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# Developing a laboratory facility to assess friction coefficients of standing samples

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## Abstract

The numerical representation of the dynamic response of art works is the most reliable instrument to predict their seismic safety. Their adoption, however, require the knowledge of the effective mechanical properties of the artifacts and their restraint conditions. Namely, the amount of friction arising between standing art works and their supports largely affects the quality of their collapse and, therefore, the choice of the model to adopt in the analysis. In this work a facility for assessing the dynamic contact behaviour of marble sample standing on different supports has been investigated. The facility consists of a dynamic test to perform through the bidirectional shaking table at the Disaster Resilience Simulation Laboratory at the Politecnico di Torino. The friction coefficient has been found from the dynamic test by comparing the acceleration registered at the load cell, which is related to the reaction of the sample, and one measured at the shaking table surface. The obtained values of friction coefficient have been related to the velocity of the adopted input. A preliminary test on a single concrete sample has been performed to check the proposed procedure, by considering three different loading conditions: one of them is the acceleration history of a real ground motion, while the other two have a constant amplitude and a constant frequency, respectively.

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*Keywords:* dynamic friction coefficient; marble mechanical behaviour; dynamic response of marble statues; artefacts analysis; seismic safety of art works.

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## 1. Introduction

In these years, the seismic safety of art collections has been collected a great attention from researchers and technical literature. Indeed, the importance of the art goods, both for economic and cultural matters, has imposed this issue in the scientific community. The reliability of the numerical investigations aimed at predicting the seismic response of artifacts under seismic excitations depends on the adequacy of the assumptions made in the analysis setting. The mechanical properties of the materials constituting the art goods play a crucial role in the model setting.

Many experimental tests have been performed (Monaco *et al.* 2014, Garini et al. 2018, Aydan 2020, Aydan Ö 2019) aimed at defining the mechanical properties of the most common materials used for art goods, such as marble, rock, granite etc. The main information needed for analysis consists of the compressive strength and the friction coefficient (Viti *et al.* 2020), which is at the basis of the collapse type (rocking, sliding, overturning) of the artifact.

This work belongs to a research project still ongoing, aimed at investigating the dynamic response of art goods. It already brought experimental results with regard to static tests (Tanganelli *et al.* 2019). Such experimental campaign referred to marble cubic specimens having different finishing standing over surfaces consisting of different materials, such as masonry, glass, plexiglass and metal. The angle between the sample and the standing plane corresponding to the sliding activation was checked through the device with a horizontal fixed plane, and an inclined, adjustable plane where the standing plane was fixed, whose angle can be read through a goniometer.

Compared to the static one, the dynamic test for checking the friction coefficient introduces further complexities, related to the uncertainties in the measure (Schmitz et al. 2005) and the effects of some parameters affecting the test, such as the moving velocity of the two contact surfaces velocity (Shih and Sung 2019), the frequency content of the loading force and the fixing measures adopted for the sample.

In this work, a facility for determining the friction coefficient through a dynamic test has been proposed, with reference to the shaking table at the Disaster Resilience Simulation Laboratory at the *Politecnico di Torino*. All the steps needed to perform the test, such as the fixing of the sample over the table, the position of the devices and the arrangement of the lectures have been considered. The proposed procedure has been applied to a concrete sample, in order to check its effectiveness. In the test, three different dynamic inputs have been adopted to simulate different motion conditions; one of them is the acceleration history of a real ground motion, while the other two have, respectively, a constant amplitude and a constant frequency.

The value of the friction coefficient has been found at each step of the test, and expressed as a function of the motion velocity.

## 2. The setting

The sample assumed for testing the proposed procedure is a cylindrical concrete spaceman, with a diameter equal to 11 cm, a height of 8.5 cm and a mass equal to 8 kg. In order to perform the dynamic test, the placement of sample on the shaking table plays a crucial role. A load cell is connected to the specimen through a horizontal hollow steel profile which is welded on a vertical rigid steel element. Figure 1 shows the scheme of the test setting.

The horizontal profile is directly connected on the top of the specimen, while the load cell is screwed on the horizontal steel element. The ABS specimen-load cell connection elements have been obtained through 3D printing. The relative movement between the supporting surface and the sample is induced by the shaking table, which induces the relative displacement between the specimen and the fixed steel element system, with a consequent arising of the acceleration. Such acceleration is read by a pair of accelerometers placed both on the shaking table and the upper surface of the sample. The accelerometers and the load cell are connected from each other to synchronize the output value.

The friction acceleration, $a_f$, can be defined as the difference between the acceleration derived from the load cell $a_s$, and one measured at the shaking table surface, $a_s$, according to the Equation (1):

$$a_f = a_g - a_s \tag{1}$$

The dynamic friction coefficient, $\mu_d$, in turn, can consequently be defined according to the Equation (2):

$$\mu_d = \frac{a_f}{g} \tag{2}$$

The step-by-step displacement and velocity are found by a Matlab code opportunely set (https://it.mathworks.com/products/matlab.html); in this way the values found for $\mu_d$ can be related to the corresponding value of the input velocity. A special attention has been paid to the measuring uncertainties and errors occurring in the test. One of the most common errors arises by the misalignment between the measuring axes (see Cimellaro and Domaneschi 2020), i.e. the normal and the tangential ones. Figure 2 shows the possible misalignment between the two axes, the acceleration values recorded on $X$ and $Y$ axes are the components of gravity acceleration due to the accelerometer's misalignment angles.

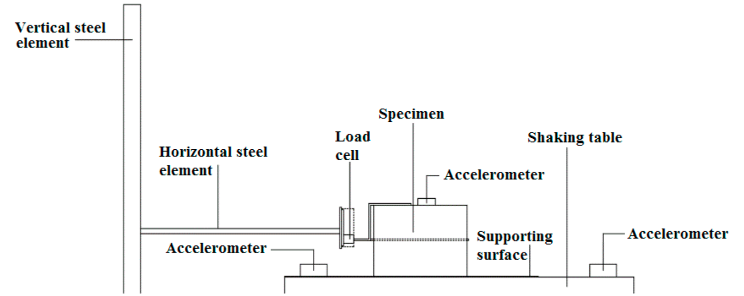

*Figure 1*. Scheme of the dynamic test.

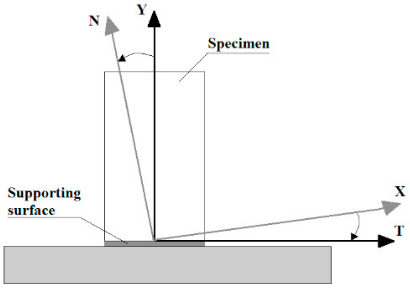

*Figure 2*. Misalignment errors

Named $a_{fx}$ and $a_{fy}$ the friction acceleration components along the axes $X$ and $Y$, respectively, the Error (E) which can affect the assessment of $\mu_d$ can be quantified by Equation (3):

$$E = \frac{a_f - \sqrt{a_{fx}^2 + a_{fy}^2}}{a_f} \tag{3}$$

## 3. The performed test

### *3.1. The shaking table*

The shaking table, shown in Figure 3a, consists of steel profiles connected through transversal rectangular sections and an upper aluminium platform. Upon the steel profiles there are aluminium guides allowing the motion, along the longitudinal direction, of sliders that support two 600x500x10 mm aluminium platforms. Each track has its own platform, which is moved by a linear electric actuator anchored under it.

On the small platforms, other two tracks and platforms are fixed. For the transversal motion other two linear electric actuators are anchored under the aluminium platforms. A more detailed description of the shaking table can be found in Cimellaro and Domaneschi (2020). The tuning of the motors, i.e. the checking of the initial configuration of all the control parameters, is made through the software LinMot-Talk, which is also used to switch on the actuators and to bring them in the home position. The seismic input is sent to the shaking table through a myRIO device manufactured by National Instruments. This device is physically connected to the motors' drivers and also to an accelerometer, which is located on the platform and allows catching the actual response of the system. The LabView code is used to set the input and output sampling rates, to generate a sinusoidal seismic signal or to load a real one, to scale it, to start and stop the motion and finally to compare the data obtained from the accelerometer with the theoretical ones. The accelerometers and the load cell are connected each other to synchronize the output value. The sampling frequency of load cells and accelerometer is 10 Hz, while a dynamic sinusoidal input with frequency of 80 Hz is adopted.

*Figure 3*. Shacking table at the Politecnico di Torino.

### *3.2. The dynamic excitation*

The dynamic excitation has been assumed according with three different inputs (see Figure 4), both natural and artificial; in this way it will be possible to affranchise the response of the sample from the dynamic properties of the motion, achieving more general results.

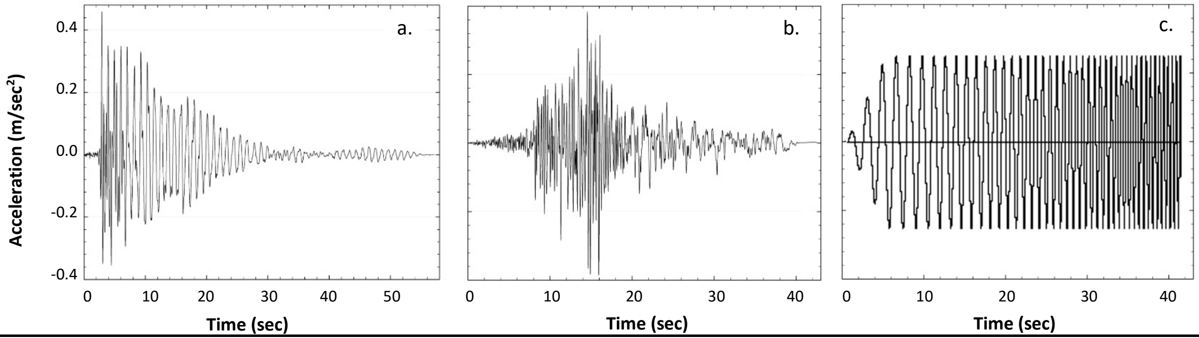

Figure 4. Acceleration histories of the three input motions: a. constant frequency; b. real acceleration history; c. constant amplitude.

The first input motion, shown in Figure 4a, has a constant frequency signal and an amplitude which decreases in the time; the second input (Figure 4b) is the effective acceleration history recorded during the Central Italy earthquake (2016/10/30). Finally, the third input, shown in Figure 4c, refers to a sweep signal with constant amplitude.

### *3.3. The results found on the sample*

Figure 5 shows, for the three input motions, the accelerations measured on the spaceman, while Figure 6 shows the values obtained for the dynamic friction coefficient expressed as a function of the motion velocity.

As can be seen, the velocity has both positive and negative values, since the sample experiences accelerations of alternative signs, passing continuously from static to dynamic conditions. The value of $\mu_d$ has a monotonic – growing – trend at the increasing of the absolute value of the velocity; moreover, it can be observed that $\mu_d$ has almost the same trend for positive and negative values of velocity.

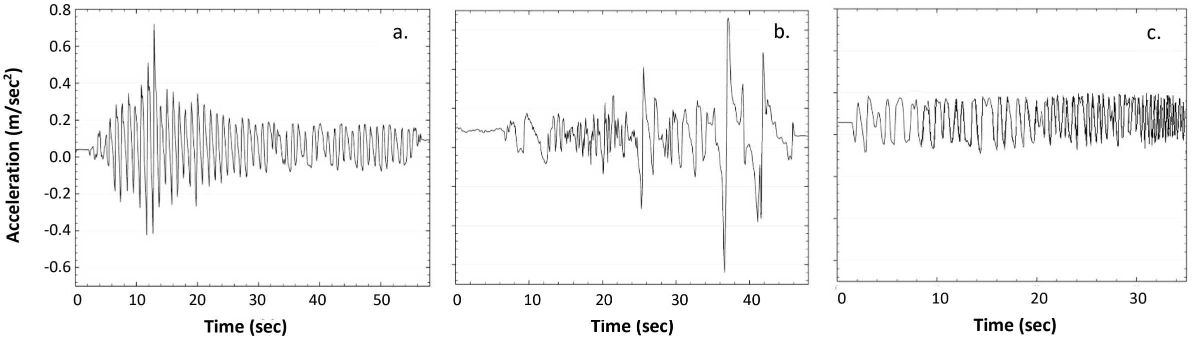

Figure 5. Acceleration histories measured on the specimen: a. constant frequency; b. real acceleration history; c. constant amplitude.

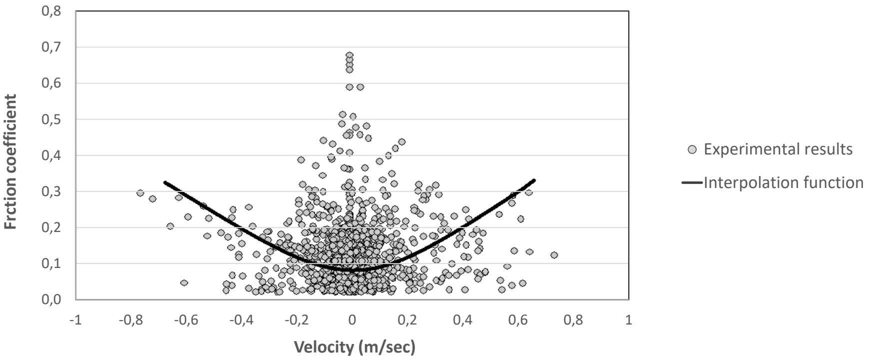

Figure 6. Dynamic friction coefficient as a function of the motion velocity.

## 3.4. The next development

The research program is still going. In the next step, the dynamic test will be carried on a marble sample compatible to the ones already checked through the static investigation made by the Authors (Tanganelli *et al.* 2019), made on cubic marble samples, having different textures in each of the six the marble sides (see Figure 7). Indeed, the type of pattern of the contact sides of the art works can hardly be checked; as a consequence, the sensitivity of the friction to the texture should be investigated.

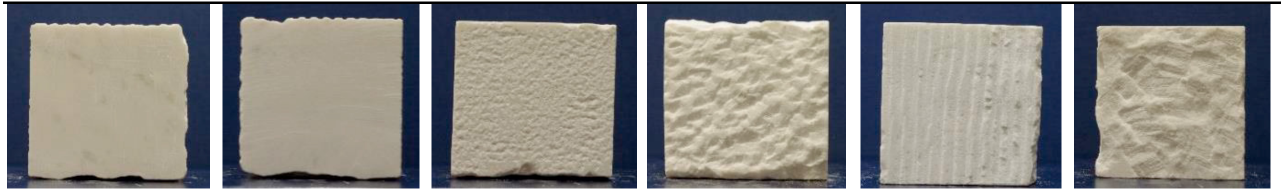
diamond sawcut | polished | fine chiselled | rough chiselled | gradined | bush hammered

*Figure 7*. The six sides of each marble sample.

In this work, for sake of simplicity, all the dynamic tests will be made by assuming the "polished" side only as contact surface. The previous investigation, indeed, showed that the polished surface provides results of the friction coefficient very close to the mean found from the six sides (see Figure 8). Furthermore, such finishing is the most likely to occur in the contact surface of standing sculptures.

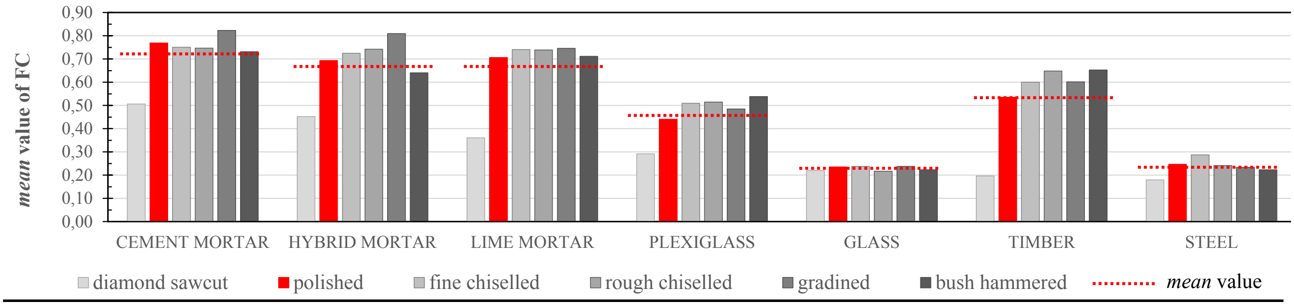

*Figure 8. Mean* values of the friction coefficient found through the static test.

## 4. Conclusive remarks

This paper shows the facility properly set to perform an experimental program for the contact behavior of stony materials under dynamic excitation. The facility has been developed with reference to the shacking table at the Disaster Resilience Simulation Laboratory at the Politecnico di Torino. A measurement procedure has been planned, able to catch the effective acceleration provided at the shaking table and the one at the specimen, and the equipment needed for the facility has been set. A first test has been made on a cylindric concrete sample, and the obtained results have been showed and related to the adopted dynamic input. This work is a preparatory step of a more general research program, aimed at describing the contact behavior of stony materials under static and dynamic loading.

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