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THE ROLE OF FRICTION IN THE DYNAMIC BEHAVIOUR OF FREESTANDING MARBLE OBJECTS

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Abstract

Nowadays, millions of art works exhibited are not always adequately protected against possible dangers and hazards, as the artifacts exhibited in churches and in small museums. An artifact can be in fact successfully modelled as a rigid body, in other word a body that does not undergo changes in shape if subjected to ground shaking due to seismic actions. In this paper the response of two marble elements in contact under sliding conditions is investigated. It is shown that the friction coefficient between object base and the supporting plane plays a key role in the overall behaviour of the rigid object during an extreme event. The experimental campaign is focused on the evaluation of the static and kinematic friction coefficient between marble specimens with two different shapes (cubic and prismatic) and three different surface roughnesses: bush-hammered, sanded and polished. The determination of the static friction coefficient has been made through a motorized plane with variable inclination angle. The influence of the friction coefficient on the dynamic behaviour of the specimens has been examined by means of dynamic tests with a unidirectional shaking table.

Keywords: Friction, Dynamic, Experimental tests.

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1 INTRODUCTION

The problem of safeguard of objects simply supported on a moving base, i.e. a building floor in case of earthquake is of great interest in several technical fields: cultural heritage, logistics, healthcare [1-5]. Since the seminal paper by Housner [6] great attention has been given to the rocking motion of rigid objects examining both the analytical [7-9] and experimental [10-12] behavior of single and double [13-15] rocking objects. The Housner basic assumption for the rocking motion is however an infinite friction coefficient between the two contact surfaces. In real cases, and especially when the protection of statues and other cultural heritage objects is involved [16, 17], and in all the cases in which the rocking motion is not an option and should be avoided [18, 19] the rough hypothesis of infinite friction coefficient must be removed. Leaving apart the discussion about the possibility of passive or active protection systems [20, 21], in all the cases in which isolation systems cannot be used, such low weight of the object to be protected, high financial commitment of the protection, a deep investigation on the real friction values should be performed. Amontons [22] defined dry friction as anything else than the force that is necessary to overcome surface inequalities and is able to cause relative motion between two surfaces subjected to normal force. Charles Augustin Coulomb [23] developed a very fine friction experimental campaign involving large rubbing surface, to take into account many factors on friction. Coulomb’s tests demonstrated that in some cases the test apparently did not follow Amontons' findings. He understood that the sliding resistance is due to multiple causes acting together, like the contribution of adhesion, especially when very smooth surfaces are in contact. Euler [24] analytical approach defined static and dynamic friction as we nowadays know them and was the first to define the coefficient of friction and angle of friction in the actual sense. Following the previous studies [22-24] and with the aim of contribute to the protection of simply supported rigid objects, this paper investigates the response of two marble elements in contact under sliding conditions. It is shown that the friction coefficient between the object base and the supporting plane plays a key role in the overall behaviour of the rigid object during an extreme event. The experimental campaign is focused on the evaluation of the static and kinematic friction coefficient between marble specimens with two different shapes (cubic and prismatic) and three different surface finishing, to reproduce the real smoothness of marble statues. The determination of the static friction coefficient has been made through a motorized plane with variable inclination angle. The influence of the friction coefficient on the dynamic behaviour of the specimens has been examined by means of dynamic tests with a unidirectional shaking table.

2 MATERIALS AND METHODS

The study provides the implementation of an extensive experimental campaign in order to calibrate the friction coefficient between two surfaces in contact with different roughness. The material chosen for experimental testing was Carrara marble.

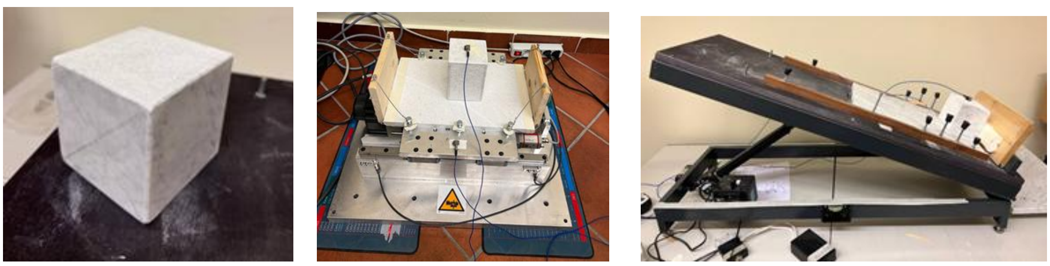

Figure 1: Marble Cube (a), shaking table (b), inclined plane (c)

In particular, three marble slabs were used, 400x250x20 mm shaped, with 3 different surface finishing: polished, honed, bush-hammered, in combination with two Carrara marble specimens, realized with cube and parallelepiped shapes, respectively 100x100x100 mm and 100x100x150 mm, was examined.

The cubic specimen had 3 different surface finishing, each one realized on two opposite faces, while the prismatic specimen had the two square bases bush-hammered and honed respectively, while the rectangular faces were rubbed-up. All the examined surfaces combinations are reported in Table 1.

Type of specimen	Surfaces combination (base x specimen face)	Label
Cube	polished x polished	LxL
Cube	polished x honed	LxT
Cube	polished x bush-hammered	LxB
Cube	honed x polished	TxL
Cube	honed x honed	TxT
Cube	honed x bush-hammered	TxB
Cube	bush-hammered x polished	BxL
Cube	bush-hammered x honed	BxT
Cube	bush-hammered x bush-hammered	BxB
Prism	bush-hammered x honed	BxT
Prism	bush-hammered x bush-hammered	BxB

Table 1: Surfaces combinations

The inclined plane consists of a steel structure with an electric piston to make it rotate around one of its edges. The engine is furthermore controlled by a speed regulator on purpose designed and realized, to perform quasi-static tests. The plane allows the placement of different slabs on the top surface. The acquisition data system consists of a set of miniaturized piezoelectric accelerometers, with sufficient sensitivity for the tests to be performed.

Dynamic tests were conducted using a unidirectional shaking table, able to perform harmonic shaking, from low frequencies with large displacements to high frequencies with small displacements.

In the experimental campaign both static and dynamic analyses were performed, with different purposes. The static analyses allowed the calibration of the static and kinematic friction coefficients by means of the inclined plane, while the shaking table tests allowed to investigate on the dynamic response of marble cube/parallelepiped freestanding on a bush-hammered slab subjected to harmonic shaking.

3 RESULTS AND DISCUSSION

3.1 Inclined table tests

The static friction coefficient has been evaluated from the value of the inclination angle corresponding to the first nonzero value of the specimen's acceleration.

A typical acceleration diagram is reported in Figure 2, where the starting motion and the impact instant, with the sudden change of acceleration sign, are clearly shown.

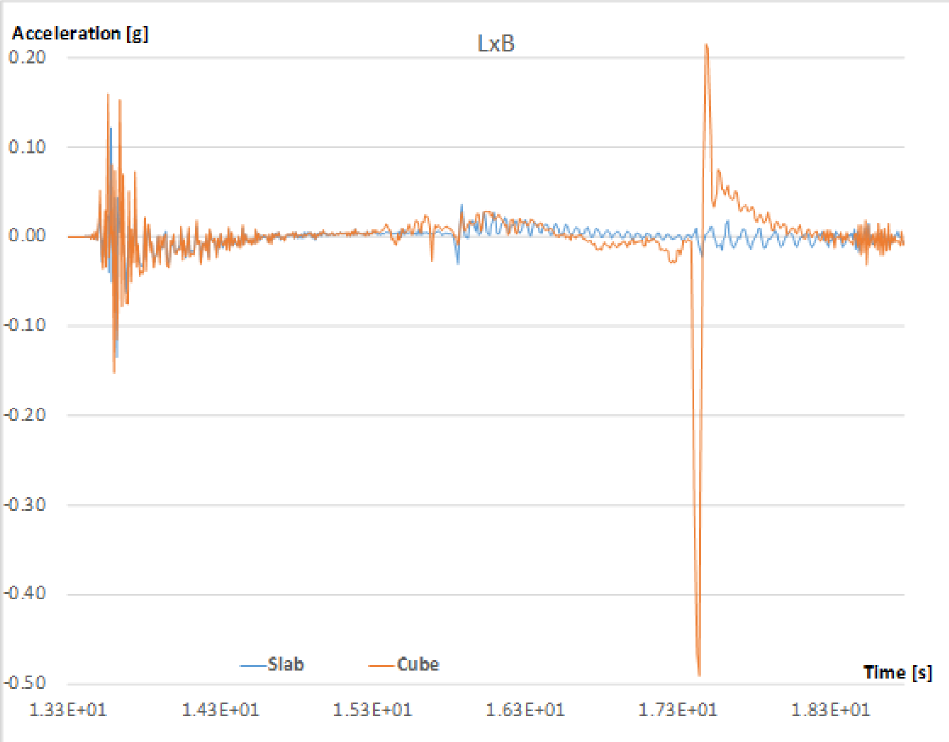

Figure 2: Acceleration time histories in the inclined plane test for the combination LxB

The determination of the motion time interval and the velocity at its end allow the evaluation of the kinematic friction coefficient.

Type of specimen	Label	N. of tests	Static friction angle [°]	Coefficient of variation [%]
Cube	LxL	17	13.43	3.80
Cube	LxT	22	13.05	7.43
Cube	LxB	15	8.02	3.37
Cube	TxL	16	25.97	3.50
Cube	TxT	17	28.12	3.98
Cube	TxB	19	9.96	3.41
Cube	BxL	18	25.70	1.71
Cube	BxT	19	24.10	2.95
Cube	BxB	20	21.64	21.34

Table 2: Mean values of friction angles and corresponding coefficient of variation for all the combinations

In Table 2 the mean values of the static friction coefficients are reported, together with the coefficient of variation for every surface combination. The only values corresponding to laboratory tests involving two bush-hammered surfaces show a high coefficient of variation, due to a large data dispersion.

3.2 Dynamic tests

The only dynamic tests with a bush-hammered base were performed. Examples of the time histories corresponding to the last rows in Table A, namely three combinations with the cube specimen and two combinations with the prismatic specimen are reported in Figures 3-6.

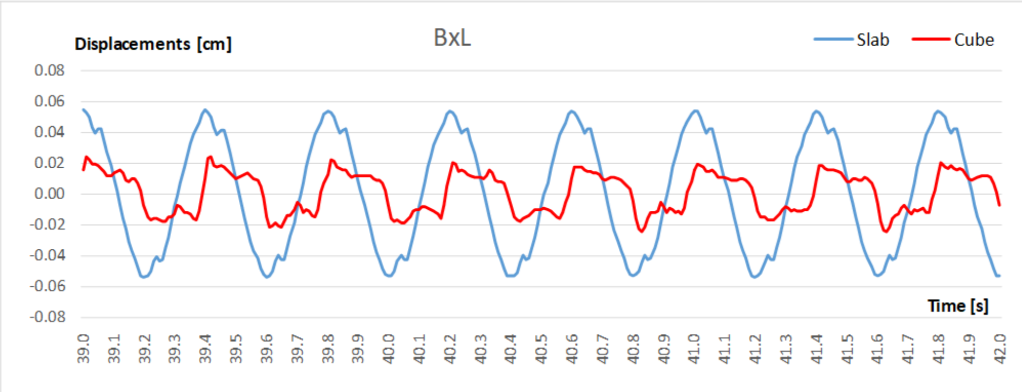

Figure 3: Time histories for the combination BxL

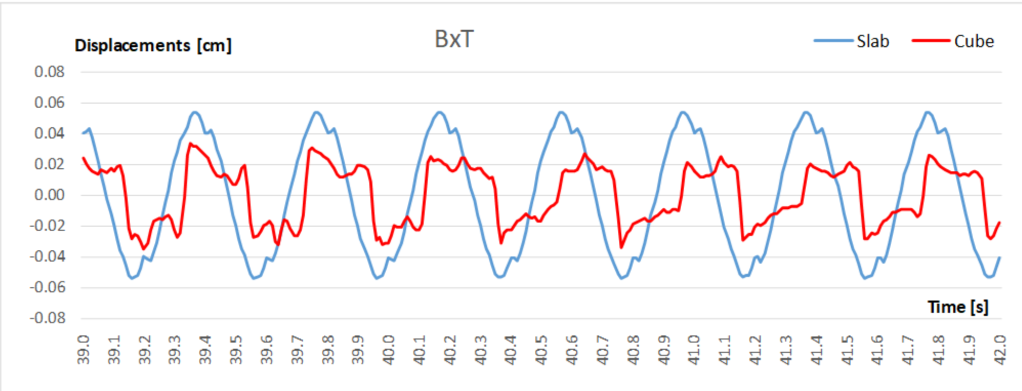

Figure 4: Time histories for the combination BxT

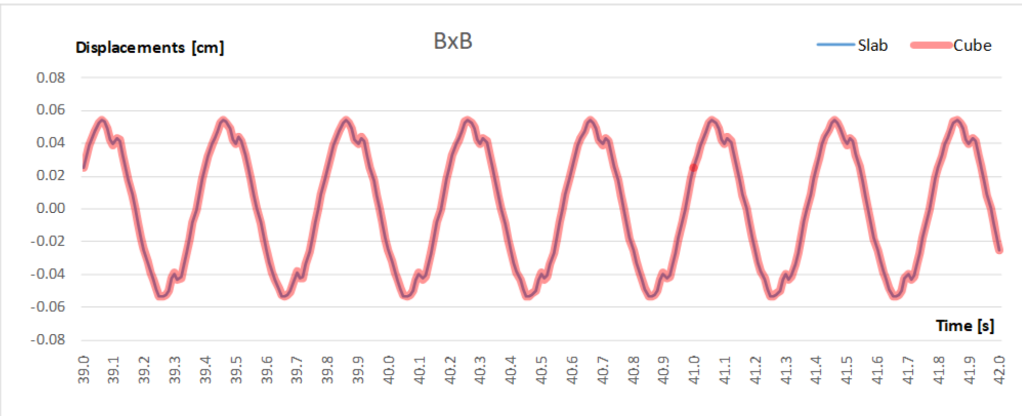

Figure 5: Time histories for the combination BxB

The base motion is a harmonic shaking with frequency 2.5 Hz and amplitude 20 mm in all the experiments. The chosen excitation shaking induces sliding motion of the specimen for all the surface combinations. It must be expected that higher frequencies cause rocking motion of the specimen [25].

The number of tests performed enable only qualitative considerations, nevertheless the increasing friction values corresponding to the time histories reported in figures 2-4 (BxL<BxT<BxB) allow some qualitative considerations. In all the diagrams the dynamic behaviour of the freestanding specimen shows the same frequency as the base excitation, while there is a reduction of amplitude inversely related to the friction coefficient. As it can be noted, in the case of maximum friction coefficient the specimen is at rest with respect to the moving base and the time histories of base and specimen are coincident in both cases, prismatic and cubic specimen. The limited possible considerations are due to the limited data acquisition system, consisting in accelerometers only. An inverse behavior has in fact been registered in the case of prismatic specimen with honed base on bush hammered moving slab. Further investigations are required in this case, involving displacements measures.

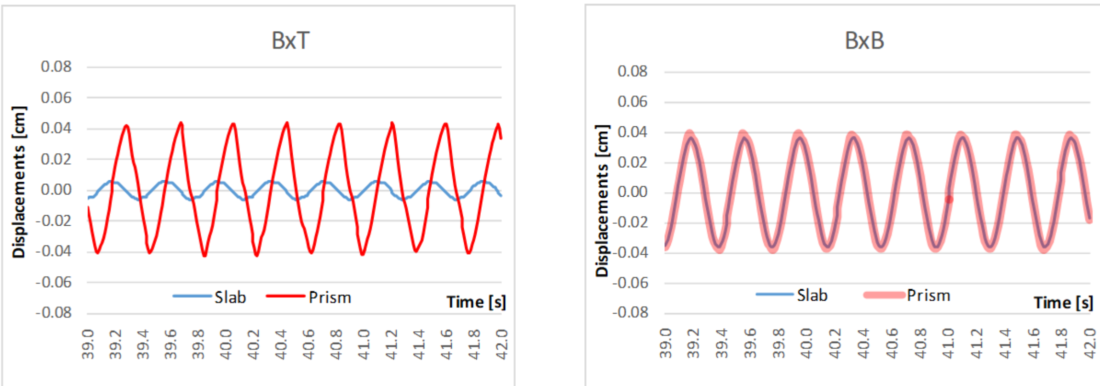

Figure 6: Time histories for the combination BxT and BxB

Due to the availability of prism surfaces finishing, the only tests corresponding to the higher friction coefficients were performed, nevertheless the dynamic behaviour in this last case follows that one observed in the cube tests, confirming the Amontons' fundamental laws on dry friction [22].

4 REVIEW

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5 CONCLUSIONS

- Limited values of friction coefficients and low excitation frequency cause sliding motion in the dynamic tests
- Frequency of moving base and specimen are the same

- The low coefficient of variation relative to the determination of the friction coefficients assures about the reliability of the tests, with the only exception of the the friction coefficients relative to bush hammered surfaces which shows a great dispersion.
- In the dynamic tests, amplitude of the specimen motion is in general reduced with respect to that of base excitation. An inverse relation has been observed with the friction coefficient, but the limited number of tests do not allow a strict quantification of the amount.

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