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SEISMIC DAMAGE SCENARIOS OF MONUMENTAL BUILDINGS IN THE HISTORIC CENTER OF FLORENCE

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Abstract

Seismic events that have hit the Italian territory in recent decades have increasingly highlighted the vulnerability of historic-monumental buildings. The seismic sequence that affected central Italy from August 2016 to January 2017 hit an area rich of historic buildings containing a remarkable number of works of art. So the loss suffered affected not only the buildings but also their contents (paintings, pictures, tapestries, sculptures etc.). The earthquake in central Italy in 2016 was only the latest of the events that caused damage to the historical-monumental heritage, the identity of an area and at the same time the driving force behind a tourism-based economy. Many historic buildings and museums hit by the earthquakes in central Italy in 2016 and Emilia-Romagna in 2012 are still damaged and inaccessible to visitors. In this paper the results of seismic damage scenarios on twenty monumental buildings in the historic center of Florence are presented. These scenarios were derived by means of expeditious seismic vulnerability assessment using simplified procedures. Evaluations of damage scenarios performed for different intensities of the seismic action allowed to obtain for each scenario multiple levels of damage up to the loss of the structure. From these results recovery curves and economic indicators of the damage suffered by the analyzed buildings were then derived for pre-assigned intervention times.

Keywords: Seismic Damage Scenarios, Monumental Buildings, Expeditious Seismic Vulnerability Assessment, Socio-Economic Loss, Resilience Index.

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1 INTRODUCTION

In the last 50 years Italy has been hit by numerous earthquakes the most recent of which occurred in central Italy in 2016. This earthquake is the most destructive event when compared to the previous earthquakes that hit L'Aquila in 2009 and Emilia Romagna in 2012. It resulted in the destruction of Amatrice, Accumuli and Arquata del Tronto with huge human losses amounting to 7% of the resident population, 9% in Amatrice alone. These events highlight how the efforts made by the community to deal with seismic risk are still insufficient. Seismic risk prevention and mitigation are the main defence strategies in which we must invest to safeguard human lives and the territory.

In Italy prevention or emergency planning policies are based on the analysis of risk (or damage) scenarios used by the Civil Protection Department to develop intervention plans in the event of disasters. Risk scenarios are defined on the basis of exposure, site hazard and vulnerability of the built heritage. They are tools for predicting damage in urban centres and assessing the consequences for the population. Risk scenarios provide important information on the size and location of areas at greatest risk, the functionality of transport networks, the state of communication and distribution routes, the expected social and economic losses [1]

The seismic vulnerability assessment of existing buildings is required by the most recent seismic codes both at national [2] and European level [3]. Depending on the structural type and the required degree of accuracy, different analysis methods can be used in both linear and nonlinear field. In the scientific field analysis methods are available that can accurately simulate the dynamic behaviour of structures and provide a good approximation of the probability of damage to buildings with respect to a given seismic intensity (fragility curve). Such analysis methods are very complex and require a high computational cost and are therefore not applicable for large-scale seismic risk assessment. For this reason simplified methods have been developed that allow the determination of vulnerability and risk on a large scale.

In the case of seismic events an accurate quantification of losses is essential to encourage the development of sustainable and resilient communities in earthquake-prone areas. Estimating losses in terms of human lives, economic resources, material assets and time to restore the functionality of buildings allows institutions to more accurately define intervention priorities. This approach supports the development of effective policies for disaster prevention, improving the quality and safety of buildings and infrastructures.

Florence is a city in central Italy recognized throughout the world for its exceptional historical and architectural heritage. It is a highly urbanized and industrialized area that extends across the alluvial plain crossed by the Arno river and surrounded by hills. The area is characterized by moderate earthquakes with a local magnitude ML of about 5. The most significant earthquakes that have hit Florence have had epicentres in Mugello (1542, 1919), Impruneta (1453, 1895) and Valdarno (1770) [4]. Historical sources indicate the earthquakes of 28 September 1453 and 18 May 1895 as the most disastrous ever to hit Florence, both characterized by a Mercalli-Cancani-Sieberg MCS scale of degrees VII-VIII [5].

In the present work the socio-economic loss associated with the damage of 20 monumental buildings in the historic center of Florence was analyzed. The estimate of the number of tourists who normally visit these monuments was derived from the 2019 'Musei della Toscana' report edited by the Tuscany Region [6]. According to this report the 20 monuments considered are visited by 8.2 million tourists per year. The seismic vulnerability index IV and the damage index ID were evaluated by means of expeditious methodologies [7, 8]. From the intersection of all these parameters, the expected average annual loss AAL was calculated [9].

2 SIMPLIFIED METHODS

There are numerous simplified methodologies used for the determination of vulnerability and risk on a large scale. The methodology of Petrini and Benedetti [10] allows to assess the vulnerability of masonry buildings on the basis of qualitative and quantitative information. The Italian National Group for Earthquake Defence has developed some vulnerability forms [11] based on two levels of detail. For masonry buildings a valid methodology is the one developed by D'Ayala and Speranza [12, 13] which allows a simplified assessment of vulnerability on a territorial scale. The procedure called FAMIVE (Failure Mechanism Identification and Vulnerability Evaluation) is based on the collection of a series of information on the building under examination (most of which can be found through an external inspection) and on its construction method, in order to provide a vulnerability index. Formisano et al. [14, 15] proposed a methodology based on a simplified and fast approach to assess seismic vulnerability taking into account interactions resulting from structural continuity between adjacent buildings.

In order to quickly acquire a homogeneous and accurate knowledge on the seismic risk of cultural heritage the Italian Ministry of Culture has developed a program to monitor the state of conservation of protected architectural heritage 'Guidelines for the assessment and reduction of seismic risk of cultural heritage' [8]. The aim of the program is to define in a reasonably short time the safety level of these buildings in seismic zones. Considering the significant number of protected historical buildings in the case of assessments on a territorial scale the program plans to use simplified methods. In any case it is necessary to quantitatively assess a seismic safety index useful for highlighting critical situations and establishing priorities for future interventions. The guidelines provide three levels of increasing completeness for the assessment of the seismic safety of protected historical buildings: i) a qualitative assessment using simplified mechanical models (first assessment level LV1); ii) an assessment on single macro-elements (second assessment level LV2); iii) an overall assessment of the seismic response of the building (third assessment level LV3) [16, 17].

The first level of assessment of seismic safety at a territorial scale (LV1) can be achieved by means of one of the four simplified mechanical models provided by the guidelines [8]. These models are identified according to the type of building: i) palaces, villas and other structures with thorn walls and intermediate floors; ii) churches, places of worship and other structures with large halls, without intermediate floors; iii) towers, bell towers and other structures with predominantly vertical development; iv) masonry bridges, triumphal arches and other arched structures. The method of Lagomarsino and Giovinazzi [18, 7, 19 , 20] defines a damage index ID through an empirical formula that is a function of a vulnerability index IV. The vulnerability index IV is defined on the basis of the European macroseismic intensity EMS-98 [21] and a ductility index Q.

3 SOCIO ECONOMIC LOSSES

In the case of natural events it is of fundamental importance to quantify the suffered losses to develop sustainable and resilient communities in earthquake-prone areas. The estimate of the loss of human life, monetary losses, resources and times for the recovery of the functionality of buildings can help institutions to define the priority of interventions and policies for disaster prevention and for the quality and safety of buildings and infrastructure. This is why both social and economic loss following a natural event is a very significant indicator even more so for tourist cities.

After a natural event such as an earthquake, flood or fire, cities suffer significant economic and tourist losses.

The collapse and damage of historic buildings, churches, museums and monuments result in high costs of reconstruction and restoration. Businesses, hotels, restaurants and shops suffer drops in turnover or forced closures. Entrepreneurs and public authorities may reduce investments for fear of economic instability. The crisis in tourism and related activities leads to job losses. Destroyed or severely damaged monuments and works of art reduce the tourist offer.

With the L'Aquila earthquake in 2009 tourism decreased by 90% in the first few years, with an estimated damage of more than 10 billion euros. The Florence flood in 1966 caused incalculable losses to the artistic heritage and a long recovery period. The Notre-Dame fire in 2019 caused a major drop in tourism and estimated restoration costs were over 800 million euros. Natural events that occurred in 2017 including hurricanes (Harvey, Irma and Maria) in the Caribbean and a major earthquake in Mexico caused the highest losses ever recorded (135 billion US dollars) [22, 23]. Mazzocchi and Montini [24] calculated the difference between estimates and actual tourist arrivals after the 1997 earthquake in 12 towns in Umbria.

The data showed that tourist arrivals dropped dramatically the first month after the main quake with a continuous loss until June 1998. From October 1997 to June 1998 Assisi, which usually accounts for one third of the total tourism in Umbria, was the city with the greatest loss of tourists with a reduction of more than 50% compared to estimates. Huang and Min [25] evaluated the recovery status of visitor arrivals in Taiwan after the earthquake of 21 September 1999. The study showed that after 11 months Taiwan had still not fully recovered from the sharp reduction in arrivals due to the earthquake. In Arrighi et al. [26] a flood risk assessment for the art city of Florence was presented. The authors showed that an event of magnitude similar to that of the 1966 event could cause 40% of the losses among the exhibited works of art. In the 20th century, in parallel with the development of modern risk management techniques, the concept of the average annual expected loss AAL took shape. The expected average annual loss AAL is an index used in risk management and represents an estimate of the average value of losses expected to occur each year due to damaging or catastrophic events considering a number of factors such as the frequency and intensity of the events.

4 CASE STUDY

Twenty monumental buildings located in the historic center of Florence were analyzed. Table 1 shows for each building the number of daily and monthly tourists that habitually visit these sites. The estimate of the number of tourists comes from the 2019 'Museums of Tuscany' report edited by the Region of Tuscany [6].

The following paragraphs describe the methodology and parameters used to define the expected average annual loss AAL.

4.1 Vulnerability, damage and seismic risk

For each building the number of visitors, the vulnerability index IV, the damage index ID for different return periods RP (10, 30, 101, 201, 475, 975 and 2475 years) and the expected closure time for damage restoration were calculated.

Starting from the seismic hazard of the city of Florence according to the Italian code NTC 2018 [8] for each return period RP (10, 30, 50, 72, 101, 140, 201, 475, 975, 2475 years) the relative macroseismic intensity IEMS98 and the peak ground acceleration Pga [7,27] were calculated. The minimum Pga for a RP return period of 10 years is 0.032 g to which corresponds an IEMS98 macroseismic intensity of 4.555, while for a return period of 2475 years the Pga is 0.221 g to which corresponds an IEMS98 macroseismic intensity of 8.413.

The vulnerability index IV was calculated by applying two different methodologies depending on the building type.

Monumental Buildings	daily visitors	monthly visitors
Duomo and Cripta Santa Reparata	3140	81912
Campanile di Giotto	2001	52189
Battistero di S. Giovanni	2230	58172
Museo del Bigallo	592	15439
Chiesa di S. Maria Maggiore	617	16093
Chiesa dei SS. Michele e Gaetano	612	15959
Museo della Misericordia di Firenze	588	15325
Capitolo Metropolitano Fiorentino	583	15209
Palazzo Strozzi	863	22500
Biblioteca Gabinetto Vieusseux	583	15209
Chiesa S.Margherita in S.Maria dei Ricci	589	15364
Museo casa di Dante	256	6667
Museo di Orsanmichele	257	6699
Palazzo dell'arte della Lana	585	15256
Chiesa della Badia Fiorentina	607	15837
Museo di Palazzo Davanzati	667	17407
Biblioteca Palagio di Parte Guelfa	584	15229
Palazzo Vecchio-quartieri monumentali	2182	56917
Galleria degli Uffizi	7090	184927
Museo di Storia della Scienza	1664	43403

Table 1: Analyzed monumental buildings and relative number of daily and monthly visitors.

For buildings characterized by thorn walls and intermediate floors the methodology proposed by Lagomarsino and Giovinazzi [7] was used. The authors define the vulnerability index IV as a function of: i) a typological vulnerability index; ii) a factor that takes into account the contribution of all the characteristics of the building that influence its seismic behaviour (height, elevation and planimetric irregularities, state of maintenance, etc.); iii) a factor that takes into account the construction typology.

For churches, places of worship and other structures with large halls without intermediate floors the LV1 assessment level of the guidelines [8] and specifically the churches form was used. The church form considers 28 damage mechanisms associated with the macro-elements that may be present in a church. The seismic behaviour of the entire building is represented by a vulnerability index IV obtained for each mechanism considered through an appropriate combination of scores derived from the survey of the vulnerability indicators of the seismic structures and weight.

The damage index ID was calculated by applying the methodology of Lagomarsino and Giovinazzi [7]:

$$ID = 2.5\left[1 + \tanh\left(\frac{I + 6.25 \cdot IV - 13.1}{Q}\right)\right] \qquad 0 < ID < 5 \qquad (1)$$

where I is the seismic input provided in terms of macroseismic intensity, IV is the vulnerability index and Q is the ductility index. The macroseismic intensity I provided by EMS 98 [21] was calculated following the procedure of Margottini et al. [27] while the ductility index Q was assumed equal to 2.3 since it was considered representative for buildings not specifically designed to have a ductile behaviour [7].

The damage indices ID were divided into 6 intervals to which a damage D ranging from 0 to 5 (0, 1, 2, 3, 4, 5) was associated. On the limited basis of previous events for each damage D the cost (percentage) of repair of the building RC [9] and the time (months) of closure of each building to return to pre-earthquake conditions were defined (Table 2).

LS	RP [years]	ID		RC [%]	Recover [Months]
		Range	Damage D		
ID	10	0.0 – 0.05	0	0	0
O	30	0.05 – 0.2	1	7	0.33
DL	50	0.2 – 1.0	2	15	4
LS	475	1.0 – 2.2	3	50	48
C	975	2.2 – 3.2	4	80	132
R	2475	3.2 – 5.0	5	100	168

Table 2: Damage index ID range, damage level D, repair cost RC, and months of closure for the considered limit states LS.

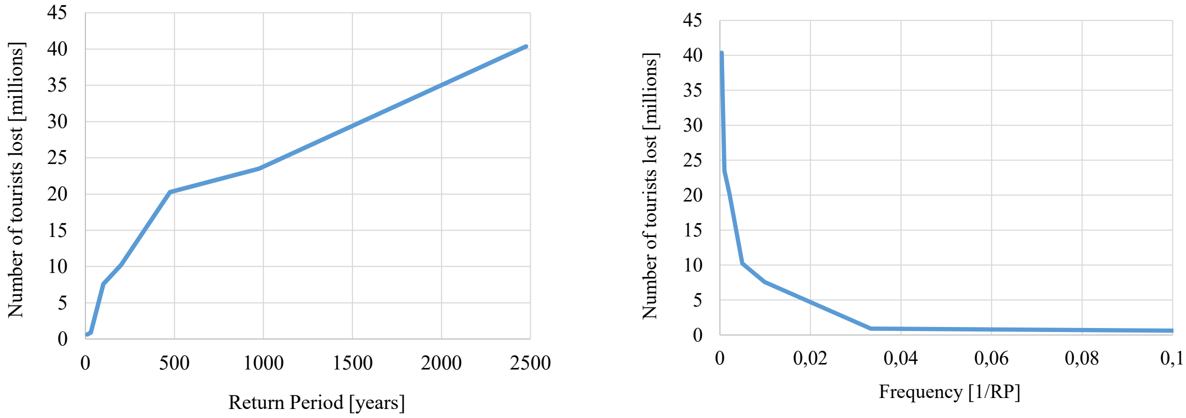
4.2 Expected average annual loss

The expected average annual loss AAL due to seismic events was calculated based on the seismic zone in which the city of Florence falls and the vulnerability assessment of existing structures. Costs were estimated on the basis of the damage suffered after having identified the relative percentage of the expected average annual loss AAL of the economic value of lost tourists.

Figure 1 (a) shows the number of tourists lost as a function of the return period. The loss ranges from 0.6 million tourists for a return period of 10 years to 40.4 million tourists for a return period of 2475 years. The number of tourists lost as a function of the frequency 1/RP is shown in figure 1 (b). The 20 monuments considered are visited by 8.2 million tourists per year [6]. The performed analyses show that the expected average annual AAL loss is equal to 0.38 million tourists.

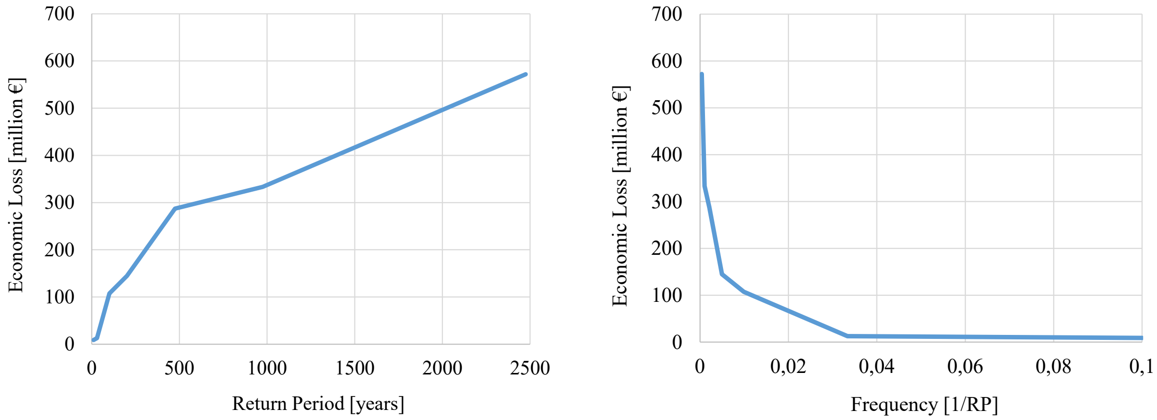
To evaluate the economic loss the cost of the Firenzecard of € 85 for 72 hours of visits to Florentine museums was considered. A weight of 0.5 was assigned to this cost considering that a visitor is not able to access several places at the same time. The economic loss as a function of the return period is reported in figure 2 (a). The economic loss ranges from 8.9 million euros for a return period RP of 10 years to 571.9 million euros for a return period RP of 2475 years. The performed analyses show that the closure of the monuments for 72 hours results in a loss of 5.80 million euros.

The economic loss as a function of the frequency 1/RP is reported in figure 2 (b). The performed analyses show that the expected average annual loss AAL is equal to 5.4 million euros.



(a) (b)

Figure 1: Number of tourists lost vs: (a) return period; (b) frequency.

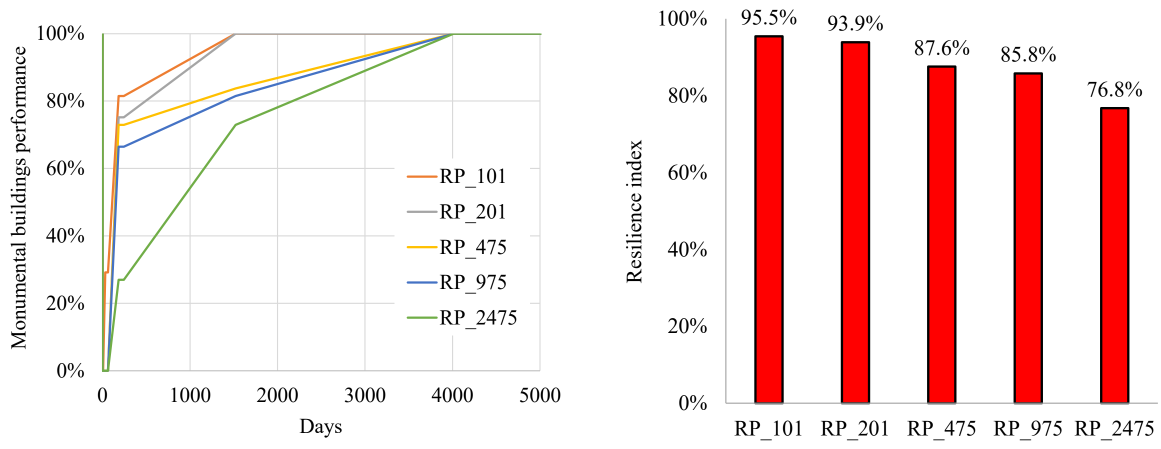


(a) (b)

Figure 2: Economic loss vs.: (a) return period; (b) frequency.

Figure 3 (a) shows the performance of the 20 monumental buildings considered in terms of percentage of reopening after the seismic event. The curves in figure 3 (a) show that for a return period of 101 years 29% of the buildings reopen after 60 days (2 months) while 100% of the buildings reopen after 1500 days (50 months). For a return period RP of 2475 years 27% of the buildings reopen after 240 days (8 months) while for the reopening of all 20 buildings 3960 days (132 months) are needed. The resilience of the 20 monumental buildings considered was evaluated through the resilience index, that is the ratio between the area under the performance curve corresponding to a given return period RP (figure 3 (a)) and the area under the curve corresponding to a reopening of 100% of the buildings.

Figure 3 (b) shows the resilience index as a function of the return period RP. The resilience index is equal to approximately 95% for a return period RP of 101 years while it is equal to approximately 77% for a return period RP of 2475 years.



(a) (b)

Figure 3: (a) Monumental buildings performance vs. number of days for reopening; (b) resilience index vs. return period RP.

5 CONCLUSIONS

In this paper an assessment of damage and socio-economic losses on 20 monumental buildings in the historic center of Florence was performed. The results show significant variability in losses depending on the return period RP of earthquake events with an exponential growth of losses as the return period RP increases. The loss of tourists ranges from 0.60 million for a return period RP of 10 years to 40.4 million for a return period RP of 2475 years, while the economic loss ranges from 8.9 million euros for a return period RP of 10 years to 571.9 million euros for a return period RP of 2475 years.

The resilience of the buildings was evaluated through the resilience index. The resilience index showed a significant resilience of the considered buildings for events with short return periods RP while for extreme events such as those with a return period RP of 2475 years the resilience decreases significantly. Indeed the total reopening of the buildings requires a time of 11 years.

The estimates of costs and losses highlight the importance of adopting prevention and resilience improvement measures to reduce the negative impact that an earthquake event could have on the historic heritage and tourist economy of the city of Florence. Intervention policies should be planned taking into account the specific vulnerability characteristics of each building and the economic implications deriving from the temporary closure of monuments.

In conclusion the proposed methodology offers a useful tool for the assessment of seismic risk and related economic losses supporting the planning of strategies of protection and recovery for the cultural heritage of Florence.

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