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Monumental buildings used as museums: Protection or danger for the artifacts?

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Abstract

Many art collections are hosted in monumental buildings with high artistic and historical value. While the esthetic of the buildings provides an enhancement to the artifacts, their structural performance could be detrimental in extreme hazardous events, such as windstorms, floods, fire or earthquakes. The buildings hosting the artifacts, which are supposed to protect against all possible dangers, may become the main source of hazard for their precious and priceless contents. Several researchers recognize the interactive effects and recommend that the safety of the artifacts should be evaluated jointly with the buildings where they are exhibited. Special attention should be paid to check structural behavior of monumental buildings along with their sensitive contents; a selection of procedures and response parameters such as those describing filtering the base motions should be defined and developed to assure the required safety to the content. Moreover, solutions may be thought to remedy deficiencies, by uncoupling the artifacts from the damaging filtered motion. Isolation of artifacts and of host monumental buildings may turn to be cost effective in providing a reduced risk.

Keywords: monumental buildings; hazardous structures; filtered hazard; decoupling structure and content; earthquakes.

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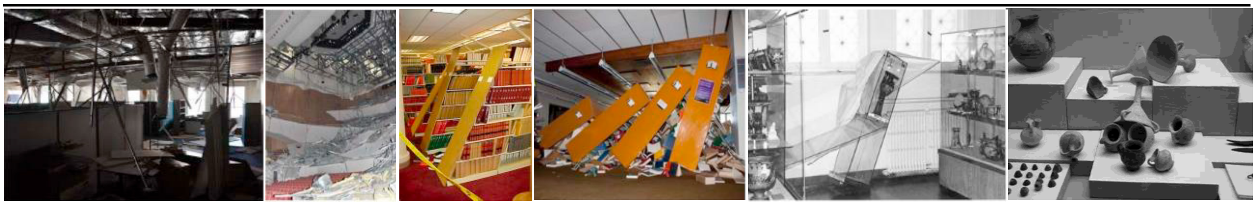
1. Introduction

1.1. Monumental palaces at risk

Many art collections are hosted in monumental buildings with high artistic and historical value (see Fig. 1). The buildings hosting the artifacts, which are supposed to protect against all possible dangers, may become the main source of hazard for their precious and priceless contents. During the last four decades, many researchers, engineers, architects and cultural communities became aware of the endangered artifacts in seismically hazardous areas such as California (Agbabian *et al.,* 1990; Podany *et al.* 1996), Italy (Augusti *et al.* 1992), Turkey (Erdik *et al.,* 2008), Greece (Spyrakos *et al,.* 2008) to name a few (note the list is illustrative only and not exhaustive). They note that such monumental buildings, most housed in old palaces and villas, are massive construction with single high story or multiple stories, usually enclosed by heavy cladding or stone masonry with or without concrete and steel construction. In the storied structures the floors provide support for heavy artifacts and enclosures, for visitors' walkways and for connectivity with the building enclosures.

Getti Villa Museum, USA | Palazzo Vecchio, Italy | Palazzo Madama, Italy | Topcapi Palace, Turkey | Uffizi, Italy

Fig. 1. Examples of monumental villas, palaces or offices serving as museums



Office space lost | Hall lost | Library lost | Library shelving lost | Museum cabinets lost | Unanchored artifacts lost

Fig. 2. Content damage in various buildings due to external disturbances

Additionally, in later construction or modern restorations, suspended ceilings are added to hide the utilities' wiring, piping, lighting, and ventilation services. Many such structures showed increased vulnerability (see Fig. 2) due to soil movement or other extreme loadings such as hurricanes, tornadoes, tsunamis, or strong earthquakes. While the exterior construction may have shown good resistance to such extreme disturbances, the interior objects, architectural and non-structural components suffered damages that rendered the space unusable. Moreover, in museums that are housing expensive and invaluable artifacts, the damages of structural, non-structural and architectural components further endanger and destroy precious exhibits.

Numerous scientific and engineering works define the local seismic hazard based on local recorded history, or on standards and regulations describing the ground shaking as expected within the lifetime of the monumental building. While this is sufficient for evaluation of the expected damage of the monumental buildings themselves, this may not be sufficient to predict and plan measures to protect the artifacts and perhaps reduce the joint risks of structures-artifacts' losses. Recent papers described the efforts of modeling the structural and material behavior of artifacts going through detailed formulation of geometrical meshes representing the masterpieces forms (see for example the numerical analysis of Cerere in Pintucchi *et al.,* 2019). Mostly they analyze their vulnerability due to the ground shaking expected at the base of the hosting buildings, which may not be, however, the worst case scenario, if those were located in the higher floors for hazards affecting the artifacts.

1.2 Artifacts at risk

Recognizing their vulnerability, researchers summarize the risks of damage to the artifacts in two main categories: (*i*) the direct risk of damage and collapse of the artifact due to sliding, overturning, brittle cracking and shattering under its own inertial movement and *(ii)* environmental risk due to the falling ceilings, roofs, sidewalls and structural components – columns, joists and girders – or collapse of floors and bridging structures. The direct risk is mostly controlled by the slenderness (ratio of height to base width), the acceleration, *a*, of movement and friction at the interface (see Ishyama, 1984, Podany, 2015).

The recent literature shows that many of the monumental buildings, some old palaces or new heavy structures, are generating more of the second category of environmental risks to the artifacts. A classification of artifacts as a function of their seismic vulnerability was determined by Ciampoli and Augusti (2000), McKenzie *et al.* (2007) and Podany (2009). Mass distribution and slenderness are accredited as the most important quantities which affect the dynamic response of artifacts (Wittich *et al.,* 2016; Pascale and Lolli, 2015); in particular, sculptures and statues are usually assumed to be the most vulnerable to seismic excitation. The staging usually adopted in the museums, such as pedestals, can further worsen the seismic vulnerability of the art works (Wittich and Hutchinson, 2016), increasing their slenderness and changing their dynamic response.

Moreover, substantial effort is made to understand the vulnerability of the artifacts themselves to same ground motions as the buildings are exposed, and provide linking, tying and bracing to prevent the direct risk mentioned above.

2. Modified hazard as reason for increased risk

However, the host buildings, the monumental palaces and other museum structures, may modify the motions to the artifacts are subjected to, creating "filtered" hazardous conditions that either exacerbate the damaging effects or diminish their unstable behavior. "It is worth noting that, in case of art objects located in upper floors, the characterization of seismic action becomes a challenging task due to the need of considering that the host building filters the seismic signal, modifying, with its response, the frequency content and the amplification of the strong motion applied to the base (see Fig. 3). As shown by Taghavi and Miranda (in NIST Report 2017) the accelerations, which produce the inertia forces applied to the artifacts at the upper floors are twice to four times higher than those at base (see Fig. 4). Much of the work by Baggio et al, (2018) shows the differences between the floor motions and the motions at the ground were the building is located (see Fig. 5), which compares the interactive spectra results with the European Standards (EC8, 2004), with substantial increase in accelerations and displacements over a wide period range imposing larger demands for the artifacts which have dynamic characteristics in these affected ranges. Several researchers recognize the interactive effects and recommend that the safety of the building contents and artifacts should be evaluated jointly with the buildings where they are exhibited (Podany, 2009; Hutchinson *et al.*, 2010; Baggio *et al.*, 2018; Viti *et al.,* 2020). The interaction can be analyzed "through cascading approach, i.e. according to floor response spectra formulations both by using simplified and more refined approaches (e.g. Lagomarsino, 2015; Degli Abbati, 2016)" as Baggio *et al.* (2018) recommend.

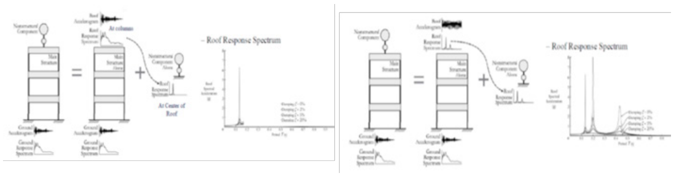


Fig. 3. Amplification of base motions at higher floors –vertical (left) and horizontal (right)- NIST-ATC (2017)

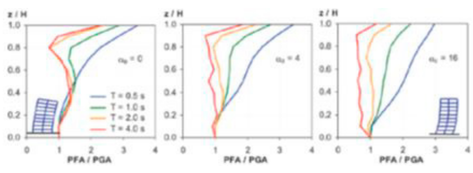


Fig. 4. Variation of peak floor vs ground accelerations (PFA/PGA) along height of frame structures (Taghavi and Miranda, 2006)

Similar behavior was observed and well documented for buildings' precious contents, such as hospitals (Hutchinson *et al.,* 2012), supported by controlled experiments and analytical evaluations. Moreover, in the authors' experience, building components such as suspended ceilings used in museums and modern exhibit halls become unstable and collapse in ranges amplified by the host structures endangering, or destroying exposed artifacts (see Figs 2 and 6).

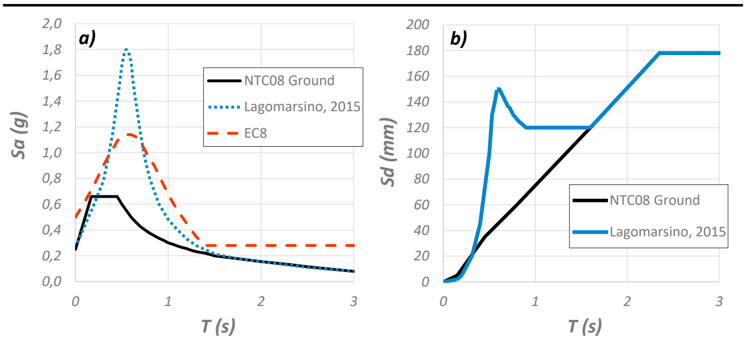


Fig. 5. (a) Acceleration and (b) Displacement response spectra for 2nd floor according to EC8, Lagomarsino *et al.* (2015) compared to ground spectrum NTC08 (from Baggio 2018).

Fig. 6. Fallen statues and ceilings, damaged artifacts, due to external explosions (similar to earthquakes) in Palmyra, Syria

3. Assessment of risk of considering modified hazard

Special attention should be paid to evaluate the artifacts together with the structural behavior of monumental buildings and palaces along with their sensitive contents; a selection of procedures and response parameters such as those describing filtering the base motions should be defined and developed to assure the required safety to the content. Such tasks are usually tedious and expensive and most of the time cost ineffective. However, filtered motions affecting specific or assembles of artifacts can be derived to evaluate their behavior when located in monumental structures. While this process is not usually done for museums and artifacts, procedures and methods were developed by Merino *at al*., (2019), for sensitive contents and for equipment of buildings (such as hospitals) and for architectural and non-structural components (Ryu and Reinhorn, 2017).

The floor accelerations can be described as a function of the ground motion as (Ryu and Reinhorn, 2017):

$$\ddot{u}_S(\omega) = H_{SG}(\omega) \cdot \ddot{u}_G(\omega) \tag{1}$$

where $u_S(\omega)$ represents the structural response, $u_G(\omega)$ the disturbance function and $H_{SG}(\omega)$ is the structures transfer function. This frequency domain formulation includes contribution of all parts of structure between ground and a j location in structure. For a simple storied structure experiencing base motions the floor acceleration response at level j can be expressed as:

$$\ddot{u}_j(\omega) = \sum_{k=1}^{n} \left[\Gamma_k \phi_{jk} \frac{\left(2i\omega\xi_k\overline{\omega}_k + \overline{\omega}_k^2\right)}{\left(2i\omega\xi_k\overline{\omega}_k + (\overline{\omega}_k^2 - \omega^2)\right)} \ddot{u}_g(\omega) \right] = H_{SG,j} \cdot \ddot{u}_g(\omega) \tag{2}$$

The maximum acceleration at level j can be approximated from a modal superposition of spectral accelerations:

$$\ddot{u}_{j,max} = SQRT\left\{ \sum_{k=1}^{n} \left[\Gamma_k \phi_{jk} \frac{S_A(T_k, \xi_k)}{R_k} \right]^2 \right\} \tag{3}$$

where S_A is the spectral acceleration of the base motion and ξ_k is the modal damping. Note that this acceleration can be defined as the floor's acceleration. However, the response of the artifact is further amplified by the transfer function $H_{AS}(\omega)$, of the artifact to the floor, where it is anchored:

$$\ddot{u}_{AS}(\omega) = H_{AS}(\omega) \cdot \ddot{u}_S(\omega) = H_{AS}(\omega) \cdot H_{SG}(\omega) \cdot \ddot{u}_G(\omega) \tag{4}$$

For stiff structures or artifacts, the transfer functions $H_{AS}(\omega)$ or $H_{SG}(\omega)$ equal *unity* in which case the response is identical to the ground motion. However, for just a stiff structure the floor response is identical to that of the ground, while for stiff artifacts the response is identical to that of the floor. Note that this is true when the two transfer functions are independent, which is not the case when the mass of the artifacts is very large or when the structure is very flexible. In such case the transfer function of the artifact in respect to the ground $H_{AG}(\omega)$ must include the interaction of structure to the artifact.

The forces acting in the artifacts are proportional to the weight of the artifact W_P and the acceleration developing at floor *j* where the artifact is located applied at its center of gravity.

$$F_p = \ddot{u}_j \cdot W_p / g \tag{5}$$

for a rigid body, or,

$$F_p(\omega) = \ddot{u}_j(\omega) \cdot H_{AS}(\omega) \cdot W_p / g \tag{6}$$

for a flexible body artifact (where $H_{AS}(\omega)$, the transfer function of the artifact body, containing the distribution of the weights and the dynamics of the body). It should be noted that the second equation considers all the flexibilities and the dynamics of the structure and the artifact.

For simplified static equivalent calculations it is suggested by the US standard, ASCE 7-16, to determine the forces on an artifact, or piece of equipment, *P* by using:

$$F_P = \left[0.4 a_P S_{DS}\left(1+2z/h\right)/\left(R_P/I_P\right)\right]*W_P = \left[S_a\right]*W_P \tag{7}$$

where F_P is the force on the component *P* with a weight of W_P, a_P is an amplification factor spcific to either architectural components (Tbl. 13.5-1in the standard) or mechanical components (Tbl. 13.6-1 in the standard), S_{DS} is the acceleration response spectrum *on the ground*, z/h is the relative position of the artifact's floor about the height of building, R_P/I_P is a ratio of modification ductility based factor to the importance of component (provided by Tbls 15.5-1/2 and 15.6-1 in the standard, resp.)

At the same time the European standard, EC8, suggests for the response spectrum acceleration (equivalent to $[S_a]$ in the ASCE 7-16):

$$\left[S_a\right] = \alpha S\left[3\left(1+z/h\right)/\left(1+\left(1-T/T_1\right)^2\right)-0.5\right] \geq \alpha S \tag{8}$$

where $[S_a]$ has same significance as in the ASCS 7-16 with the distinct difference that it includes the ratio of periods of vibration of the artifact and the building (when the artifact if flexible) and a local soil factor α.

In summary the forces which act in the artifacts are amplified by both the structural system up to the floor where the artifact is located and by the flexibility of the artifact itself. The standards for non-structural components recognize these facts and offer some approximated and simplified recommendations. However, when the structures are complex and flexible would require individual considerations based on equations (4), (6) or (8) depending on the evaluation's rigor.

4. System modifications considering modified hazard

Solutions of ways to strengthening and rehabilitating the structures were suggested in order to mitigate the hazardous effects on the artifacts in particular when affected by the structural systems, but not always achieving their purpose. However, such strengthening although reduce the displacements of structure and movement of the artifacts, tends to increase the accelerations (and with it the inertia forces) leading to deformations and eventual cracking and collapse (of brittle artifacts).

Since most damages are result of excess movement and increased forces on the artifacts, solutions may be thought to remedy deficiencies, by uncoupling the artifacts from the damaging filtered motion. Moreover, major improvements could be obtained by isolating the entire museum base or palace structures. In such case the accelerations in the structure could be reduced to almost one order of magnitude, same at all floors (see Fig 7 developed by Chen *et al.*, 2015). The global retrofit solution using base isolations can be effective that could protect the entire museum and numerous artifacts located in as numerous locations without need to touch the individual artifacts (see Fig 8). However, such a global solution can be prohibitively expensive.

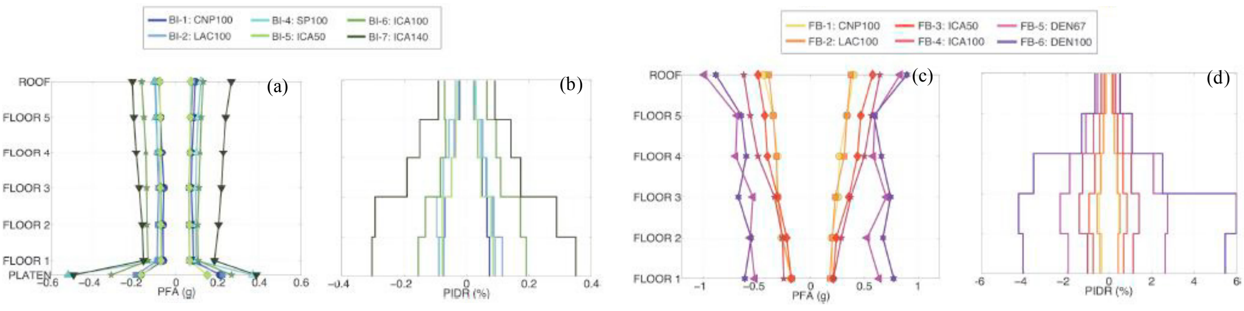
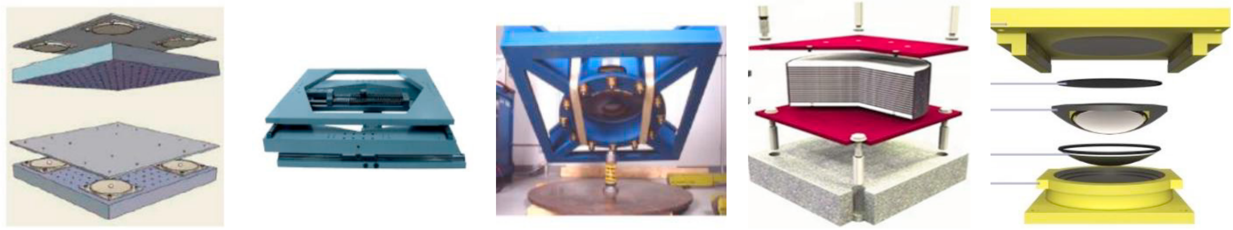


Fig. 7. Measured response: (a) PFA and (b) PIDR in base isolated building; (c) PFA and (d) PIDR in fixed base building for six ground motions (Chen et al. 2015).

Isolation of artifacts and of host monumental buildings may turn to be cost effective providing a reduced risk. There are many such solutions, however, not all guided by the understanding of filtered motions. Some of the most promising recent solutions for seismic-resistant staging consist of base-isolated pedestals (Baggio et al. 2015, Storace and Terenzi 2015), some combined with intelligent links. Such devices (see Fig. 9) can provide an effective protection to the artifacts, reducing substantially the amount of seismic demand accelerations, limiting them to the level of friction forces. Moreover, artifacts may be displaced from their position and a system of restoring links or damping can maintain them in place. For example, the statue of Hermes with the Infant Dionysus located at Archaeological Museum of Olympia in Greece was base isolated with four friction pendulum (FPS) devices (Fig. 10).

Fig 8. Base isolated monumental building of Court of Appeals – San Francisco, CA – with multiple artifacts.

This type of intervention, however, is quite expensive, besides requiring a proper design work. When the artifacts are strong enough to resist to the seismic acceleration, enforcing the restraint at their base, in order to avoid overturning, rocking and sliding phenomena, could be enough to ensure the required safety condition. Several technological solutions, compatible to the aesthetic features of the art goods, can be adopted for this purpose. Depending on type, mass and shape of the artifact different devices can be adopted, such us stops, clips and contours, or plates and frames (as presented by Podany 2015).



BNC Isolator | Getty Isolator | Quantec isolator | Elastomeric Isolator | Friction concave isolator

Fig. 9. Isolators for individual protection of artifacts (artifact above floor below)

Base Isolated statue Hermes with the Infant Dionysus located at Archaeological Museum of Olympia in Greece with FPS

Fig.10. Local isolation of statue in Greece (Univ.at Buffalo, Reporter, Feb. 17, 2005)

5. Concluding remarks

Precious artifacts housed in monumental structures, such as palaces and museums, are at great risk in major extreme disturbances such as ground movements, blasts, tornadoes, etc., in particular in storied structures where the effects are amplified at the floors where those are placed without proper anchors and connections. The evaluation of risks to the artifacts should include the models of buildings and the artifacts together, with suitable considerations for interaction when the flexibilities and weight distributions are comparable, which may exacerbate the potential for damage. While it may be impossible to eliminate the risks, it is possible to reduce them by uncoupling globally the structure from the extreme disturbances, thus protecting both the monumental structure and the contents, usually at great costs, or by uncoupling locally the artifact individually from the motion where it is located. Base isolations offer solutions for both cases, but their cost-efficiencies must be adequately modeled and predicted considering interactions where necessary. Unfortunately, in many cases insufficient resources prevent performing a comprehensive seismic analysis for achieving a reliable structural model of both artifacts and monumental buildings and the prediction of seismic performance of such complex buildings and their contents could rely on simpler models using basic response parameters and simplified checking approaches as the standards recommend for non-structural components.

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