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Mitigation of seismic risk for museum contents: An introductory investigation

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ABSTRACT: The problem of reducing the seismic risk for art objects, that is, the objects generally contained within Museums, is examined. The behaviour of objects that can be classified as rigid, either isolated or kept in display cases, is studied in depth; numerical analyses are performed of the response to seismic oscillations. A few indications regarding the criteria to be followed to safeguard art objects of the type examined are finally derived, with specific reference to the Civic Museum of Avellino. Simple provisions to reach these objectives can be an appropriate choice of the geometry of the display cases, inexpensive modifications of their structure (e.g. an increase of the stiffness), heavier plates for the support of the exhibits, or pieces of inexpensive materials (like felt or similar fabrics) below the objects prone to rocking.

1 INTRODUCTION

Motivated by an increasing consciousness about the preservation of the cultural heritage for future generations, the seismic behaviour and safety of monumental and ancient buildings are receiving a great deal of attention in current developments of earthquake engineering.

On the contrary, still surprisingly little research work has been devoted to their contents, and to that of museums, although art objects and historical exhibits constitute a substantial part of the cultural patrimony. To our knowledge, the only systematic study in this respect is the one developed at the University of Southern California by Agbabian and his collaborators, which was presented at the 9th WCEE (1988), and later originated a detailed report (1990). Firstly, they propose a classification of art objects, of their supports and of their seismic behaviour, in order to identify simplified models for the analysis of the dynamic response; then, after going through a series of analytical and experimental checks, criteria are defined for reducing the seismic damage of the most significant objects.

Recently, Agbabian's work has been revisited and developed, with special attention to the conditions of an area of medium seismicity, like Central Italy: the main results of this study are summarized in the present paper, and illustrated in detail in a companion full-length paper (Augusti *et Al.*, 1992). In order to refer to a real example, the "Museo Irpino", the Civic Museum of the City of Avellino, has been chosen: this Museum contains a variety of exhibits ranging from 19th Century historical curios to prehistorical relics, but the majority of them consists of objects from the Greek and Roman periods found in the area.

Numerical analyses are developed with regard to objects rigid with respect to the seismic response, isolated or contained in display cases (the influence of the latter appears to have been rather overlooked by Agbabian *et Al.*, 1988); the records of Italian earthquakes of 1976 and 1980 (the most severe in recent history), and artificial accelerograms in agreement with the design response spectra S1 and S2 of Eurocode No. 8 (1988) are used as inputs of the dynamic analyses.

Two main types of response of the exhibits are recognized: rocking and sliding. It appears that the essential objectives of a policy for mitigation of seismic effects must be to avoid rocking in all foreseeable circumstances, and to limit sliding displacements to acceptable values (depending on the size of the case, and/or the display plane). Therefore, the numerical analyses deal in particular with the latter type of response.

As to conditions under which rocking, and possibly overturning, take place, the simplified criteria proposed by Ishiyama (1984) are adopted, which, as demonstrated by experimental tests, are generally biased toward safety. These criteria in fact appear to be convenient in the present case, from both the viewpoint of the rapidity with which the protective measures can be taken for the numerous objects contained within any museum, and the simplicity of their use by non-specialized workers; furthermore, their conservativeness meets the need to ensure a high level of protection to objects that, by their nature, are unique and irreplaceable.

The final objective of this research is a tentative set of simple rules and provisions to be followed in setting up future Museums in seismic areas or in reorganizing the existing ones.

2 A SIMPLIFIED MODEL OF THE DYNAMIC RESPONSE OF ISOLATED ART OBJECTS

As noted in the Introduction, this study is aimed at evaluating the effects of earthquakes on objects that can be considered as rigid bodies, since their natural frequencies of vibrations are very large, well beyond the range of the frequencies typical of seismic action. These objects can be supported in several ways: in particular, objects that stand on a building floor must be distinguished from those contained in display cases. A complete description of the object+support systems has been first presented by Agbabian *et Al.* (1988,1990) and then elaborated by Augusti *et Al.* (1992).

In this paper, rigid bodies simply supported - with frictional contact - on a horizontal plane are considered (Fig. 1). For simplicity, it will be assumed that the body can either remain stuck on the plane, or slide, or rock and possibly overturn: in other words, the possibility of complete uplifting (jumps and/or free flight) and of slide-rock motions are ignored. Also, rotations around vertical axes are excluded (i.e. plane motion is assumed). The actual motion of the block depends on the geometric properties of the block (slenderness ratio λ, height H of center of mass above the support plane, rotational moment of inertia I - Fig.1), on the characteristics of the seismic action (magnitude of peak ground acceleration, spectral properties, energy content, influence of the vertical component of motion), and on the magnitude of the friction between the block and the plane.

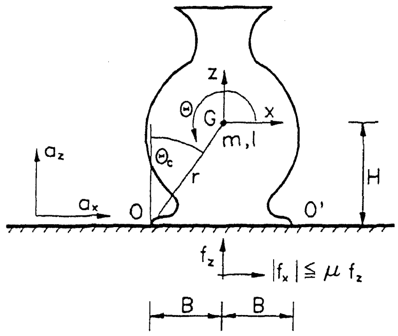


Fig. 1. Diagram of rigid body on moving rigid plane.

More precisely, with reference to the scheme of Fig. 1, and indicating by: $|a_g| = \sqrt{a_x^2+a_y^2}$ and a_z respectively the components in the support plane and the vertical component of the acceleration applied to the base, by g the acceleration of gravity, and by μ the value of the friction coefficient, the three alternative behaviours take place if the following criteria are met:

a) if $|a_g(t)| < [g+ a_z(t)]$ B/H and $|a_g(t)| < [g+ a_z(t)]\ \mu$ the body sticks to its support plane;

b) if $|a_g(t)| < [g+ a_z(t)]$ B/H and $|a_g(t)| > [g+ a_z(t)]\ \mu$ the body slides with friction on its support plane;

c) if $|a_g(t)| > [g+ a_z(t)]$ B/H and $|a_g(t)| < [g+ a_z(t)]\ \mu$ the body rotates around the axis through O or O'.

In what follows the three possibilities of movement will be analyzed separately.

2.1 Sliding

The analysis of the sliding motion of a rigid body on a rigid plane is based on the assumption that the friction at the interface is of the Coulomb type, defined by a coefficient μ (more sophisticated analyses would require the introduction of a "static" coefficient μ_s in the condition for starting the relative motion, of a "dynamic" coefficient μ_d for maintaining it). Indicating by u, v, w the components of the relative motion of the center of mass in the x, y, z directions, the motion of the rigid body free to slide with friction on a moving plane is governed by the following equations.

- during the phases of "stick-mode" motion, which takes place under condition (a) above:

$$u = \dot{u} = \ddot{u} = 0 \tag{1}$$

$$v = \dot{v} = \ddot{v} = 0 \tag{1'}$$

$$w = 0 \tag{1''}$$

- during the phases of "slip-mode" motion, which take place under condition (b):

$$\ddot{u} + \mu\, g\, (1+ a_z/g)\ [\dot{u} / (\dot{u}^2 + \dot{v}^2)^{1/2}] = -\, a_x \tag{2}$$

$$\ddot{v} + \mu\, g\, (1+ a_z/g)\ [\dot{v} / (\dot{u}^2 + \dot{v}^2)^{1/2}] = -\, a_y \tag{2'}$$

$$w = 0 \tag{2''}$$

The sliding motion of a rigid body subjected to an excitation of the oscillatory type has been the subject of a few recent studies. For this paper, two results appear of particular interest: the peak value of the (absolute) horizontal acceleration of the body is equal to μ g, hence depends only on the value of μ; in case of harmonic excitation, a critical value of the coefficient of friction μ can be determined below which phases of stick motion do not take place, and the mean relative displacement between body and support plane increases with time and tends asymptotically to a limit (Younis *et Al.*, 1984).

2.2 Rocking and overturning

For the analysis of the rocking motion of rigid bodies many more or less rigorous models have been proposed, which make it possible to follow the motion and in particular to represent the effects of the impacts that take place between the body and the support plane (for a recent review see Augusti, Sinopoli, 1992). It is however well known that these models are difficult to apply and do not furnish ready-to-use systematic and general indications, at least for bodies subject to seismic action. The adoption of simplified, conservative criteria for this case is then preferred, in the spirit of this paper.

In this context, the "overturning criteria for slender rigid bodies" formulated by Ishiyama (1984) appear particularly interesting.

Regarding the horizontal ground acceleration a_g, one can refer to West's formula:

$$a_g/g > B/H \tag{3}$$

which establishes, as well known, only a necessary condition for rocking motion to start.

For the body to overturn, it is also necessary that the acceleration is applied to the body over a time interval such as to give rise to a large enough velocity. The condition expressed by ineq. (3) is therefore completed by a condition on the center of mass velocity, which is limited to the velocity of a horizontal impulsive force able to cause the body to overturn, that is, to make it rotate by an angle equal to the critical value: θ_c = artan B/H. This velocity is expressed by the relation:

$$v^2 > v_c^2 = (2gr/H^2)\,(i^2 + r^2)\,(1 - \cos\theta_c) \qquad (4)$$

where r is defined in Fig. 1 and i is the centroidal radius of inertia: $i = \sqrt{I/A}$, I being in turn the moment of inertia of the object relative to an axis through its center of mass G and parallel to the axis of rotation, and A the area of the cross section of the object in the vertical plane containing the axis through G and normal to the axis of rotation.

For slender parallelopipedal bodies (small θ_c), rel. (4) simplifies into:

$$v^2 > v_c^2 = (4/3)\, g\, B\, \theta_c \qquad (5)$$

On the basis of a series of experiments on parallelopipedal specimens, Ishiyama (1984) suggests that the peak velocity of the action must be precautionarily less than 0.4 v_c. The condition for the body to overturn is then conservatively expressed by:

$$v^* > 0.4\, v_c \qquad (6)$$

which, for slender parallelopipedal bodies, becomes:

$$v^* > 10\,(2B) / \sqrt{(2H)} \qquad (7)$$

(with H and B in cm, and v^* in cm/sec).

The criteria can be easily applied to bodies of any shape, by introducing the concept of equivalent height H', defined as the height of a parallelopiped having the same characteristics, in regard to rocking and overturning motion, as the body in question (Agbabian *et Al.*, 1990):

$$H' = (8/3)\, H / (i^2 + r^2)^2 \qquad (8)$$

The third condition set forth by Ishiyama (1984), that concerns the magnitude of the displacement, is not of interest here since less conservative.

3 SAFEGUARDING ISOLATED ART OBJECTS

The impacts taking place between object and support plane during rocking, if on the one hand are an asset from the viewpoint of stability because they dissipate energy, on the other hand are a liability because of the damages that valuable, fragile objects can suffer. To ensure an adequate level of protection of isolated art objects, and keep the stresses induced by seismic action within permissible limits, it then appears that it is best to avoid any rocking, while letting the object slide on the support plane. In this way the peak acceleration, hence the stress in the critical sections, are reduced.

It is however necessary in this case to check the magnitude of the relative displacements, in order to avoid the object impacting against nearby objects or against obstacles delimiting the support plane, or running beyond the limits of the plane.

Fig. 2, which visualizes relations (3) and (6) for a given $a_g/g < \mu$, shows the existence of three distinct zones:

- zone A, which corresponds to objects whose "stockiness" $1/\lambda$ = B/H, is greater than the ratio a_g/g, and which thus will not undergo any motion (neither rocking nor sliding);
- zone B, which corresponds to objects which may undergo rocking motion, but at a velocity not sufficient to be overturned;
- zone C, which corresponds to objects having a slenderness λ so high that they might overturn.

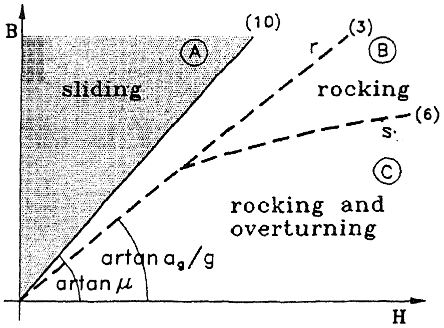


Fig. 2. Ishiyama (1984) criteria for a given $a_g/g < \mu$.

Now, to prevent the objects from rocking, the condition on the maximum horizontal acceleration undergone by an object permitted to slide with friction on its support plane can be exploited. In fact, the second condition (b) in Section 2, neglecting the vertical ground acceleration $a_z(t)$, states that sliding motion take place if:

$$a_g/g > \mu \qquad (9)$$

The inception of either sliding or rocking motion depends therefore on whether the limit set by ineq. (9) or by ineq. (3) is reached first: the body starts by sliding if

$$\mu < B/H \qquad (10)$$

Therefore, given the slenderness of the object(s), a choice of materials for the support plane such that ineq. (10) holds, will make the object(s) slide rather than rock.

As already said, Fig. 2 refers to the case in which ineq. (9) does not hold: therefore, sliding motion cannot start: the whole region A above the line B/H = a_g/g, correspond to bodies that neither rock nor slide, i.e. do not move ("stick") on the support plane.

Fig. 3 refers to the case in which ineq. (9) holds. The objects whose ratio B/H falls above the line B = H artan μ, slide on the support plane (including those below the line B = H a_g/g), (which according to Ishiyama's criteria should rock or overturn). Thus, choosing an appropriate value of the friction coefficient, the range of objects can be extended that undergo sliding and not rocking when subjected to seismic forces.

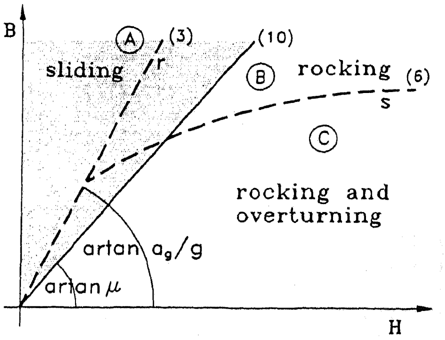


Fig. 3. Regions of behaviours for a given $a_g/g > \mu$.

4 ANALYSIS OF SLIDING OSCILLATIONS OF A RIGID BODY

To determine the dynamic response of a rigid body sliding with friction on its support plane, a step integration programme for solving the equations of motion (1), (1'), (1") and (2), (2'), (2") has been developed. The analysis has been performed first for harmonic horizontal oscillations of the supporting plane; then for the recordings of the earthquakes of Bagnoli Irpino, Mercato S. Severino and Sturno (November 1980) and Tolmezzo (May 1976), scaled to the same peak ground acceleration (0.35 g), to put in evidence the effects of the different spectral contents. Finally, the effects have been calculated of two series of 20 artificial accelerograms consistent with the frequency content of the response spectra S1 and S2 of Eurocode No. 8 (1988) (total duration: 27 seconds; duration of the stationary part: 15 seconds; acceleration peak: 0.35 g).

Fig. 4 shows, as an example, the displacements resulting from a sinusoidal oscillation of the support of frequency 2 Hz and amplitude 0.35 g. It can be seen that the mean displacement of the body tends asymptotically to a definite value if the friction coefficient is less than a critical value (equal to 0.19, for the specific case), according to what has been already indicated in Section 2.1.

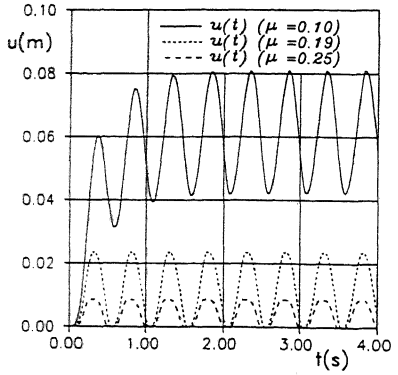


Fig. 4. Time-histories of displacement under a sinusoidal excitation, for several values of μ.

A parametric analysis of the effects of several harmonic inputs has shown that the maximum relative velocity and the maximum relative displacement monotonically increase with the natural periods and the peak base acceleration, while decreasing as the value of the friction coefficient increases.

With regard to the effects of seismic-type action, it has been noted that the Bagnoli Irpino and Sturno earthquakes are much more damaging, due to a significant spectral content extended over a wider frequency range: this is shown, in terms of maximum (relative) displacement, in Fig. 5. In the same Fig. 5, also the significant values (mean over 20 samples) are plotted of the maximum displacements of the object subjected to the action of the artificial accelerograms. The differences between the two types of spectra are around a factor of 2, as it was to be expected considering the greater extension of the flat stretch of spectrum S2.

The values found for the displacements may be used for a first evaluation of the distances at which the object must be placed from the edges of the display case or from other objects to prevent impact in case of an earthquake.

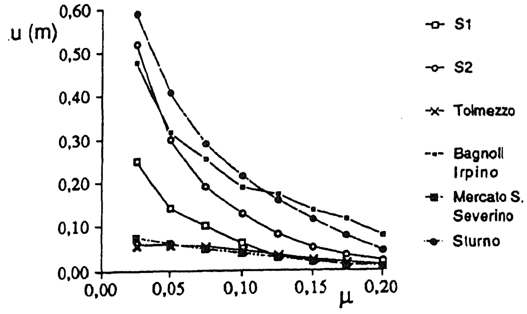
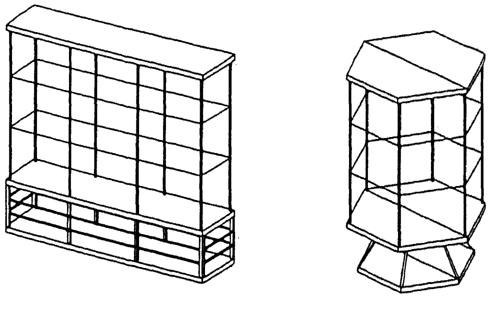


Fig.5. Maximum displacements for seismic excitations.

5 EFFECTS OF ELASTIC DISPLAY CASE ON THE MOTION OF THE CONTAINED OBJECTS

5.1 Display case

Most of the art objects in the "Museo Irpino" are kept in steel and glass display cases. They present a variety of geometries, that can be referred to two typical shapes: rectangular parallelopiped and hexagonal prism (Fig. 6). The structures (2 m high) are made up of hollow steel bars (30 x 30 mm square, or triangular 40 mm deep, or circular with 20 mm outside diameter); the shelves are of glass, supported by stirrups attached to the steel bars. The cases can be schematized as space trusses of linear-elastic behaviour, while the glass plates, both horizontal and vertical, are assumed not to contribute to the structural response of the case.



Type 1 *Type 2*

Fig. 6. Typical shapes of display cases in the "Museo Irpino", Avellino.

To avoid a further cause of uncertainty, it has been assumed that the seismic excitation at the base of display cases or isolated objects is not affected by the dynamic response of the building in which they are contained. This assumption, that is surely questionable for the r.c. building housing the Avellino Museum, could however turn out not to be necessary, were a complete analysis of the coupled system (structure+cases) made, or the spectra for the floors of concerns evaluated.

But definitely not to be neglected is the filter effect of the display cases; the objective of this part of the study is thus to determine the optimum shape and strength characteristics of the cases in regard to their influence on the frequency content of the motion and on the amplification of the acceleration peak at the level of the four shelves.

The modal analysis of the case structures, carried out considering the first six modes of vibration, and assuming the design response spectrum S2 scaled to a base peak acceleration equal to 0.35 g, suggested the following remarks:

- since the display cases can lift up from the floor, it is necessary to anchor them at the base;
- since the intermediate shelves can come out of their supports, they should be fixed to the case.

The time-history analysis of the display cases under the accelerations recorded in the quoted 1976 and 1980 Italian earthquakes were then performed. The amplification effects were evaluated at the shelf levels: it was noted that the acceleration peak is amplified by a factor a little over 3 for the Type 1 display case, and between 2 and 3 for the Type 2 display case.

5.2 Sliding objects

Assuming that a rigid object is located on the top shelf of a display case and is allowed to slide with friction on the support plane, it can immediately be seen that:

- with regard to the peak absolute acceleration μg, only the value of the friction coefficient is relevant. Furthermore, the influence of the vertical component of acceleration (that in the numerical calculations was assumed equal to 2/3 of the horizontal component) is minimal and does not show significant differences among the several earthquakes;
- with regard to relative velocity and relative displacements, the most important factor is the frequency content of the earthquake, in relation with the case stiffness characteristics. Generally, in fact, the more deformable cases (Type 2) display higher relative velocities for the earthquake characterized by a large spectral energy content at the lower frequencies: the peak velocity undergo a mean amplification of around 28%. Also, assuming for the friction coefficient a value of at least 0.15 ÷ 0.20, the maximum values of the displacements are less than 0.10 m.

The very high amplification of the peak acceleration caused by the case structures suggested to look whether appropriate modifications might reduce the amplification, at least for the highest shelves. In other fields, analogous examples are frequently tackled by making the supporting structure more deformable. In our case, this may be achieved either by reducing structural cross section and at the same time by increasing the shelf masses (modification 1) or by interposing rubber supports under the feet of the display case (modification 1').

On the other hand, in sliding motion the maximum relative displacement of a rigid body depends not just on the magnitude of the maximum acceleration, but also on the frequency content on the action. This would suggest a modification quite different from the preceding, it having been noted that a stiffer and lighter case yields lower relative displacements (modification 2).

The effects of the above summarized modifications have been stated in detail (Augusti *et Al.*, 1992) and can be summarized as follows:

- for the case where the structure is made more deformable (modifications 1 and 1'), no substantial reduction in the peak acceleration is obtained, while the low-frequency components of the motion are heightened;
- for the case where the display case structure is made stiffer (modification 2), there is no reduction in the peak acceleration, but neither is there any modification in the motion frequency content;
- the larger displacements are found, obviously, considering the more deformable structure.

Therefore, while in both cases the initiation of motion becomes more probable, the second solution makes it possible to keep down the magnitude of the maximum relative displacement of the objects, provided ineq. (10) holds, so that the objects slide but do not rock. For this reason it appears possible to conclude that it is worthwhile to have display cases with higher natural frequencies, that is, structures of moderate slenderness, built with lightweight material.

6 CONCLUDING REMARKS: FIRST INDICATIONS FOR EARTHQUAKE-PROOF MUSEUMS

Summing up, the seismic protection of art objects requires the following checks and provisions.

6.1 Strength check

This check requires at least a rough estimation of the maximum stresses generated by the inertia forces and must never be omitted. Should the stresses be excessive, the following measures can be taken:

- to strengthen appropriately the object, without modifying its aspect or nature (this latter condition, in general, leads to discarding this kind of operation, except in very special cases);
- to allow the object to slide on its support plane (thus reducing its absolute acceleration, hence the inertia forces);
- to place the object on an isolating device.

6.2 Rocking and overturning check

Ishiyama's criteria, presented in Section 2.2, can be used, provided relevant peak values of the input acceleration and velocity can be estimated.

As for the peak acceleration, for isolated objects reference will be made to the maximum acceleration value expected in the site of the Museum; account will be taken, where necessary, of the filter effect of its building structure. For objects kept in display cases, account must always be taken of the amplification effects of the display case structure.

To determine the input peak velocity, it does not suffice to set the peak acceleration value, but the frequency content of the seismic action must be defined as well, and an adequate number of time histories compatible with the relevant spectrum must be integrated.

If the threshold set by one of Ishiyama's criteria is reached, the object will rock, and therefore can be damaged. To prevent this:

- the object can be fixed to its support plane;
- its center of mass can be lowered, by adding mass in the object's lower portion;
- the base width may be increased, by fastening the object to a plate of the desired shape and size;
- the object can be allowed to slide on its support base.

More than one remedy can be applied at the same time: such is the case for objects permitted to slide within display cases, that are placed on deformable supports.

6.3 Sliding motion check

As stated earlier, to permit an object to slide on its support plane can reduce the danger of rocking and/or excessive stress. To prevent excessive stresses, the value of the acceleration a_{max} is determined that would cause the maximum admissible stress σ_{max}: then, a_{max}/g is an upper limit value for the friction coefficient μ at the interface between the object and its support plane. Provided this condition can be met, the validity of ineq. (10) must be checked.

Finally, the maximum displacement undergone by the body must be evaluated, to keep it from impacting with other objects and/or the walls of the case, or falling over its support plate. In general, a value of the friction coefficient should be chosen yielding the best compromise among the various behaviours.

The calculation of the relative displacements usually requires to set the spectrum of the seismic action expected for the site, to simulate an adequate number of accelerograms compatible with it, to integrate numerically the equation of motion and to derive the average values (or the values characterized by a defined probability of their being exceeded) of the maximum displacements.

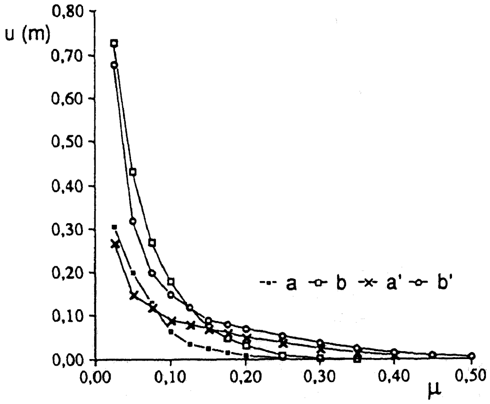


Fig. 7. Maximum sliding displacement under simulated accelerograms (mean plus one standard deviation): a - a') response spectrum S1; b - b') response spectrum S2.

As an example, Fig. 7 shows the values of the relative displacements of the object derived by considering two series of 20 artificial accelerograms scaled to a peak acceleration of 0.35 g, and respectively in agreement with the design response spectra S1 and S2 of Eurocode No. 8 (a and b curves); also reported are the values derived considering the filter effect of a Type 1 (modification 2) display case (a' and b' curves). These values correspond to the mean plus one standard deviation, and therefore, on the basis of the admissible value of the friction coefficient, can be used to provide the minimum distance to be left between sliding bodies and from shelf edges.

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