly, the tests have been performed at the same load levels of previous tests (with steel plates) and, secondly, other tests have been carried out with the full-scale replica of the Goddess of Morgantina statue fixed on the device. In Fig. 3, the comparison between the Response Spectra (RS) computed 5% damping of the input and of the accelerations at the rigid base for Norcia signal and for all load levels is reported. The RS curves prove that the device strongly reduce the accelerations transmitted to the protected item independently of the load level.

The seismic tests performed with the statue mounted on the isolating device shown the effectiveness in the seismic protection of the statue. Fig. 4 illustrates the trends of peak accelerations at shaking table and on the rigid base with seven increasing input intensity (from 20% to 120% of the actual one) for both directions and with reference to Kobe and L'Aquila signals.

![Figure 3. Response Spectra comparison for Norcia signal.](image)
Model calibration

The first step in characterizing the device was to identify the geometric properties of the double-curved surface. Bi-axial horizontal displacements have been imposed to the rigid base, the trajectories have been acquired by a 3-D motion capture system [8] and it has been found that the surface containing the trajectories can be modelled as an elliptical paraboloid, expressed as:

\[ z = ax^2 + by^2 \quad (a > 0, b > 0) \]  

(6)

where the parameters \( a = 0.3391 \, \text{m}^{-1} \) and \( b = 0.3190 \, \text{m}^{-1} \) have been evaluated by a fitting procedure. The equivalent oscillation periods, slightly variable along the stroke, have been estimated to be close to 2.5 s, typical values of base-isolation devices.

The remaining parameters of the analytical model, namely the masses, the damping coefficients, the friction at high and low velocity and their variation rate, have been evaluated by means of an optimization procedure, by minimizing the following objective function:

\[
J(X) = \sum_{j=x,y} \frac{1}{2} \sum_{i=1}^{N} w(i,j) \left[ x_{exp}(i,j) - x_{th}(X,i,j) \right]^2
\]

(7)

being \( X \) the vector that collects the optimization parameters, \( x_{exp} \) and \( x_{th} \) the \((N \times 2)\) matrices of experimental and analytical horizontal components of displacements, respectively, and \( w \) a weighting function which is calculated as the time derivative of the Arias’s Intensity function, in order to better reproduce the strong motion phase of the response.

Fig. 5 depicts the results of the proposed procedure for the seismic test conducted with Kobe signal at 100% of its actual intensity. The comparison among the acceleration time history recorded at the rigid base and the analytical one is reported. This latter, is obtained in correspondence of the
following optimal set of parameters: \(m_x = 900\text{kg}\), \(m_y = 980.6\text{kg}\), \(c_x = 133.4\text{N}$/m\), \(c_y = 137.4\text{N}$/m, \(a_x = 0.3070\text{m}^{-1}\), \(a_y = 0.3693\text{m}^{-1}\), \(f_{\text{max}} = 0.88\%\), \(f_{\text{min}} = 4.54\%\), \(\alpha = 5.43\). It appears that the proposed analytical model is able to capture the essential features of the response in terms of accelerations, but further in-depth investigation is needed to enhance the model.

**Conclusions**

In order to characterize the dynamic behavior of a bi-directional isolating device based on the patented KSJ system, an experimental and analytical research has been carried out.

An analytical model of the device has been set up and calibrated, basing on the results of a full-scale shaking table tests campaign performed at L.E.D.A. Research Institute of Kore University of Enna. At this aim, a full-scale replica of the Goddess of Morgantina statue, chosen as case-study, has been constructed, placed on the isolation device and subjected to broadband random noise and seismic tests with increasing intensities. Test results demonstrated the ability of the device in highly reducing the seismic acceleration transmitted to statue-like art objects.

Finally, the calibration parameters of the analytical model have been evaluated by an optimization procedure, so that the model is able to capture the essential feature of the response.

**Acknowledgements**

This work has been carried out in the framework of the research project "eWAS An Early WArning System for Cultural Heritage" (ARS01 00926), funded by Italian Ministry for University and Research, whose financial support is gratefully acknowledged.

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