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SEISMIC RISK ASSESSMENT OF A MEDIEVAL TOWER: THE CASE STUDY OF CRACO

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Keywords: Slender Structure, Risk assessment, historical buildings, seismic hazard.

Abstract. *In the present paper the risk assessment of the medieval Norman tower of Craco (Matera, Italy) is discussed. Craco is a totally abandoned little town because of the activation of landslide motions of its soil depth. The medieval tower is one of the few buildings still standing as it is built on a fixed stiff foundation ground. Nevertheless, the tower is, indirectly, subjected to the movements of the close landslide.*

The tower is located in the highest and more stable part of the hill where the old town was built in the XII century for protection from enemy attacks. It is 20 m tall and has a (11 x 11) m^2 *square plan. The basement has a truncated pyramid shape; originally it had two masonry vaults, one barrel on the first floor, which no longer exists, and a still visible cruise at the second order, connected by a now destroyed internal staircase. In 1949 a reinforced concrete cistern was placed inside the tower.*

Craco is classified as a town with a medium level seismic hazard. The main aim of the present study is to evaluate the seismic risk by means of a Finite Element model, calibrated through dynamic tests performed on the tower and considering the historical value of the structure and the context in which it stands. In fact, the structure is characterized by several peculiarities: the presence of a reinforced concrete cistern, the interaction with the surrounding buildings, the closeness to the landslide, the topographical exposition, etc. Moreover, the structure has a great impact on the society due to its touristic interest, as it is an emblem of the, so-called, "ghost town" of the Appennino mountains.

A new approach is proposed to evaluate the effects of all the previously cited features on the evaluation of the seismic risk of the tower, introducing also economical and sociological parameters.

1 INTRODUCTION

In Italy the preservation of architectural heritage towards seismic actions, occupies a prominent place in the social and scientific community priorities. The recent seismic events in Italy underlined the fragility of the historical heritage, which is vulnerable to horizontal forces. Such structures, as well known, were realized only in accordance with the rules of "good practice", which of course were defined considering the ordinary service conditions, i.e. the presence of vertical loads. Thus, in most of these structures a detailed analysis is required to safeguard this heritage, and, consequently, it is necessary to define procedures for evaluating their vulnerability. These procedures can be a tool for the Authorities, which have the responsibility of their maintenance, for judging and scheduling possible interventions. In recent years, the mechanical characteristics of the masonry walls, which make up a historical building, have been a topic of discussion in various studies; in fact, due to the historical value of such structures, the use of traditional tests for the evaluation of the mechanical properties is not allowed. As a consequence, the researchers' attention was devoted to the use of dynamic tests and the results are utilized to obtain the global mechanical characteristics of the structure [1-5].

However, for a complete evaluation of the seismic hazard of a historical structure more considerations/information are needed.

In the report Natural Disasters and Vulnerability Analysis [6], based on the Expert Meeting held in 1979, the scientific community proposed to unify the evaluation of disaster expected damage in any area of interest, through the definition of three parameters:

- *Hazard (H),* consisting in the probability that a disaster can occur;
- *Vulnerability (V),* consisting in the evaluation of the consequences of a disaster;
- *Exposition/Exposed elements (E),* consisting in the socio/economic evaluation of the consequences; this parameter is linked to the context of communities.

On such basis, in [6] the following relationship for the evaluation of the *Risk (R)* was suggested:

$$Risk = Hazard \bullet Vulnerability \bullet Exposition \quad (1)$$

In the last decades, on the basis of this general formulation, several conceptual approaches were developed for the risk assessment related to technological hazards (i.e., nuclear risk) [7, 8] and to natural disaster hazards (i.e., seismic, landslide, blast, flood) [9-13].

In particular, for seismic hazard several models are proposed in [14, 15] to evaluate and estimate the economic losses due to earthquakes for different Italian building typologies.

Recent seismic events highlighted that significant damages were attained in structural and non-structural components of Italian Heritage also under low-to-medium intensity earthquakes. For the purpose of improving the seismic safety of all existing Italian buildings, the Italian "Guidelines for the seismic risk classification of constructions" approved in February 2017 [16] provides technical principles for all seismic risk assessment.

Although several methodologies are available in literature, the evaluation of the risk for a historical building is still under discussion, because for this kind of structures the same procedures of a common building cannot be adopted, due to their peculiarities.

The present work is focused on such topic; in detail, the seismic risk evaluation and the expected damage computation due to a possible seismic event on a historical tower is discussed.

In this paper a new approach is suggested for extending the procedure proposed in [16] to typical buildings of the Mediterranean area, in particular to historic masonry buildings. Since the fragility functions of structural and non-structural components, which are defined for reinforced concrete and residential masonry structures, still need a calibration and validation for other masonry buildings, in this paper the methodology of Italian legislation [16] is applied to the specific case of the Norman Tower of Craco.

2 PROPOSED APPROACH

The Italian guidelines approach for the evaluation of the seismic risk is described in detail in [17], which reports the fundamental principles and the procedures for determining the seismic risk class of a building and, moreover, for designing reinforcement interventions to reduce the seismic risk. The guidelines introduce several risk classes, from A to G, whose seismic risk increases passing from A^+ to G. To evaluate the risk class of a building, the document refers to a conventional approach and a simplified one. The conventional method, which requires a detailed seismic evaluation of the structural system for different limit states and is principally calibrated for the application to reinforced concrete structures, is the only one that allows improving the building risk class of two or more classes through adequately designed reinforcement interventions. However, the simplified approach, based on the European macro-seismic scale [17], is proposed for masonry buildings. The latter defines the seismic risk class based on the structural type and potential structural deficiencies. In this case, the local strengthening interventions allows to improve the seismic risk of only one class.

Based on the conventional approach and in accordance with eq. (1), the Seismic Risk Assessment (SRA) is identified by three parameters: *H* is the probability that an earthquake occurs considering the seismic zone in which the building is located, *V* is the vulnerability of the structure, in term of load-bearing capacity during the earthquake and *E* is a parameter which takes into account the socio/economic consequences of structural damages. In particular, the SRA of buildings is conducted at different Limit States: Operational Limit State and Damage at Serviceability Limit State; Life Safety and Collapse at Ultimate Limit State, according to the current Italian building code [16-18].

Following this approach, the seismic risk class of a building is defined as the minimum between two classes: one associated with the *Safety Index* of the structure at the Life Safety Limit State (namely *SI-LS*) and the other one related to the expected annual loss, in Italian code [16] namely *Perdita Annuale Media Attesa (PAM)*.

In detail, the first index, *SI-LS*, of the structure is defined as the ratio between Peak Ground Acceleration capacity (PGA_C), which determines the achievement of the Life Safety Limit State, and the Peak Ground Acceleration design (PGA_D) referring to the Peak Ground Acceleration (PGA) of the Life Safety Limit State for the specific site where the construction is located, indicated by the Italian code for the design of a new building. Thus, the class associated with this parameter may be evaluated [16], namely $Class_{SI\text{-}LS}$.

The second index, *PAM*, estimates the overall behavior of the construction in terms of economic value (*PAM*) and computes the performance of the structure for different earthquake intensities/return periods T_r. Such index is obtained by plotting the percentage *Reconstruction Costs* (*RC*) vs. the mean annual frequency of exceedance (equal to $\lambda = 1/T_r$) and connecting the points representative of each limit state. The so-obtained broken line is the PAM-curve, the PAM value corresponds to the area under the broken line; the smaller the area subtended by this curve, the lower the expected average annual loss (see Figure 1). *RC* is defined considering the building collapse due to earthquake event and the relevant costs needed to rebuild (according to regional price lists).

Each PGA_C corresponds to a given return period and a mean annual frequency of exceedance, λ. Once the building performance associated with a specific limit state is known in terms of $\lambda = 1/T_r$, a reliable correspondence between each λ and the repair/reconstruction cost of structural and non-structural components expressed as a percentage of RC, is needed.

The return periods, T_{rC}, associated with the peak ground accelerations corresponding to the achievement of the Damage and Life Safety Limit States for the examined building may be evaluated adopting the following relationship:

$$T_{rC} = T_{rD} \, (PGA_C/PGA_D)^{\eta} \tag{2}$$

with η equal to:

$$\begin{array}{ll} \eta = 1/0.49 & \text{for } a_g > 0.25g \\ \eta = 1/0.43 & \text{for } 0.15\,g < a_g \leq 0.25\,g \\ \eta = 1/0.356 & \text{for } 0.05\,g < a_g \leq 0.15\,g \\ \eta = 1/0.34 & \text{for } a_g \leq 0.05\,g \end{array} \tag{3}$$

where a_g is the maximum acceleration on rigid soil for the considered site.

For each return period T_{rC} the average annual frequency of exceedance is defined by equation (4):

$$\lambda = 1/T_{rC} \tag{4}$$

To estimate the repair/reconstruction cost associated with each limit state, [16] provides conventional repair costs in terms of a percentage of RC for each limit state, properly calibrated to include all the repair actions associated with a specific damage level. Easy formulations to determine the capacity of the structure at Operational Limit State and Collapse Limit State are suggested in [16], once those at Damage Limit State and Life Safety Limit State are known. In particular, the annual frequency of exceedance at Operational Limit State and Collapse Limit State can be computed according to the following simplified formulations:

$$\begin{array}{l} \lambda_{OLS} = 1.67\lambda_{DLS} \\ \lambda_{CLS} = 0.49\lambda_{LSLS} \end{array} \tag{5}$$

where λ_{OLS} is the annual frequency of exceedance at Operational Limit State, λ_{DLS} is the annual frequency of exceedance at Damage Limit State, λ_{CLS} is the annual frequency of exceedance at Collapse Limit State, λ_{LSLS} is the annual frequency of exceedance at Life Safety Limit State.

The percentages of RC were estimated according to the actual repair costs monitored in the reconstruction process of buildings. Based on the costs analysis and taking into account studies based on macro-seismic analyses as well as post-earthquake observational data reported in [3], the percentage of RC associated with Damage Limit State and Life Safety Limit State were set equal to 15% and 50%, respectively; moreover, the percentage of RC for Operational Limit State and Collapse Limit State were set equal to 7% and 80%, respectively. The repair costs associated with the Initial Damage Limit State and total loss or "Reconstruction" Limit States, conventionally related to a fixed λ = 10% and λ = 0%, were assumed equal to 0 and 100%, respectively (see Figure 1 and Table 1).

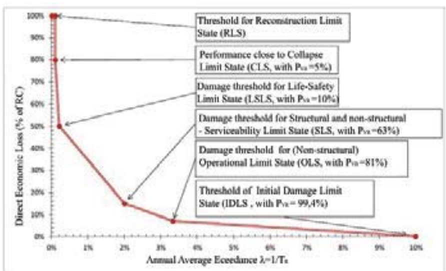

Figure 1: Trend of the curve that identifies PAM referring to a construction with a nominal life of 50 years and belonging to the use class II in according to [18].

Limit State	Percentage of RC [%]
Reconstruction	100
Collapse	80
Life Safety	50
Damage Limitation	15
Operational	7
Initial Damage	0

Table 1: Reconstruction/Repair Costs, expressed as percentage of RC, associated to each Limit State.

To determine the seismic risk class, the approach proposed in [16] requires evaluating PAM, according to the following equation:

$$PAM = \sum_{i=2}^{5} [\lambda(LS_i) - \lambda(LS_{i-1})] * [RC(LS_i) + RC(LS_{i-1})]/2 + \lambda(CLS) * RC(RLS) \quad (6)$$

where index "i" represents the generic limit state (i=5 for Collapse Limit State and i=1 for Initial Damage Limit State). Thus, the class associated with this parameter may be evaluated [16], namely $Class_{PAM}$.

Hence, the seismic risk class of the analyzed building corresponds to the worse risk class between $Class_{SI-LS}$ and $Class_{PAM}$.

The described procedure allows to simplify the seismic risk assessment and to have a design-oriented approach suitable for common practice applications. It is necessary to specify that the computation of the PAM class relies on the assumption that the repair costs at the different limit states are constant for private residential buildings without any distinction at component level.

This aspect obligates to calibrate the repair cost for different types of Italian construction heritage. In detail, for non-residential buildings the repair cost must be calibrated considering all their characteristics which lead to their proper value. In the following, a new approach is calibrated for the analysis of the case study of the Norman Tower of Craco.

2.1 Case of study

In this research the interest is centered on the Medieval Town of Craco, near Matera (Italy) and in particular on its tower. Today visiting Craco, the scenario is a village completely abandoned due to severe landslide motion, developed in the south-western part between 1959 and 1972, which damaged most part of the existing buildings. The Norman tower, object of the present study, was endowed with a defensive purpose and, for this reason, located on the highest point of the hill. The city has developed over time around it, thus creating the actual historic center (see Figure 2).

The Norman tower is one of the few structures remained unharmed by the effects of the landslide, until today. The defensive character of the tower is underlined by its robust appearance and by a quadrangular structure of 11 m size in compact masonry. The structure consists of an architrave opening on the East side at the first level, which allows access, and arched openings on the second level (12.5 m), one for each side, with the exception of the one facing North. Cracks arranged in three rows at the height of the crown (triangular in the lower rows and quadrangular in the third row) mark the horizontal closure placed at 20 m from the ground level, while the basement has a truncated pyramid shape.

Originally the structure had two masonry vaults, a barrel one (no longer existing) on the first floor and a cruise vault on the second level, connected by an internal staircase which was destroyed. In relatively recent times, the inside of the tower has been subjected to manipulations, which have affected the general state of conservation. In 1949 the barrel vault and the staircase were demolished, and a municipal reinforced concrete tank of water with a cylindrical shape was realized. The cistern is not connected to the tower, but at some levels it is perfectly adherent to it.

Figure 2: South-East view of Craco with Normand tower.

A geometric survey was performed for evaluating the main characteristics of the structure: the wall thickness varies from 2.15 m at the base of the tower, to 1.70 m at the top. Based on a visual inspection and on the analysis of documents, it is assumed that the wall is realized by rubble masonry with a sand-interposed core. Externally the masonry base consists of a set of irregular river stones and shows conditions of advanced decay; the upper part of the tower, apparently in good conditions, consists of sandstones of varying sizes, with the exception of the cantons where cut stone blocks prevail, used for the double rings of the arched openings.

2.2 A new approach for the Reconstruction Cost calibration

The Reconstruction Cost [16] is the fundamental parameter for the evaluation of the PAM class, $Class_{PAM}$. In the specific case of the Norman Tower, it is not plausible to hypothesize a mere reconstruction cost which cannot take its significant historical and cultural value into account. In fact, even if the reconstruction could be economically estimable, however in no way it could replace the historical and cultural value lost in the event of its collapse and/or serious damage.

For this reason, the approach here proposed envisages the definition of a new *Reconstruction Cost* (RC^*), in accordance with equation (7), which, for the present case, is specified by introducing a new parameter, the *Usability Loss* (C_{UL}). Therefore:

$$RC^* = RC + C_{UL} \tag{7}$$

In the following, the evaluation of such parameter is proposed.

In the last decade, Craco has become a tourist attraction centre for its history, social value and historical and architectural heritage, becoming a symbolic ghost town. For this reason, the "Scenographic Museum of Craco" was realized with the aim of organizing touristic tours in the historic centre of Craco and in particular some visits of its symbolic structures, including the Tower.

It is possible to assume that the collapse of the Tower by seismic events and, therefore, the loss of a symbolic element of the historical centre would cause the non-usability of the latter. Consequently, the non-visitability would produce an economic loss during the whole period, which coincides with the "Recovery Time" of the structure. Such loss is here utilised for the evaluation of the proposed *Usability Loss* (UL) parameter, as a tool to estimate the historical-artistic value of the Tower.

The introduced parameter may be applied to any kind of structure with a historical/architectural value, by adopting a criterion able to describe the specific characteristics of the examined structure.
In this paper, the Usability Loss is quantified by calculating the monthly number of tickets sold (N_T), the time to rebuild the structure (t) and the average ticket price (C_T). In particular, the number of annual users of 2017 has been divided on a 12 months-period, so the monthly number N_T is equal to 1416.

The average ticket price C_T available from the "Parco Scenografico Museale di Craco" web, is equal to €10 [20].

To identify the recovery time *(t)* and the Reconstruction Costs *(RC)* an intervention has been hypothesized, which foresees the faithful reconstruction of the "as it was, where it was" type, in accordance with the costs of [21]. It was therefore estimated that this intervention lasts 12 months, probably the shortest, to try to create the least possible discomfort at the museum.

Thus, *Norman Tower RC** is given in Table 2.

New Parameters	Acronym	Costs (€)
Cost of reconstruction	RC	€ 316,468.00
Loss of usability	C_{UL}	€ 170,000.00
Cost of reconstruction'	**RC***	**€ 486,468.00**

Table 2: New parameters and their economic value.

2.3 Seismic risk class of the Norman Tower

To evaluate the seismic risk class of the Norman Tower of Craco, the conventional method was applied as indicated by [16], adopting the prescription of the current Italian Technical Standards for Construction "NCT 2018" [18, 19].

The analysis of the structure was carried out by means of PROSAP software [22]. The structure was modelled through 12,160 shell elements, 12,470 nodes and a rigid floor. The following mechanical parameters for the masonry walls have been assumed:

- Young's modulus (E_m) equal to 1050 MPa
- Poisson's Modulus (ν_m) equal to 0.2
- Average specific weight of the masonry (w_m) equal to 19 kN/m^3,

while for the reinforced concrete elements the following values have been assumed:

- Young's modulus (E_c) equal to 27460 MPa
- Poisson's Modulus (ν_c) equal to 0.2
- Average specific weight of the masonry (w_c) equal to 24 kN/m^3

All the walls have been considered pinned at the base. The gravitational loads are the ones due to the structural masses, as no servicibility loads are acting on the tower.

In the following, the detailed procedure for the evaluation of the the Norman Tower seismic class is described. In the first part, the PAM graph is evaluted, while in the second part the safety index is discussed, and, finally, the risk class is defined.

The Italian building code [16] gives the design PGA for the Life Safety Limit State ($PGA_{D-LS-LS}$) and for the Damage Limit State (PGA_{D-DLS}), by using the Elastic Demand Spectrum for Craco town (Figure 3):

- $PGA_{D-LS-LS}$= 0.103g
- PGA_{D-DLS}= 0.048g

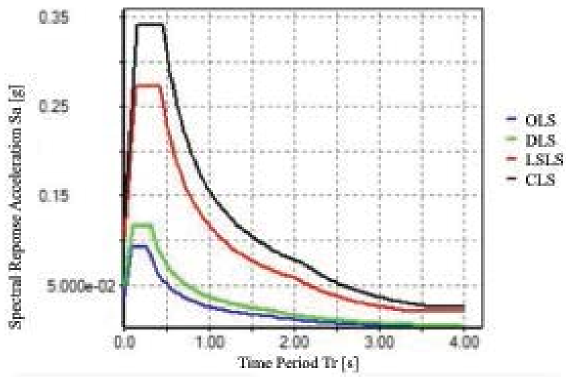

Figure 3: Elastic Demand Spectrum of Craco Town

The FE analysis allows the evaluation of the capacity peak ground acceleration related to the achievement of the Life Safety Limit State ($PGA_{C\text{-}LS\text{-}LS}$) and the Damage Limit State ($PGA_{C\text{-}DLS}$):

- $PGA_{C\text{-}LS\text{-}LS}$= 0.083g
- $PGA_{C\text{-}DLS}$= 0.0336g

The return periods, T_{rC}, associated with the considered limit states (LS-LS and DLS) were then evaluated by using the equation (2), where η was set equal to 1/0.43, in accordance with equation (3) (Craco lays in the seismic zone 2 [23]). In the following, the calculated T_{rC} values are reported:

- $T_{rC\text{-}LS\text{-}LS}$= 287 years
- $T_{rC\text{-}DLS}$= 22 years

Finally, in accordance with the Italian codes, the Annual Average Exceedance (λ) (see equations 4-5) and the minimum/maximum values of the economic loss for the reconstruction of the Tower were evaluated. The procedure adopts the same percentage.

For each considered Limit State, the value of the reconstruction cost percentage and the annual average exceedance values are reported in Table 3, which has been defined adopting the same percentages of Table 1.

Limit State	Percentage RC* [%]	Cost (€)	Annual Average Exceedance (λ)
Restoration	100%	€486,468.00	0
Collapse	80%	€389,174.00	0.0015
Safety Life	50%	€194,587.00	0.003
Damage	15%	€29,188.00	0.046
Operational	7%	€2,043.00	0.076
Initial damage	0%	€0.00	0.1

Table 3: Reconstruction/restoration costs (RC*) and Average annual frequency of exceedance, associated with the achievement of each Limit State for the Tower of Craco.

Finally, $Class_{PAM}$ is identified by means of Table 6 [16] which associates the class to the range of values assumed by PAM.

For the Tower studied in this paper, the *PAM*-value is equal to 2.07%, corresponding to C_{PAM}- class (see [16]).

The second step of the procedure, needs the evaluation of the safety index of the structures, which is defined as the ratio between the peak ground acceleration capacity PGA_C for which

the building reaches the Life Safety Limit State and the peak ground acceleration demand PGA_D of the site where the construction is built, with reference to the same limit state. In the case here examined, the first PGA is equal to *0.083g* while the second to *0.103g*, thus the safety index is equal to 81%.
The risk class associated with the Safety index can be derived through [16] and is equal to A_{SI-LS}.

On the basis of the aforementioned parameters, the Seismic Risk Class of the Tower is ***C***, that coincides with the worst/lowest class between the $Class_{PAM}$ and the $Class_{SI-LS}$, i.e. the one corresponding to the highest risk. It is useful to point out that the seismic risk class corresponds to the one associated with the PAM class, that is the one modified by the proposed procedure.

In conclusion, for the Norman Tower, being an asset with significant historical and cultural value, hypothesizing a cost of reconstruction alone is not plausible. Its reconstruction, however, economically estimable, can in no way being representative of the historical and cultural value lost in the event of its collapse. The identified approach, therefore, for the estimation of the RC* parameter represents a possible proposal for the determination of an economic value of PAM, associated with types of buildings with high historical and cultural value and accessible to the public.

3 CONCLUSIONS

A new methodology able to evaluate the seismic hazard of the medieval tower of Craco has been proposed, being this construction a historical-monumental building. The current Italian guidelines for seismic risk assessment provide a method based on both the indices PAM and SI-LS. However, this method is proposed for application to residential buildings in reinforced concrete, here such method is extended to the analysis of historical masonry structures.

In detail, the calibration of the *Reconstruction Cost* (RC), necessary to the PAM index calculation for the seismic classification, has been developed. PAM is evaluated by different parameters in the formulation of the new reconstruction cost (RC*). These parameters take into account the socio-economic, architectural, historical and cultural value of the structure. Specifically, in the study case of the Norman Tower, the Usability Loss has been considered as crucial parameter. This choice depends on the museum function of the tower and the *ghost town* of Craco.

From the analysis the tower *PAM*-value was equal to 2.07%, corresponding to C_{PAM}-class.

Further in-depth studies and analyzes are necessary for the validation of the proposed methodology. Additional parameters could be identified in order to take into account several aspects that can condition the value of the building.

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