Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 271-284

ECCOMAS Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

HUMAN-INDUCED VIBRATIONS ON MUSEUM ARTEFACTS: LITERATURE REVIEW AND CALCULATION EXAMPLE

Elena Sara Saeed[1], **Linda Giresini**[2], **Olimpia Niglio**[1] **and Francesco Graziotti**[1,3]

[1] Department of Civil Engineering and Architecture – DICAr
University of Pavia
elenasara.saeed01@universitadipavia.it, olimpia.niglio@unipv.it, francesco.graziotti@unipv.it

[2] Department of Structural and Geotechnical Engineering – DiSG
Sapienza University of Rome
linda.giresini@uniroma1.it

[3] European Centre for Training and Research in Earthquake Engineering – EUCENTRE

Abstract

Museums and artworks are visited by thousands of people every day and they are usually located in the city centers, often near train and subway stations. Moreover, renovations of art galleries are sometimes necessary in order to improve their usability.
For these reasons, visitors, construction work and rail and road traffic constitute the most common sources of vibration in art galleries. Vibrations may potentially interfere with the usability of art objects and may be potentially dangerous for their preservation.
Despite these issues, the researchers are mainly focused on mitigating the risk related to earthquake-induced vibrations, while the studies on the vulnerability of artistic heritage exposed to human-induced vibrations are still few and fragmented. Reference guidelines or codes to address this problem are not available at the moment.
Therefore, the purpose of this article is to propose a literature review on that topic and to provide an example of calculation for a selected case study.
This work is conducted in the framework of a larger study with the goal of understanding these phenomena and filling the lack of proper guidelines, for example, setting values of acceptable human-induced vibration levels.

Keywords: Human-induced Vibrations, Cultural Heritage, Artworks Preservation, Museum, Flexible floors.

Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10404.20706

1 INTRODUCTION

The conservation of cultural heritage is essential for keeping alive the memory of our past. The musealization and protection of movable property need to be further investigated to better ensure its transmission to future generations.

To date, significant progress has been made in preserving art objects from harmful environmental conditions [1] [2], such as humidity, temperature, chemical interactions or, mainly, earthquakes-induced vibrations [3]. Whilst seismic actions generate higher amplitude excitations on artefacts [4] [5], the vibrations most encountered in museums and historic buildings are those generated by visitors' circulation and by social activities. Vibrations may cause physical stress on the artwork and its support structure leading to cracking, breaking or displacements of components.

Despite these concrete problems, the scientific literature is mainly focused on mitigating the risk associated to earthquakes, while the studies about the vulnerability of artistic heritage exposed to human-induced vibrations are still few and fragmented. This lack of knowledge about the materials, mechanical proprieties and actual conditions of artworks, as well as the complexity of interpreting the effects of vibrations, makes it difficult to establish clear guidelines and properly defined damage limit states for protecting collections. This poses a problem for stakeholders such as curators, show-case designers, art historians, museum owners and superintendents who lack practical tools or instructions for protecting art objects from vibrations. However, some researchers have focused on examining the impact of ambient vibrations caused by visitors' circulation, construction activities and railway and road traffic on museums [6]. The findings suggest that repetitive exposure to these virtually imperceptible vibrations can greatly harm artworks over time, although it may take several years and a significant number of cycles to get it visible [7]. Figure 1 shows a schematic representation of different types of mechanical loadings that can stress artworks.

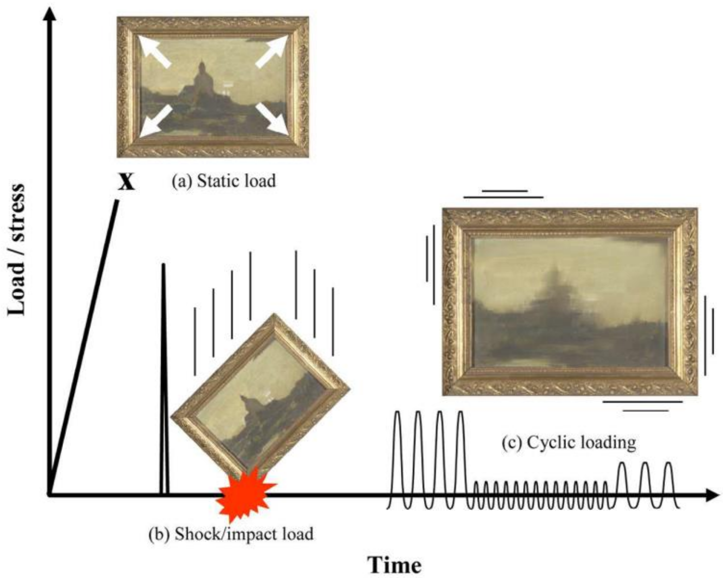


Figure 1 – Three examples of mechanical loading that can stress artworks [7].

The purpose of this article is to propose a short literature review on these topics and to provide an example of calculation for a selected case study: the Croce of San Teodoro, located at Gallerie dell'Accademia in Venice, Italy.

2 LITERATURE REVIEW

The relatively fragmented existing art-conservation literature on the effects of human-induced vibrations shows that all research undertaken has been specific, that is it only referred to selected case studies. This may be due to the unique nature of each artwork, with its response and vulnerability to vibrations varying based on material, shape, size, condition and mechanical properties.

While most research focuses on the impact of vibrations on the museum's structures, less attention is given to the collections themselves. It is also important to notice that human-induced activities are generally perpendicular to the floor (i.e. vertical [8], unlike earthquake shakes, which have a main horizontal acceleration component).

Unfortunately, there are currently no generalized criteria for assessing the risk related to ambient vibrations. Indeed, international guidelines and standards such as UNI 9916:2014 [9], ES ISO 10137:2012 [10] and DIN 4150 [11] deal with the effects of vibrations in residential buildings, industrial facilities and monumental structures; those indications are not specialized for the distinctive features of museums artworks. The only guideline that considers limits of vibrations on historic buildings is the Swiss Standard SN640 312 [12], which sets the appropriate vibration limit in the range of 3.0 mm/s to 12.5 mm/s, but the design still depends on professional judgment for the individual case [13].

In conclusion, safeguarding artworks from vibrations includes risk assessment (i.e. by taking into account exposure, vulnerability and hazard), designing adequate galleries (i.e. with sufficiently stiff floors or vibration isolation systems), monitoring and staff training.

Before taking actions on these steps, for a clearer perspective on the involved considerations, it is crucial to understand the reference values concerning the levels of vibrations perceivable by the human body and their impact on the building environment. The human body can perceive very low levels of vibrations. As reported by Johnson and Hannen [13], human occupants can perceive steady-state vibrations at around 0.75 mm/s, which can vary depending on the frequency of vibration, and become disruptive at approximately 2.5 mm/s to 5.0 mm/s. The ambient levels of vibrations in buildings resulting from normal day-to-day activities usually range from 0.5 mm/s to 2.5 mm/s. However, the authors observed that it takes a minimum of 52000 cycles of continuous vibrations for threshold cracking to occur in a tested wood and masonry building.

Understanding the factors that contribute to vibrations in a building is crucial. As investigated by Zini et al. [14], vibrations within a building result from the interaction of three factors: (i) the type of vibration source, (ii) the soil-structure interaction (in case of external sources such as traffic) and (iii) the structural typology and its current health status. In simpler terms, vibrations originate from a source, spread through the soil and, at the end, reach a building.

The following sections present different case studies available in the literature classified by the type of vibration source.

2.1 Internal sources of vibrations

Internal sources refer to vibrations generated within a structure that may have a significant impact on the comfort and well-being of the building occupants. They tend to be more localized and affect a smaller area than the external ones. There are three main internal sources: (a) the impact of visitors walking, (b) the shock from dropping or moving the artwork and (c) the construction work within the building.

(a) Human foot traffic, typically at a frequency of 1.5 to 2.2 Hz [15], represents one of the most common sources of human-caused vibrations for museum contents and it can be particularly hazardous on poorly supported wooden floors [16]. This flexibility may be particularly relevant in museums with long-span wooden floors.

The vibration may differ a lot between different rooms of the same museum. For instance, a study conducted in the Czech Museum of Music in Prague demonstrated that amplitudes in vertical vibrations may remarkably differ for two adjacent rooms, due to differences in the floor constructions [17].

Literature suggests that these vibrations may affect fragile art objects as well as sculptures, paintings or the museum's structure itself. For example, the Michelangelo's sculpture "David" [18] [19] [20] and the Tyrannosaurus Rex skeleton at the Field Museum in Chicago [15] were found to be susceptible to visitors' circulation, as they are located on pavements subjected to relevant vibrations. Analytical modelling showed that the seismic isolation underneath the base of "David" and the installation of three columns below the footprint of the Tyrannosaurus Rex would be effective mitigation solutions. The retrofit application was in fact successful in the case of the Tyrannosaurus Rex skeleton, while the solution for "David" was designed but not realized. Visitor-related vibrations are generally expensive to mitigate, but, for example, moving the vulnerable manufactures to a different location within the room or to a different room may be a viable solution in case it does not compromise the accessibility of the artwork. In fact, museums have the duty to protect their collections but also to make them accessible to the public.

(b) Moving art objects may be dangerous due to the shocks that may occur during transportation (i.e., in the case of the Michelangelo's "Pietà Rondanini" [21]), which can also lead to the possibility of falling or damage due to high stress. Indeed, the vibrations that art objects commonly experience during transit between museums typically range from 40 mm/s to 75 mm/s, which are several times higher than the vibration limits often used to protect museum buildings and collections [22]. However, damage to art during shipment is rare and, although vibrations are higher in this case, they are generally of shorter duration. Additionally, special attention is paid to packaging the artworks that are shipped and anti-vibration devices are also used in most critical cases.

Collisions can also occur between objects placed close to each other (i.e., on the same shelf) wandering under the influence of vibrations. This topic has been studied by Wei and Dondorp [22]: resonance, wandering and possible damage tests were conducted on various kinds of natural-history objects provided by Naturalis Museum in The Netherland. The results of the experiments showed that the wandering of objects were amplified due to the resonance effects of the supporting structures.

(c) In order to improve museum's usability or to modernize the exhibitions, sometimes renovations works inside the building are necessary. However, the vibrations generated by construction site works in the museum represent one of the highest risks for the artworks because of the response of museum's structure and the museum's content (especially in case of fragile and weak objects), due to the resonance phenomenon [23]. Moreover, most of the museums remain open during the construction works and the use of some tools and the respective working techniques may lead to damage. To mitigate this risk, museums may opt to temporarily remove or relocate vulnerable objects while the work is being conducted.

A significant example of this phenomenon has been identified at the Royal Gallery, Palace of Westminster, UK, where the restoration of the hall had direct effects on the monumental wall painting of Trafalgar [24]. The effective method employed to minimize the painting's exposure involved identifying the tools and building techniques that generated the most significant vibration levels, avoiding the use of those that produced excessive vibrations.

As already mentioned in (b), another example may be found at the Naturalis Biodiversity Center in Leiden, The Netherlands, where resonance tests were conducted to set allowable vibration limits for shelving at floor level during construction, with the limit being set at 1.5 mm/s to 2 mm/s [22].

2.2 External sources of vibrations

External sources refer to vibrations generated outside the structure and transmitted through the soil. They can have significant impact on the integrity and safety of a structure and tend to be more widespread than the internal ones. There are mainly three external source types: (d) rail and road traffic, € nearby construction and/or demolition works and (f) explosions.

(d) As already mentioned, museums and artworks are usually located in the city centers, often near train and subway stations. Although the amplitude of vehicle-induced vibrations is generally milder than that yielded by earthquakes, traffic is a persistent action, especially in urban areas. Such a persistent action may cause fatigue phenomena and damage accumulation, particularly in objects made with brittle materials or in poor conservation conditions. This constitutes a problem since the hazard represented by railway and road traffic is expected to grow in the future. Recently, the need of limiting greenhouse gas emissions in European countries has spurred the construction of new underground railway lines in major cities thereby increasing the overall level of ground vibrations. The increasing use of public transportation and the consequent resulting intensity of the vibration field calls for the need to introduce innovative technological systems to protect artefacts. The road conditions should also be closely monitored due to the presence of holes or cracks, which can affect acceleration levels.

Since the ‘70s, researchers have been studying the impact of traffic-induced vibrations on buildings finding out that most vibrations occur because of trucks and buses while cars and minibuses have a less significant impact but should be considered in cases of intense traffic [25].

The study by Whiffin et al. [26] suggests that peak particle velocities in the ground up to 5 mm/s may cause architectural damage in buildings. However, even for lower-amplitude vibrations, tremors may become intrusive and even annoying to occupants at about 2.5 mm/s, as already mentioned.

While road and rail traffic may generate accelerations with a wide range of frequencies, several authors reduced this range to 5-20 Hz for vehicular traffic. There’s still an open debate on the acceptable limits of vibrations on monumental buildings. However, the German code sets 2 mm/s as the allowable velocity in the basement of these buildings [14].

Examples of historic structures impacted by rail and road traffic vibrations include “The Anphiteatrum Flavium” [27] and “Villa Farnesina” [28] in Rome, “SS. Annunziata’s lodge” [14] in Florence, the Museum of Chengdu [29], “Villa d’Elboeuf” [30] near Naples, “The Great Court” [31] at the British Museum in London, the Sarcophagus of the Spouses at the National Etruscan Museum in Rome [32] and “The City Court of Braila” [25] in Romania.

Although these structures highlight the issue, most of these cases were used to test if recorded vibrations met acceptable limits but did not provide practical mitigation solutions for all the cases.

The mitigation measures found in the previous examples were: the anti-vibration system installed under the pavement at Villa Farnesina (Rome) [28]; the use of vibration-absorbing mounting systems and sympathetic design at the Great Court [31]; the restriction of heavy traffic at the City Court of Braila, combined with the improvement of the soil through the deep mixing method and construction of cement barrier columns [25].

(e) Construction near heritage structures and art objects can be potentially more hazardous than traffic-induced vibrations and may cause damage. Several researchers have examined the hazard of dust and vibrations due to construction activities, such as museums expansions and renovation, and investigated vibration thresholds for historical buildings and art collections.

For example, this is what happened at the Viking Age Museum in Oslo [33] and at the National Gallery's paintings collection in London [34] during the respective expansion projects. To address the vibration issue at the Viking Age Museum, floor vibrations near the objects were monitored for 20 months and the limits for groundwork were set to 3-5 mm/s. However, some relevant types of groundwork still exceeded these limits, emphasizing the need for custom solutions for each specific case and the lack of universal regulations.
At the National Gallery, the installation of chains incorporating elastomeric hangers to support the paintings reduced the points of contact between the frame and the wall, successfully keeping the artworks on display instead of having to remove them.
(f) Explosions, although uncommon in many countries, can pose a major threat to museums and their contents. They can generate very high, unexpected and potentially catastrophic accelerations. This was highlighted by Hiswa et al. [23] in their proposal aimed at protecting museums of Shrines in Iraq from the impact of explosions.

3 CASE STUDY: THE CROSS OF SAN TEODORO

3.1 The artefact

The Cross of San Teodoro (see Fig. 2), exposed at the Galleria dell'Accademia (Venice), is a precious processional sculpture created by the Venetian artisan school in the 15th century for the School of San Teodoro, an ancient confraternity dedicated to the soldier who was the patron of the city before the arrival of the relics of San Marco. After a series of ownership changes, the Cross was returned to Venice following post-war restitutions in 1919 [35].
The Cross, partly gilded and chiseled in silver and transparent rock crystal, is decorated with vegetal motifs and figurines of angels and prophets. On the front, one can admire the scene of the Crucifixion of Jesus, while on the back, San Teodoro impales the lance into the mouth of a winged dragon.
The dimensions of the Cross are 925 mm by 425 mm [35] and it rests on a pedestal added in 16th century. It is a pyramid with a triangular base, made of decorated bronze with dimensions of 463 mm by 360 mm.

Figure 2 – Cross of San Teodoro (left) and supporting floor (right) at the Gallerie dell'Accademia, Venice.

3.2 The hosting hall and the museum exhibition design

The First Hall of the Gallerie dell'Accademia, which can be reached via the eighteenth-century double staircase, occupies the area of the Sala del Capitolo of the Scuola Grande della Carità, a secular confraternity founded in 1268 and one of the oldest in Venice. The floor was re-built during the eighteenth-century refurbishing [36]. The Cross of San Teodoro is part of a museum exhibition designed in the early 1950s by the Venetian architect and designer Carlo Scarpa, who was responsible for the restructuring of the Galleries from 1952 to 1955 [35]. The arrangement of the artworks in the room, which include various painted panels in addition to the cross, was designed by the architect with the aim of creating a specific path. For this reason, the selection of the works and their placement play a fundamental role in the museum exhibition.

The importance of the Cross is highlighted by its display case, which was designed by Scarpa himself. The glass case, in which the jewelry is kept, is supported by an iron structure with brass elements, which creates a chromatic contrast effect. The connections between metal and glass are mechanical, without the use of any adhesives or gaskets. The Cross rests on a base surmounted by an antique red porphyry slab which has been protected with microcrystalline wax in 2008 [37].

3.3 The supporting floor

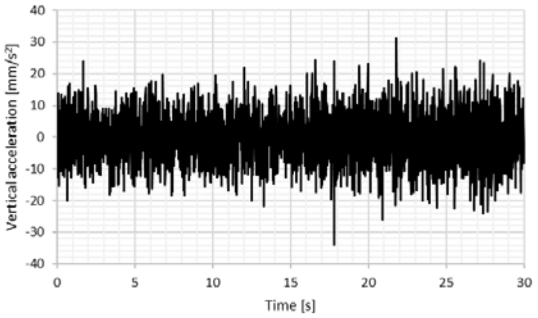
The room where the Cross of San Teodoro is located has dimensions of 32 m by 12.5 m, placed right above the main entrance of the building. As already reported, the floor was re-built during the eighteenth-century refurbishing. It is made of primary wooden beams (supposed to be fir, $E \simeq 10000$ MPa), with a cross-section of 550 mm by 850 mm supported by columns every 4 m, and secondary beams, measuring 180 mm by 300 mm with a span of 6.4 m (Fig. 2). The primary beams direction follows the lengthwise of the building, while the secondary beams are perpendicular to them. The exact composition of the topping slab of the floor is unknown, but it is believed to consist of a 10-mm-thick layer of wattled material, topped by a 100-mm-thick mixture of cement and sand, a 100-mm-thick screed layer and a 10-mm-thick layer of marble cladding (all the measures are approximated). The Cross of San Teodoro is positioned at the center of the shorter side of the building, 20 meters away from the perimeter wall of the entrance, in fact in the middle of the secondary beams system (see yellow circle in Fig. 2).

3.4 Effects of vibrations due to visitors' circulation

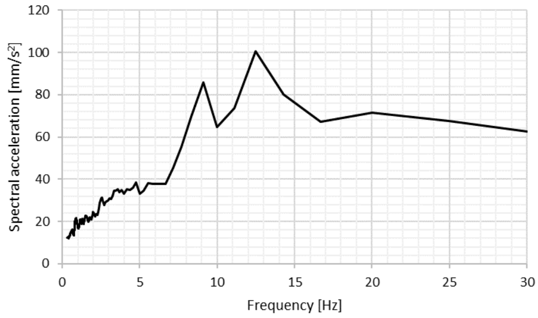
The Cross of San Teodoro, housed among many other works at the Gallerie dell'Accademia, drew attention due to the constant swinging of a decorative element (i.e. censer) resembling a pendulum on one of its arms. Although this does not pose a threat to the stability or preservation of the artwork, the continuous oscillation with an approximate period of 0.4 s does affect the enjoyment of the piece. Another factor that may disturb the enjoyment of the artwork is the visible trembling effect on the transparent materials of the cross (i.e. rock crystals) as a single visitor approaches. In fact, the human eye perceives more easily the vibration of reflective surfaces caused by the fluttering of light. Even the glass of the display case in which the object is located experiences visible oscillations as soon as a group of visitors walks nearby the object. The interest in this case study is not only limited to this particular manufact but it can be extended to all other very flexible or reflective installations or artworks (e.g. slender reading desks, suspended items, crystal, glass, silver).

On-site recordings

Acceleration recordings were conducted on site. The vertical acceleration was measured by placing an accelerometer at the base of the artwork directly on the floor. One of the most interesting recordings is the one taken when four people were visiting in the room: this may represent a sort of average level of vibration on a standard day.



(a)



(b)

Figure 3 – Time-history of vertical acceleration (Fig. 3a) and correspondent elastic response spectrum (Fig. 3b).

Fig. 3 displays the time-history recording with a sampling frequency of 100 Hz as well as the elastic acceleration response spectrum (5% damping) of the vertical motion. From Fig. 3a is possible to observe a maximum vertical acceleration of approximately 35 mm/s^2, and a maximum spectral acceleration between 90 mm/s^2 and 100 mm/s^2 (i.e. 0.1 m/s^2) in correspondence with the fundamental frequencies (first and second mode) of the floor (respectively 8 Hz and 12.5 Hz).

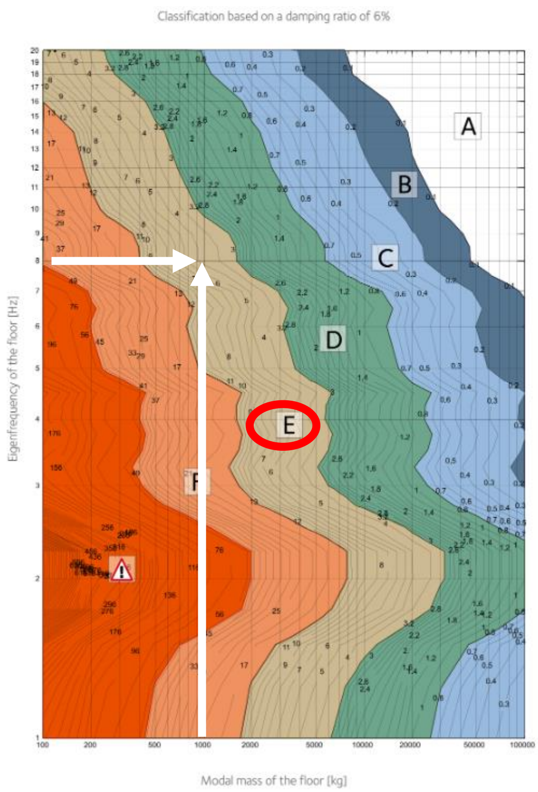
Classification of the floor

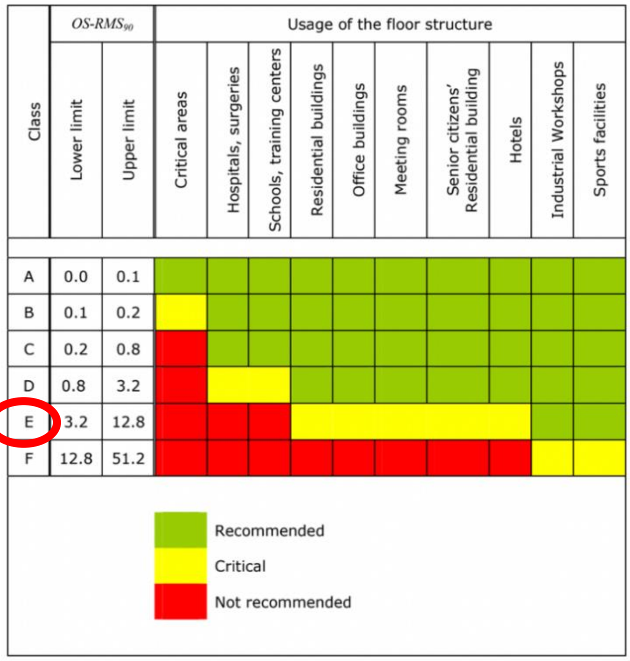
The flexibility of the floor was considered to classify it according to the guidelines on the design of floor structures for human-induced vibrations proposed by Feldmann et al. [38] (and further elaborated in [16]).

The dynamic proprieties of the floor structure relevant to the floor response, for each vibration mode, are the eigenfrequency, the modal mass and the damping value.

Initially, by considering the characteristics of the beams and assuming the non-structural layers as mentioned earlier, the natural period of the floor was analytically calculated byusing the equation for the natural frequency of a single degree of freedom system. This calculation resulted in 8 Hz frequency, which was verified by the elaboration of acceleration measurements conducted on-site (see previous section). The effective mass was also calculated ($\simeq$ 1000 kg considering a free span of secondary beams of 6.4 m and a 0.6 m-wide strip, i.e. floor sustained by single timber beam).

Knowing these two values allows the use of the abacus with a 6% damping ratio (a value commonly used for wooden floors) to determine the floor's classification according to Feldmann et al. [16]. The analysis revealed that the floor where the Cross of San Teodoro is located belongs to category “E”, as reported in Fig. 4a. Fig. 4b also reports a table that establishes the acceptability of a particular floor classification for different usage of the building. Although the table does not indicate a specific category for museums, it is evident that, at least for objects particularly sensitive to vibration as the one herein present, a category “E” floor should be considered “not recommended” (as for example as per hospitals and schools). The table reports also the interval in terms of OS-RMS, value of the velocity (mm/s) for a significant step covering the intensity of 90% people's step walking normally [38].





(a) (b)

Figure 4 – Abacus for the determination of class for a 6% damping floor (Fig. 4a [16]) and allocation of classes of perception A to F to threshold values and relation of occupancies of floor to comfort limits in terms of OS-RMS, value of the velocity (mm/s) for a significant step covering the intensity of 90% people's step walking normally (Fig. 4b [38]).

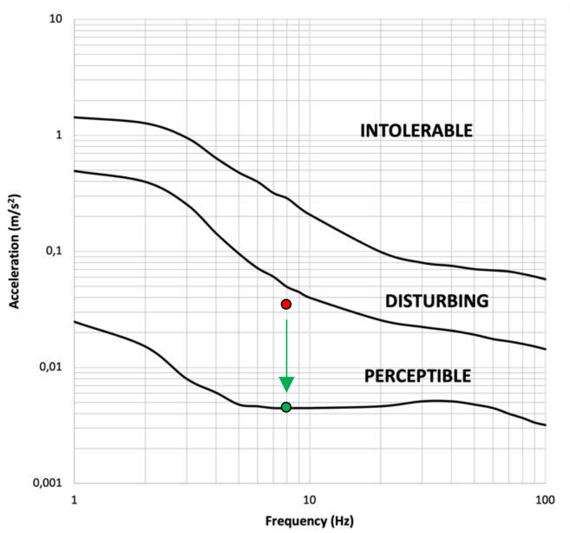


Figure 5 – Human perceptibility of vibrations and *in-situ* measurements (red dot), adapted from [13].

Another classification is reported in Johnson and Hannen [13], where acceptable limits in terms of maximum velocity vs. frequency are specified for human perceptibility of vibrations. Fig. 5

was plotted in terms of maximum accelerations vs. frequencies from [13]. It shows that the maximum recorded acceleration (approx. 35 mm/s^2) corresponds to a level of vibration "very perceptible", "almost disturbing" for human perceptibility for the fundamental frequency of the floor of 8 Hz (see red dot of Fig. 5).
Further studies should be conducted on the ultimate and serviceability limit states for artefacts in terms of maximum vibrations; the limit threshold for artworks should be likely set not greater than the level of vibration corresponding to human perceptibility, even though smaller values could be appropriate in specific cases. In the scenario of this study, for example, a reduction of almost 8 times (to 4.5 mm/s^2) as depicted in Fig. 5 (green dot) would be required to reach this level. By following this approach, the values would also meet the acceptable criteria for class "C" in the graph presented in Fig. 4.

3.5 Possible mitigation solutions

When considering solutions to protect artworks from vibrations, it is important to understand the limitations and potential costs associated with each option. Based on the considerations reported in the previous sections, three theoretical mitigation interventions may be identified:

1. Relocation of the artwork
2. Isolation of the display case
3. Stiffening of the floor

Due to the differences in applications, these solutions have boundaries related to their nature, which have been ideally classified based on their potential costs, feasibility and compatibility with the use of the asset.
After reviewing the options, it was found that relocating the Cross of San Teodoro, from a cost standpoint, would be a viable solution as the expense would only involve hiring specialized personnel to move the artwork safely and without causing any damage. Additionally, given that the manufact is not of significant size, there should be no feasibility issues, although utmost care must be taken while moving it due to its fragility. Nevertheless, moving the item would be incompatible with the arrangement of the room since the latter was designed by Scarpa within a specific context. Moreover, relocating it to a different position would result in a loss of meaning or in a not compatible aesthetic impact.
On the other hand, stiffening of the floor incurs high short-term costs due to expensive materials, labor and increased installation complexity. This mitigation solution could provide the best results in reducing vibrations. However, considering the history and tradition of Venice, a city with a rich heritage of wooden constructions and numerous historical preservation regulations, replacing or upgrading a wooden floor with a steel or a reinforced concrete floor may compromise the building's authenticity. While renovating the floor would not impact the artwork's accessibility, it could entail removing some parts of the original pavement with significant historical and artistic value, diminishing the overall experience of the piece. This is especially true since architect Scarpa transformed the entire room into an artistic wholesome exhibition layout.
Due to these limiting factors, isolating the display case seems to be the best option: it is a cost-effective, feasible and non-intrusive solution to protect the Cross of San Teodoro from vibrations.
The cost of adding springs and dampers is relatively low compared to other solutions and it has been proven that it's a widely used practice in the museum industry to safeguard artworks. For example, recently, a base dissipator with frictional curved base surface and circumferential springs and dashpots was developed to protect museum artefacts from earthquakes-induced

vibrations [39] [40] or human-induced ones [41]. In terms of feasibility, the isolators can be easily adjusted to accommodate the weight and size of the object, they can be customized to fit the specific dimensions of the display case and they do not require any major modification to the museum's infrastructure.

In conclusion, the addition of vibration isolators does not compromise the accessibility or overall viewing experience of the Cross because they are usually installed at the base of the display case, which means that they are not visible to the visitors. Therefore, visitors can still appreciate the art creation without any distractions or obstructions.

This could be, with the appropriate design phase, a potential mitigation solution to apply to the case study or to artefacts subjected to similar tremors.

This shows that, with a proper knowledge of expected vibrations and with proper thresholds for different objects, solutions can be found to mitigate the effects of vibrations especially in a design phase, where all the options could be easily taken into account.

4 CONCLUSIONS

The article discusses the importance of preserving cultural heritage and the challenges that museums face in protecting artefacts from human-induced vibrations.

However, the lack of knowledge on the vulnerability of art to vibrations makes it difficult to establish clear guidelines for protecting collections, posing a problem for curators, engineers and architects. The paper proposes a literature review with a classification of vibration sources based on internal and external and discusses the impact of visitors, construction work and nearby traffic on museum collections.

The example of the Cross of San Teodoro, an artwork in the historic museum of Gallerie dell'Accademia in Venice is presented. In this case visitors excite the flexible floor causing visible vibrations of the artefact. Examples of calculation have been proposed to classify the floor, noticing that the vibration limits could be very similar to the ones proposed for hospitals or schools in available guidelines. On-site recordings have also been presented to validate the calculations. Potential mitigations strategy has been proposed by also considering their cost, feasibility, and compatibility with the asset's use.

The article highlights that with proper knowledge of expected vibrations and proper limits for art objects, solutions may be found to protect sensitive objects, especially during the design of an art gallery but also as a retrofit strategy.

ACKNOWLEDGEMENTS

The authors would like to thank Galleria dell'Accademia (Venice, Italy) for the opportunity to conduct research at the museum. The authors would like to extend a special thanks to Dr. Serena Bidorini and Dr. Arch. Elena Azzolin for their generous assistance throughout the time at the museum. Their expertise and guidance have been (and will be) instrumental in the success of the research. The first author is deeply grateful for the hospitality and support provided by the institution. Thanks also goes to the student Marta Bertassi.

REFERENCES

[1] G. Pavlogeorgatos, Environmental parameters in museums. *Building and Environment*, **38**, 1457-1462, 2003.

[2] G.J.A.M. Eumelen, E. Bosco, A.S.J. Suiker, A. van Loon, P.D. Iedema, A computational model for chemo-mechanical degradation of historical oil paintings due to metal soap formation. *Journal of the Mechanics and Physics of Solids,* **132**, August 2019.

[3] F. Parisi, N. Augenti, Earthquake damages to cultural heritage constructions and simplified assessment of artworks. *Engineering Failure Analysis,* **34**, 735-760, January 2013.

[4] A. De Stefano, E. Matta, P. Clemente, Structural health monitoring of historical heritage in Italy: some relevant experiences. *Journal of Civil Structural Health Monitoring,* **6**, 83-106, 2016.

[5] J. Podany, *When Galleries Shake.* Getty Publications, 2017.

[6] A. Siami, H.R. Karimi, A. Cigada, E. Zappa, Vibration protection of cultural heritage objects. *Vibration control and actuation of large-scale systems, Elsevier INC.,* 107-156, 2020.

[7] W. Wei, Vibration research and testing: what was the question?, *Eastern Analytical Symposium, Conservation Science Session: Vibration Science and Technology for Cultural Heritage,* Plainsboro, NJ, USA, November 14-15, 2017.

[8] A.S. Mohammed, A. Pavic, V. Racic, Improved model for human induced vibrations of high-frequency floors. *Engineering Structures,* **168**, 950-966, 2018.

[9] UNI 9916:2014, Assessment of the impact of ambient vibrations on residential buildings, industrial facilities and monumental structures. Italian National Standardization Body (UNI). Italian language version, 2014.

[10] ES ISO 10137:2012, Assessment of the impact of vibrations on residential buildings, industrial facilities and monumental structures. European Standard (ES) version. International Organization for Standardization (ISO), 2012.

[11] DIN 4150, Assessment of the impact of vibrations on buildings and structures. Deutsches Institut für Normung (DIN).

[12] Swiss Standard SN640 312, Vibration limit for historic buildings. Swiss Standards (SN).

[13] A.P. Johnson, W.R. Hannen, Vibration Limits for Historic Buildings and Art Collections. *APT Bulletin*, 66-74, 2015.

[14] G. Zini, M. Betti, Gianni Bartoli, Experimental analysis of the traffic-induced-vibration on an ancient lodge. *Struct Control Health Monit.* 2021.

[15] A.P. Johnson, M. ElBatanouny, W. Simpsonn, Vibration Mitigation and Sound Testing in SUE Hall at the Field Museum in Chicago. *APT Bulletin,* **51***,* N. 4, 45-50, 2020.

[16] M. Feldmann, Ch. Heinemeyer, B. Völling, Design Guide for Floor Vibrations. *ArcelorMittal.*

[17] J. Valach, B. Wolf, S. Urushadze, E. Paulova, P. Stefcova, Quantification of mechanical loads induced by traffic and visitors on museum collections placed in a cultural heritage building. *Sustainable Development,* **2**, 773-779, 2015.

[18] A. Borri, A. Grazini, Diagnostic analysis of the lesions and stability of Michelangelo's David. *Journal of Cultural Heritage,* **7***,* 273-285, 2006.

[19] A. Borri (a cura di), La stabilità delle grandi statue: il David di Michelangelo. *Dei, Tipografia del Genio Civile,* Roma, 2005.

[20] A. Martelli, Problematiche sismiche. Convegno di studi sul tema La Stabilità delle Grandi Statue: Il David di Michelangelo, Gallerie dell'Accademia, Firenze, 9 June 2004.

[21] A. Siami, A. Cigada, H.R. Karimi, E. Zappa, E. Sabbioni, Using inerter-based isolator for passive vibration control of Michelangelo's Rondanini Pietà. *IFAC-PapersOnline,* **50**, 13372-13377, 2017.

[22] W. Wei, E. Dondorp, Testing to Determine Allowable Vibration Limits at a Natural-History Museum in the Netherlands. *APT Bulletin,* **51**, N. 4, 19-26, 2020.

[23] A.A.M.R. Hiswa, A.J. Alabidi, M.S. Shubber, A proposed Design to Protect Museums of Shrines in Iraq Against Vibrations. *Journal of Engineering and Applied Sciences,* 931-934, January 2019.

[24] R. Lithgow, S. Whittaker, T. Bower, K. Corda, E. Woodley, C. Higgitt, C. Vlachou-Mogire, C. Babington, Vibration Monitoring of Daniel Maclise's Wall Painting Trafalgar. *Studies in Conservation,* April 2020.

[25] M. Picu, L. Picu, Experimental Study of Road Traffic Vibrations Impact on Heritage Buildings in Braila, Romania. *Acoustics and Vibration of Mechanical Structures,* **46**, 389-395, 2018, Proceedings of the 14th AVMS Conference, Timisoara, Romania.

[26] A.C. Whiffin, D.R. Leonard, A survey of traffic induced vibrations, Transport and Road Research Laboratory (TRRL), Workingham, Berkshire United Kingdom, 1971.

[27] G. Bongiovanni, G. Buffarini, P. Clemente, D. Rinaldis, F. Saitta, Dynamic characteristics of the Amphiteatrum Flavium northern wall from traffic-induced vibrations. *Annals of geophysics,* **60**, 4, 50439, 2017.

[28] P. Clemente, D. Rinaldis, Protection of a monumental building against traffic-induced vibrations. *Soil Dynamics and Earthquake Engineering,* **17**, N. 4, 289-296, 1998.

[29] L. Shi, N. Zhang, The Simulation Analysis on Vibration of a Museum Building Nearby Induced by Urban Subway Transit. *Advanced Materials Research,* **243-249**, 3427-3431, 2011.

[30] A. Ruggiero, D. Russo, Misura di vibrazioni indotte da traffico ferroviario su edifici storici: il caso "Villa d'Elboeuf". *Atti del 43° Convegno Nazionale di acustica AIA,* 1-8, Alghero, Italy, May 25-27, 2016.

[31] D. Thickett, Vibration damage levels for museum objects. *13th Triennial Meeting Rio de Janeiro,* **1**, 90-95, September 20-27, 2002.

[32] V. Fioriti, A. Cataldo, I. Roselli, A. Colucci, P. Clemente, M. Lamonaca, L. Sorrentino, Advanced Digital Video Analyses to Estimate the Dynamic Behavior for Proper Design of a Base-Isolation System of the Sarcophagus of the Spouses at the National Etruscan Museum in Rome: Preliminary Results. In *Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures: 17th WCSI,* 707-716, 2023.

[33] S. Ellingsen, K. Norén-Cosgriff, A. Brekke, K. Vedholm, J. Langford, Protection of ancient Viking ships from vibrations caused by groundworks. *Conference Proceedings, Inter. noise,* 850-859, Madrid, June 16-19, 2019.

[34] C. Higgitt, L. Harrison, T. Galikowski, M. Pau, P. Henson, Protecting the National Gallery's Paintings Collection from the Impact of Vibration During Building Work. *Studies in Conservation,* **65**, issue sup1, 148-153, May 2020.

[35] https://restituzioni.com/opere/croce-di-san-teodoro-piedistallo-vetrina/, consulted on 20/02/2023 (in Italian)

[36] https://www.gallerieaccademia.it/en/hall-i, consulted on 20/02/2023

[37] https://www.gallerieaccademia.it/croce-di-san-teodoro/, consulted on 20/02/2023 (in Italian)

[38] M. Feldmann, Ch. Heinemeyer, Chr. Butz, E. Caetano, A. Cunha, F. Galanti, A. Goldack, O. Hechler, S. Hicks, A. Keil, M. Lukic, R. Obiala, M. Schlaich, G. Sedlacek, A. Smith, P. Waarts, Design of floor structures for human induced vibrations. *JRC Scientific and Technical Reports,* Publications Office of the European Union, Luxemburg, 2009.

[39] L. Giresini, M.L. Puppio, F. Laccone, M. Froli, Experimental and numerical investigation on a passive control system for the mitigation of vibrations on SDOF and MDOF structures: mini Tribological ROCKing Seismic Isolation Device, *Journal of Earthquake Engineering (ASCE)*, 2021.

[40] M. Froli, L. Giresini, F. Laccone. Dynamics of a new seismic isolation device based on tribological smooth rocking (TROCKSISD). *Engineering structures,* **193**, 154-169, 2019.

[41] W. Wei, N. Krumperman, N. Delissen, Design of a vibration damping system for sculpture pedestals: an integral object-based approach. *ICOM Committee for Conservation,* 16^{th} *Triennial Meeting,* Lisbon, Portugal, September 19-23, 2011.