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Seismic-risk Mitigation for Brittle Museum Exhibits: Zagreb Experiences and Perspectives

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Abstract

A strong ML5.5 earthquake, that struck Zagreb in March 2020 caused significant damage to many buildings in the city centre and several museums had to be temporarily closed or relocated. However, what is sometimes being overlooked, are the many valuable museum collections that were severely damaged or irreparably destroyed due to the excessive seismic vibrations. Mainly due to a lack of financial resources and inadequate spatial conditions and capacities, even the most valuable and unique artifacts in Croatian museums are often insufficiently seismically protected. The paper addresses seismic risk mitigation for sculptures and other brittle artworks that are particularly sensitive to strong seismic accelerations. In contrast to the traditional rigid securing of protected objects, a novel technique, namely base isolation, benefits from their partially unrestrained sliding movement, which accommodates the ground vibrations. Although it has proven effective for many valuable sculptures around the world, it is however, extremely costly and mostly out of reach of the limited financial resources of the Croatian cultural sector. The experiences of the Zagreb museums and the implemented protection mechanisms before and after the March 2020 earthquake are being examined, with the aim of discussing feasible solutions that suit local means and circumstances.

Keywords

2020 Zagreb earthquake, museum artworks protection, earthquake risk mitigation, rigid-body seismic response, base-isolation systems

1. Introduction

The recent M_L5.5 magnitude earthquake in Zagreb, which occurred in the early morning of Sunday, March 22, 2020, was located at a 10 km depth, about 7 km from the city centre. The aftershock sequence of weaker quakes followed the main one. Ground shaking caused significant damage in the central part of the city, where the seismic intensity was estimated at MMI 7 - 8 according to the modified Mercalli scale (Markušić et al., 2020). The most damaged were the non-structural elements, such as chimneys and architectural decorations of the unreinforced masonry in the historical part of the city (Atalić et al., 2021). Approximately nine months later, the damage was further aggravated by the even stronger (M_L6.2 earthquake in the neighbouring town of Petrinja. While the public attention was primarily directed towards residential buildings, about 13% of total damage and losses caused by the earthquake has been sustained in the cultural sector (Government of Croatia, 2020). Some museums had to temporarily close or even relocate parts of their collections. Due to the excessive ground vibrations, many precious exhibits and artifacts stored in the depots were overturned, seriously damaged or even destroyed.

Zagreb is located in the seismically active region and, for years now, seismologists and civil engineers have been continuously warning about possible strong earthquakes and about the risk they present to the life and the society. The seismic building codes, based on the seismic hazard maps and the structural response analysis, are nowadays an unavoidable part of contemporary construction and are regulated by the government and EU legislation (HRN EN 1998-1, 2011). On the contrary, however, the internal content of the buildings is mostly decided based on exclusively aesthetic considerations and its seismic safety is left to the proprietary's individual assessment. Museums and their inventory are not an exception, in Croatia, as well as in other parts of the world.

One of the first to emphasize the necessity of seismic risk mitigation for sculptures and other museum artifacts was Jerry Podany, the former Senior Conservator of Antiquities at the J. Paul Getty Museum in Los Angeles (California, USA). The initiative, undertook in the early 90's, has been continuously promoted and the experiences selflessly shared among the cultural workers around the world (Podany, 2017; Podany, 2020). It has been followed by the interest of many scientists who considered the seismic response of rigid, but fragile objects of art, which is in many respects more challenging and different from that of usually ductile modern building structures. A cooperative work of multidisciplinary teams of scientists, engineers and museum professionals resulted in various novel seismic-risk mitigation techniques which have been applied in the recent years for protection of some of the most valuable sculptures all over the world. The aim of this paper is to raise awareness of such an initiative and discuss it in the context of Zagreb and, more generally, Croatian museums.

The article is organized as follows. Chapter 2 introduces seismic-risk assessment, based on the Zagreb local seismic demands, for sculptures and other brittle and exceptionally vulnerable museum exhibits. The traditional and some of the novel seismic risk-mitigation techniques, such as base isolation and damping systems, applied and tested on certain valuable sculptures worldwide, are presented in Chapter 3. Chapter 4 analyses the seismic protection measures that were in use in Zagreb collection displays and depots before the earthquake and discusses the post-earthquake damages and possible seismic protection for museum exhibits in the Croatian context. The concluding remarks are given in Chapter 5.

2. The seismic-risk assessment for brittle artworks in Zagreb museums

The magnitude (M) and the peak ground acceleration (PGA) are the principal data reported after an earthquake. Closely related and both reflecting the seismic movements and the energy released at the bedrock level, they are the main factors influencing the overall human earthquake experience. However, they provide only partial information about the seismic demands on buildings and other man-made structures. Due to the local site effects, the seismic energy is often concentrated in the narrow intervals about some dominant frequencies, whose resonant coupling to the structural natural modes can have devastating and unexpected consequences. The resonant amplification can occur on each of the seismic transfer steps, from the hypocentre to the ultimate targeted object, leading to the spectral accelerations which can be much higher than anticipated for a given earthquake magnitude.

This is what happened in the M_L5.5 Zagreb 2020 earthquake. While the reported PGA at the bed-rock level was about 0.22 g (expressed in the units of g =9.81 m/s^2), it was the frequency matching of the local ground response spectrum and the natural frequencies of the unreinforced masonry buildings that led to the resonant amplification of the seismic drifts. A maximum spectral acceleration of more than 0.6 g at frequencies 2 to 10 Hz (fundamental periods of 0.1 and 0.5 s) was obtained in the historic city centre (Atalić et al., 2020; Markušić et al., 2021). Although frightening for the occupants, the seismic displacements were, fortunately, kept within the limits of the buildings shear strength and flexibility and, mostly, did not endanger their structural stability or human lives. However, the damage within the buildings (furniture, equipment, and other internal items, including museum collections), especially in the higher floors, was much worse than what might have been expected for the reported earthquake magnitude and the earthquake-source distance.

Earthquakes are extremely rare and therefore hardly predictable events, and their characteristics can be studied only on the unreliable probability grounds. The values of peak ground acceleration, expected at a specific site, are usually presented on the seismic - hazard maps. The hazard map of Croatia (Herak et al., 2011, Herak et al., 2021), designed on the basis of the Croatian Earthquake Catalogue, is a part of the National Annex of the Eurocode-8 (HRN EN 1998-1, 2011). According to the map, Zagreb is one of the

Croatian areas with the highest seismic hazard (besides the coastal region), with the PGA about 0.26 g for the return period of 475 years. It corresponds to the probability of about 10% of 0.26 g acceleration exceedance in Zagreb region over the period of 50 years, a common-standard designed lifespan for buildings.

While alarming by itself, even this value underestimates a seismic risk for the precious artworks stored in the Zagreb museums. Often unique and irreplaceable, they are meant to be preserved for future generations, in principle indefinitely. Their seismic protection calls therefore for the hazard assessment based on much longer earthquake return periods, which further increases the likely seismic accelerations. As argued in the following and confirmed by the unfortunate Zagreb experience, statues and similar brittle artifacts are particularly vulnerable to such high and/or long-lasting accelerations. Often free standing on the shelves or high pedestals, they tend to slide and rock during an earthquake and there is a high risk of collisions, overturning or even falling off the shelves. A risk which is by no means acceptable for the precious artworks, among which many present an important part of Croatian national heritage.

At first sight, there are several simple ways to prevent their destructive movements. The sculpture stability may be improved by lowering its centre of gravity or increasing the size or the weight of its base, for example. One of the simplest traditional methods is to anchor the art object to the floor or walls of the hosting building or to attach it to a special protective frame. However, while these methods are effective for moderate earthquakes (or within the earthquake-resistant museum buildings), a firm attachment of the object to the building causes a direct transmission of strong building displacements and high accelerations to the art object. Such accelerations may not be tolerated by sensitive and brittle materials, such as marble, clay or plaster, from which such objects are usually made.

While apparently rigid and often of high compressional strength, brittle materials are prone to failure. Once the (narrow) elastic region is exceeded, no seismic energy can be relaxed through further elastic and/or plastic deformations. Instead, the input seismic energy is accumulated within dislocations, inducing high shear stresses within material and sudden local cracks and fractures, with no apparent plastic deformation prior to fail. Stress concentrations are usually enhanced at local material imperfections (defects) as well as at the points of abrupt changes in geometry. Extremely sensitive spots, such as ankles or hands, may further weaken the sculpture and lead to fractures well below the ultimate material strength. The points at which the sculpture is tighten to the base are particularly exposed, thereby also putting into question the traditional securing itself.

Avoiding strong stresses within the rigid but brittle objects of art, while simultaneously preventing their sliding and overturning, is a challenging task. As discussed in the following, instead of (re)designing a sculpture and/or securing it to the base to make it more stable, it is the opposite - allowing its controlled and partly restrained sliding motion - that might help the structure to survive the strong earthquakes and violent ground displacements. A novel protective technique grounded on these observations, analogous to the well-known base isolation systems in civil construction, is considered one of the most appropriate.

3. Novel seismic protection techniques and base isolation

A base isolation consists essentially of two parallel planes, attached respectively to the ground and to the artwork. The low friction between the planes ensures that the planes can slide almost freely relatively one to another. While the lower plane follows the ground motion during an earthquake, practically no seismic forces are transmitted to the upper level. The artwork is effectively decoupled (isolated) from the seismically shaking ground and its high accelerations.

Various technical solutions for the base isolation have been proposed – from perfectly polished marble upper and lower surfaces to multiple unidirectional sliders inserted between the two levels - many of them realized in the neighbouring Italy and Greece (Sonda et al., 2017; Cigada et al., 2016; Berto et al., 2013). Among the most ingenious is the seismic isolation proposed for the *Bronzes of Riace* at Archaeological Museum of Reggio Calabria (De Canio, 2012). The four marble spheres, inserted between the two concave marble planes, allow the sculpture to freely adopt both the base horizontal displacements and rotations, while the vertical oscillations are controlled by means of dissipative elements. The overall natural frequency of the system is controlled by the base curvature and can be therefore customized to the anticipated local seismic frequencies. The curved (concave) planes ensure, after an earthquake, the sculpture recentralization by the effect of gravity force.

The base isolation is proven to be effective also for some other statues around the world, many of them under the patronage of the Getty Museum. However, having to be tailored to each and every individual sculpture, such systems acquire an accurate knowledge of the object structural and material specifics and are to be preceded by a comprehensive seismic-response analysis and experiments on multi-axial shaking tables. They are therefore accessible only to big universities or large-scale projects and reserved for the most valuable and unique sculptures.

Meanwhile, simpler earthquake protection systems are being sought. They are mostly based on the commercially available vibration-control systems, developed in the diverse industries whose investment is incomparably higher than the restricted cultural funds. An active control of seismic accelerations by means of actuators, which can be adopted to different structures and seismic demands, is proposed (Venanzi et al., 2017). A good example is also viscous dampers - cheap, non-toxic and easy-to-install devices, proposed to be inserted between the museum shelves (Ning et al., 2018). By absorbing the seismic energy and converting it into a thermal one, they reduce the excessive shelves vibrations and may seismically protect small and sensitive artworks whose individual protection would be too expensive and therefore unfeasible.

4. Zagreb museums before and after the M_L5.5 earthquake

The March 2020 earthquake in Zagreb caused significant damage, especially to the old Downtown and Upper Town areas of the city, primarily to the old historical core. Nearly all of the Zagreb museums have suffered some damage, and according to the first estimate of the structural engineers, 33% of them were labelled as temporarily or permanently unsuitable/unsafe for use (Rihtar Jurić et al., 2020). According to the research conducted by the Museum Documentation Centre, permanent collections of ten museums are closed for visitors: Archaeological Museum in Zagreb, Croatian School Museum, Croatian Sports Museum, Croatian Railway Museum, HT Museum, Museum of Arts and Crafts, Strossmayer Gallery of Old Masters (Rihtar Jurić et al., 2020).

The lack of seismic protection within Croatian museums is a complex matter, intertwined with many other issues. With only a few exceptions (e. g. the Museum of Contemporary Art[1]), Zagreb's museums are housed in historic masonry buildings, most of which were built in the 19th century or even earlier.[2] No precautions about the local soil response were taken at the time, nor is there, still nowadays, a single register of their structural characteristics and the seismic performance at the city level. Zagreb museum buildings are generally not in a good condition, mainly structurally. Moreover, some of them weren't originally built as museums while others no longer meet the needs of contemporary museums. Such problems are just a fragment of a larger picture: neglected historical buildings and a general lack of care, strategy and financial resources.

Just as relevant is the topic of museum depots that has been extensively discussed within the Croatian museum community, with Ivo Maroević being one of its most active and fervent proponents (Stublić and Vujić, 2018). The matter involves other museological issues, such as the fact that 57% of all museum artifacts are located in Zagreb museums, or the fact that 42% of museum artifacts had not yet been inventoried (Marić et al., 2019). This lack of overview and systematization complicates immensely the protection and prevention procedures. Needless to say, Zagreb museum buildings are not candidates for expensive and complicated seismic retrofits, aimed at (re)adjusting the natural frequency of the building it in accordance with the local ground characteristics. The Italian architect Fernando de Simone's vision of the 100% seismically proofed museum, that would house some of the most valuable and well-known works of Italian renaissance, is a utopian endeavour not to be dwelled on in our context (McGivern and Lombardi, 2017).

Seismic-risk mitigation for Zagreb museum collections is therefore limited to the simple measures for only the most vulnerable artworks. Though not as effective as the aforementioned novel and sophisticated techniques, well-established methods such as anchoring, contour mounting or weighting the base, could help circumvent the budgetary limitations. Examples are simple padding, wrapped around particularly fragile objects stored on shelves, which can protect them from breaking during collisions, or metal and woven plastic-mesh restraints, secured across the outer lip of the shelf, that prevent objects from falling off the shelves (Podany, 2016). Similar methods are described as being used in the Museum of Arts and Crafts depots, where the museum professionals have individually wrapped artifacts and placed them in insulated

boxes (Podgorski, 2021). Obviously, this method hampers curators' work since they are unable to observe the artworks directly and is therefore not a long-term solution. However, it helped protect the objects – no artworks in the museum were damaged in the Zagreb second earthquake in December 2020 (Podgorski, 2021).

A thorough reconstruction of the Museum of Arts and Crafts is also planned. The future redesign of the permanent display will ensure that each object has an individual seismic protection system (Podgorski, 2021). Museum of Natural History has also been severely damaged, its building (the historical Amadeo palace) as well as its numerous artifacts. However, it is currently undergoing a substantial reconstruction and is scheduled to reopen in 2023 (Hrvatski prirodoslovni muzej, 2021). The architectural and museological project will most certainly consider the seismic protection, but it remains to be seen which methods will be used to preserve the artifacts. Moreover, when deciding on the exhibition displays, the object characteristics will have to be considered. For instance, fragile objects like glass and porcelain artifacts, if feasible, should not be placed in higher floors so as not to be exposed to large seismic displacements.

5. Conclusions

Zagreb's position in a seismically active region, as well as the poor seismic resistance of its museum buildings, causes an unacceptably high seismic risk for the unique and irreplaceable vulnerable artifacts stored in its museums. As pointed out many years ago by Feilden, "*we must always be aware that we live Between Two Earthquakes*" (Feilden, 1987). Zagreb museum professionals operate in a specific context, and therefore have to adopt a specific approach to museum artifact protection. Unfortunately, it is not purely a museological issue that has to be dealt with – many systemic city-governing and urban planning issues need to be tackled. While the limited Croatian cultural budgets are unlikely to allow the time demanding and expensive novel procedures, at least small but timely adjustments and relatively humble, "improvised" or even DIY methods can improve the safety of museum objects.

It must be noted that effectiveness should not be the only criteria for the protective method selection. Since presentation is a very pertinent aspect of the museum experience, the seismic protection, however technically sophisticated, should be also comparatively inconspicuous and preserve the artistic integrity and educational value of works. A collaboration and a fruitful dialogue between museum professionals – curators, restorers, museologists, archivists et al., and professionals from technical and engineering fields – engineers, physicists, architects, product designers et al. - is therefore strongly needed. Only an interdisciplinary endeavour of various professional spheres, achieved for example, through open educational workshops on earthquake protection, can lead to synergy between efficiency and aesthetic considerations.

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[1] Unfortunately, Museum of Contemporary Art Zagreb did not escape the damage entirely. Due to an unstable fire protection system that had been set off during the earthquake, the water sprinklers were activated and flooded parts the floor that houses part of the permanent collection.

[2] The Croatian History Museum is housed in the baroque Vojković Oršić Rauch palace built in mid-18th century and also damaged severely in the earthquake.