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SEISMIC SAFETY EVALUATION OF HISTORICAL CENTRES

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Abstract *After recent seismic events, the topic of seismic prevention and mitigation in historical centres is becoming very important, in particular for seismic prone areas, like Italy, Greece, Portugal, in which a lot of historical towns, for the high quantity of old buildings and for their urban structure, suffered from significant damages. For this reason, this study deals with a new strategy for the seismic prevention and mitigation of historical centres, analyzing them in terms of structural safety. The proposed approach is based on two relevant steps: the first is to study the Urban Risk, the second is to program the Post-Earthquake Activity. The first activity consists in the analysis of a complex system aiming at individuating the nodal fragility, the second tends to evaluate the buildings safety and the occupancy conditions for these buildings. In this paper a particular aspect of this topic is discussed, i.e. how different typologies of buildings, that coexist in historical towns, could influence the reconstruction strategy. In fact, the term "old buildings" surely include masonry historical building, but also includes more recent r.c. buildings designed without any seismic provisions or, as unfortunately usual, realized with poor quality material. Considering that in recent seismic events often this class of buildings caused many damages and deaths, an efficient procedure able to measure the impact of r.c. structures on seismic prevention and mitigation in historical centres has to be considered a fundamental goal to reach.*

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1 INTRODUCTION

Urban seismic risk prevention deals with the effects of territorial transformation, in order to evaluate the impact these ones may have in modifying the functions of different parts of a settlement. Unlike ordinary vulnerability analysis of structures and infrastructures [1-8], urban vulnerability depends not only on the structure characteristics but also on the functional systems that compose a city [9-14]. Urban prevention, therefore, has to be framed in a wider vision as compared to a single building and is designed to maintain the vital settlement functions.

The key issue is to identify the essential parts of the urban structure, which must remain operational even after the earthquake. This Urban Minimum System (UMS) is conditioned by the settlement strategic role as compared to the surrounding area and, with due consideration, by the different elements that compose it. This approach, i.e. the selection of some elements only, is justified by the circumstance that it is impossible to protect the entire settlement, for reasons of cost and time. It is therefore natural to make a choice: which structures, and at which level, to protect first. Prevention planning is based upon the need to maintain the vital functions that make up a city. The idea of UMS is linked to the strategic role of the different elements, within the ordinary life of a city. It is necessary to understand which are, at any given time, the components of the UMS, with the final goal of identifying the set allowing to obtain a city working after an earthquake.

On the above issue, many classical structural reliability methods have been proposed in literature in order to model and analyse the seismic safety of a system and to identify the components which, after retrofitting, maximise the system probability of survival. In particular past studies deal with the seismic safety of both stand-alone structures (e.g. a hospital, a bridge) and capacitive network like systems ((e.g. electric network, water distribution, roads network). By the word capacitive here we mean that the network has a finite (however big or small) transportation capacity, being it of goods (electricity, water) or people (roads).

The procedure described in this paper belongs to the former class and, differently from the previous studies, focuses on urban centers. The historical center of "Montebello di Bertona" (Abruzzo, Italy) is chosen as case study. The system (a portion of a municipality) is modelled via its cut sets and a fragility curve, specifically computed, is assigned to each element. An optimization procedure, aiming at maximizing the global system safety and minimizing retrofitting costs, is then set up. The results clearly indicate the best seismic retrofitting strategy.

2 A STRATEGIC APPROACH FOR HISTORICAL CENTRES

An historical center is, like a general infrastructure, a complex mix of different functions; these functions are in part in series and in part in parallel. This distinction is very relevant.

A series system is a configuration such that, if any component of the system fails, the entire system fails. Conceptually, a series system is as weak as its weakest link. Contrarily a parallel system is a configuration such that, as long as not all the system components fail, the entire system works. Conceptually, in a parallel configuration the total system reliability is higher than the reliability of any single system component.

These basic approaches have to be redefined for historical centers, above all if little towns in marginal territories are considered, like those existing in the Abruzzo Region, in Italy. In this case historical centers show low inhabitant density, a great part of uninhabited or partially inhabited buildings and a poor maintenance of these buildings.

So, under the above circumstances, it is not possible to classify a building as part of a series or parallel system: probably these buildings are out of any system from a functional point of view and it is not clear how to manage their failure. On the contrary these same buildings may have a great value from an urban point of view. That is, they may be particularly relevant in terms of architectural content and touristic use. Finally it could be extremely complex to individuate the owners of this existing patrimony, so it could be difficult to characterize these buildings in terms of fragility.

Moreover, in an historical center, the choice if restoring or not a building (or if seismically improve it or not) could be devoted to urban or architectonical considerations and not to economical or purely structural evaluations. In this framework an accurate evaluation of the historical evolution of the urban pattern should be a crucial step and the population size trend could be a fundamental parameter. In fact the population size can affect both building construction and maintenance. That is, if in a certain period a town has a great population, it needs a high number of buildings for home and service; if the same town later losses population, those buildings will be not maintained or will be abandoned. In the case of an earthquake this town will be more fragile than another one with constant population size trend. So, for historical center, there is a link between population size trend and damage response.

3 URBAN RISK ASSESSMENT AND REDUCTION

Recently, as a result of the seismic events occurred in Italy and in other parts of Europe, the analysis of urban seismic vulnerability has become a topic of considerable interest. Various procedures for the safety evaluation of network systems like electric powers, roads, hospital regional systems or hospitals, bridges or strategic buildings, were proposed in literature [15-22].

Differently from the above studies, the research herein carry out deals with the topic of Urban Risk Assessment. In this specific case, a new system has to be defined: the so-called Urban Minimum System (SUM), i.e. a peculiar urban system composed of strategic buildings, open spaces and public ways [10, 23]. Strategic here means either crucial to its operation (e.g. hospitals, industries, commercial and governmental buildings, bridges, major roads, etc.) or essential to achieve strategic objectives (e.g. if a policy of sustainable energy development is adopted, the system of production facilities, wind farms, solar, biomass power plants, etc.).

The Sum is therefore a system of paths, functions, strategic buildings and spaces that are considered essential for the post-earthquake vitality of the urban organism, even after further events caused by the earthquake (fire, landslides, damage and geological phenomena, etc.). The Sum includes structures and functions, so that no component can be removed without compromising the overall operation of the city. If the SUM includes infrastructural networks and external risks (environmental and geological risks),it can be referred to as a complex system. From a mathematical point of view, considering that many aleatory quantities are involved, a probabilistic approach should to be applied; on the other hand, if a Urban Plan has to be approved, it is necessary to assume practical and operational decisions.

Generally, when a seismic safety evaluation is carried out, it is necessary to construct a procedure able to maximize the safety of the selected nodes and minimize the economic cost, in order to identify which components, within each part of the system, have to be upgraded at the aim of obtaining the maximum economic convenience. In the case of a Urban System, this approach has to be revisited in order to take into account the functional, and social, roles of the different parts of a city. Many aspects have to be simultaneously considered in the hypothesis of a seismic event: i) structural safety; ii) functionality of shops, public offices, schools, hotels; iii) functionality of public roadways.

There is no a single Sum identification method. The approach presented in this paper is an attempt to define the minimum urban structure synthesizing structural and urban design, reassembling two different visions of the same problem, the structural engineering and the urban design. The first phase of the urban risk assessment involves the analysis of the spatial elements at risk, listed below:

- the population in the wider sense, the human element, that is the permanent population (residents and people who work in the city) as well as the temporary one (people who work but do not live in the city – professional visitors, tourists, etc.);
- the residences, buildings and infrastructures of the city frequently receiving large numbers of visitors, such as public buildings, services, buildings housing central functions.
- buildings of strategic significance characterized by their usefulness in crisis periods, such as hospitals, fire and police stations, communications centers, general infrastructure and basic decision-making centers (administrative officials, city hall, etc.), organizations.
- monuments, buildings that belong to the cultural heritage of the city, buildings of architectural significance.
- transportation networks (roadway, railway) with their subcomponents (bridges, streets, terminal stations, etc.).
- Utility networks (electricity supply, telecommunications, water supply, natural gas, sewage disposal) with their subcomponents (substations, tanks, pipelines, etc.).

Furthermore, a urban risk analysis also includes a population distribution study, an analysis of its socioeconomic characteristics and structure, functions of the city, productive and economic activities taking place within it, systems of its substructure and its superstructure as well as its relation to the wider region.

In the case of a historical center, a reasonable logical scheme for a SUM is shown in Figure 1a. This scheme is composed of four sub-systems (strategic buildings, open spaces, external risks, public ways) arranged in series; each of these sub-system is arranged in series too. When a system is arranged in series, it means that each element has to be safe in order to preserve the global safety (Figure 1b). So a strategic building, such as for example a primary school, can be considered safe if the open spaces near the school are accessible, electric power is at disposal, water network is operative, eventual ground sliding remains in a quiescent stage, public ways preserve their accessibility from the entire community and, above all, from ambulances or civil protection and fire trucks. On the other hand when a sub-system shows some redundancies, the corresponding components can be assumed as arranged in parallel. So, for example, if the same primary school can be reached by means of two different road ways, these two ways result in parallel, that is one of these can collapse if the other one remains full efficient.

Any macro sub-system is firstly assumed as in series with the others, while a punctual analysis successively allows to distinguish the two categories of in-series and in-parallel components (Figure 1c).

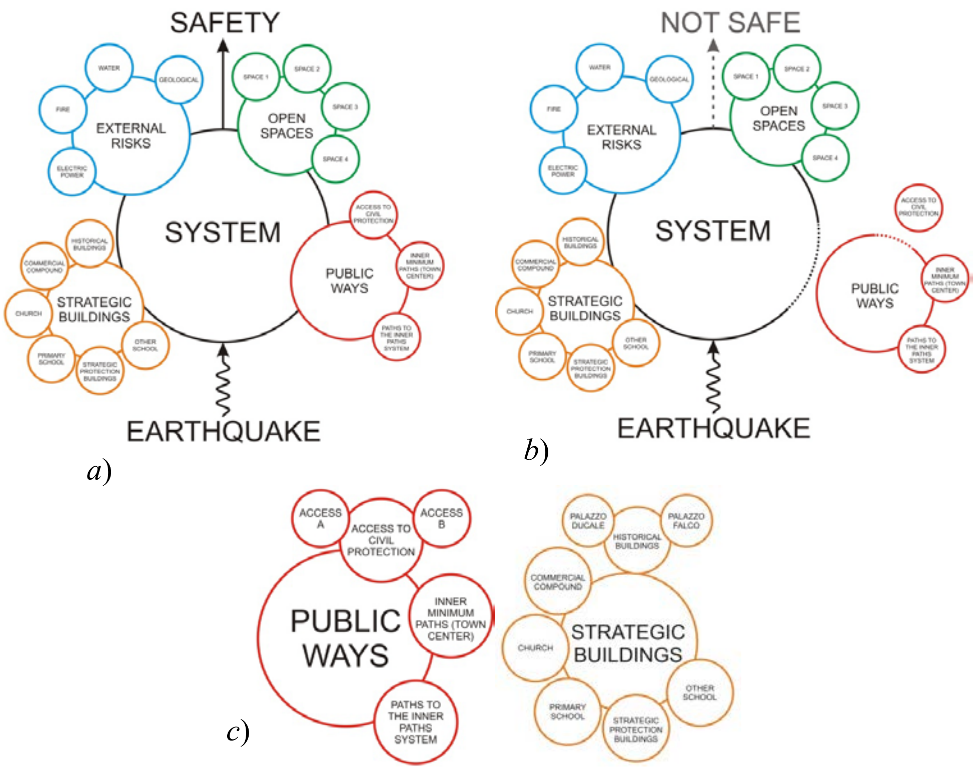

Figure 1. Possible Logical schemes for a SUM

3.1 Proposed methodology

Due to the uncertainties involved in the analysis, a probabilistic approach is herein applied. The proposed methodology involves the following steps: i) identification of the SUM; ii) selection of the target safety level, that is of the seismic intensity level; iii) definition for each component of the fragility curve, which gives the probability of a structure to exceed a certain damage state; iv) evaluation of the fragility behavior of the whole system; v) identification of an optimal retrofitting strategy.

The vulnerability assessment at territorial scale firstly requires to group the buildings that have a similar seismic behavior, in order to evaluate the damage and losses of the built environment due to a given hazard assessment.

Successively, suitable fragility functions can be defined for each building class, by using existing ones or by developing new specific curves. The fragility curves describe the probability of a structure to be in or exceed different damage states (i.e. minor, moderate, extensive and complete) for a given level of ground shaking or failure [18, 23].

The fragility curves herein adopted are empirical, that is were obtained, in a previous study, from observed damages after the occurrence of past earthquakes in Italy [24-28]. More precisely, they were evaluated by applying the bayesian updating method to damage data recorded in the 1980's Irpinia and the 1976's Friuli earthquakes. The assumed distribution function for each component fragility was lognormal, defined by the two parameters mean and coefficient of variation. Two performance levels, Immediate occupancy and Structural stability were considered. The Fragility curves so obtained define the probability of failure P_f of each class of buildings in function of the earthquake intensity expressed in terms of Mercalli - Cancani - Sieberg scale. After defining the fragility curves of the different components, the fragility curve of the whole system can be achieved by applying the classical structural reliability methods and the Monte-Carlo technique.

The component whose strengthening mainly increases the whole system safety is then searched for, through an optimization algorithm. That is, the optimal retrofitting strategy consists of the determination of the priority order according to which the different components have to be strengthened. In other words, after the as-it-is-system failure probability has been computed, it is checked the strengthening of which component, among all, increases the system safety mostly. This one is chosen as the first in the priority list (I); the check is then repeated (assuming component I as strengthened), the second one is chosen and the priority list up-dated. The increase of the whole system safety is measured in terms of increment of the mean failure probability. In this way, scarce economic resources can be optimally allocated in terms of system safety.

4 THE CASE STUDY: "MONTEBELLO DI BERTONA"

The practical application of the method concerns the town of "Montebello di Bertona", which belongs to the so called "cratere sismico aquilano" (municipalities near the epicentre of the recent L'Aquila earthquake).

All buildings are classified into six classes on the basis of three structural typologies, i.e. masonry, reinforced concrete and mixed ones, and two heights, i.e. less or more than three floors. The considered components are in total 40 and include buildings, utility networks linked to external risks, open spaces and public ways, assembled in series or in parallel.

The fragility curves for the analyzed SUM are shown in Figure 2, where the red thick line represents the actual fragility curve of the whole system. It is possible to note that the value of the failure probability PF= 50% is reached in correspondence of a value of the Modified Mercalli Intensity (MMI) equal to 5.70, i.e. this little town is too much fragile on respect to its local seismicity. A retrofitting procedure has to be carried out in order to obtain an acceptable Security Level. Considering the nature of a historical town where masonry buildings represent the prevalent building typology, a MMI = 10 level in correspondence of PF= 50%, with reference to the whole system fragility curve, can be assumed as an acceptable Risk Level target.

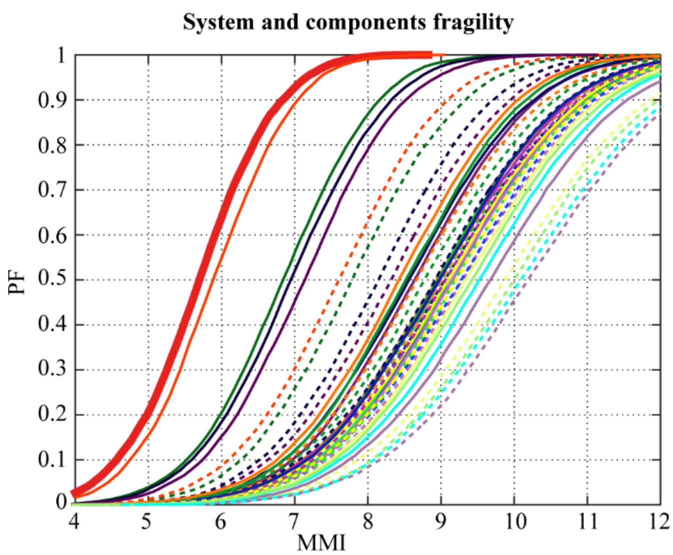

Figure 2. Fragility curves for Montebello di Bertona Urban Minimum System

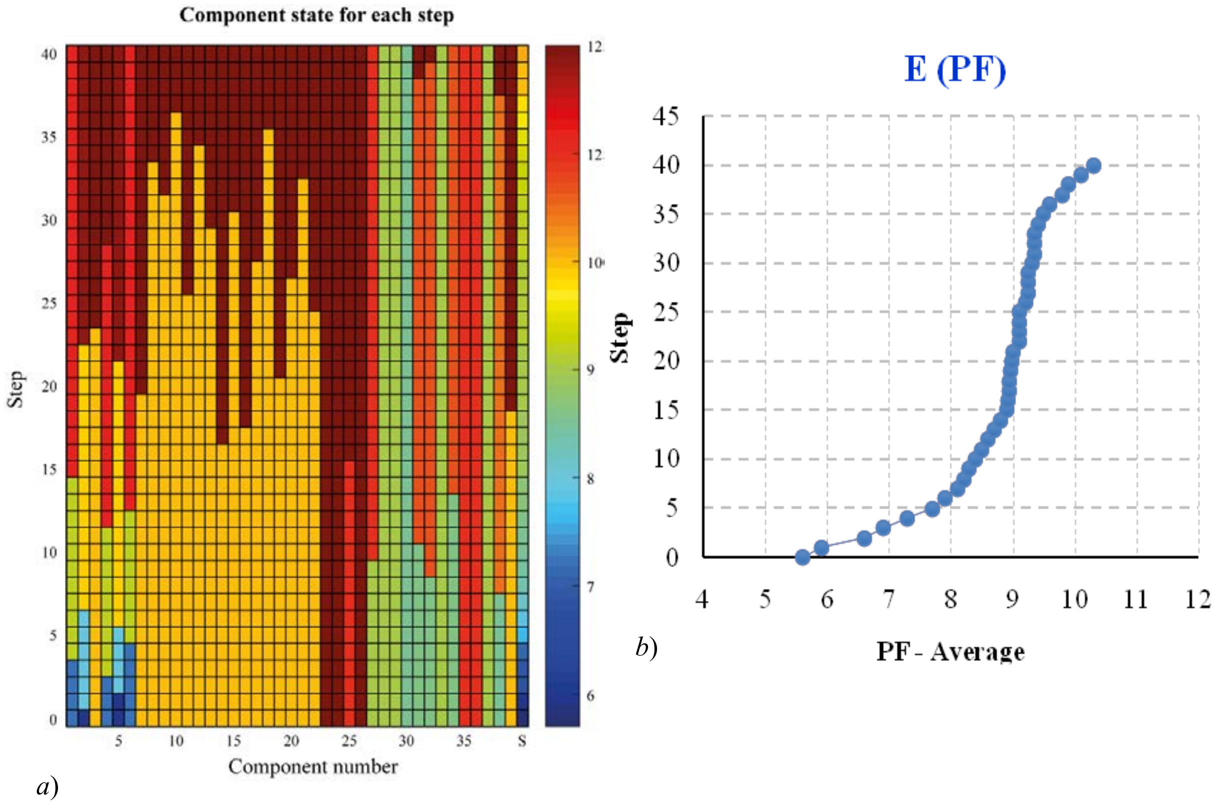

Figure 3. a) MMI failure intensity level; b) Cumulative PF average value, for each component at each retrofitting step.

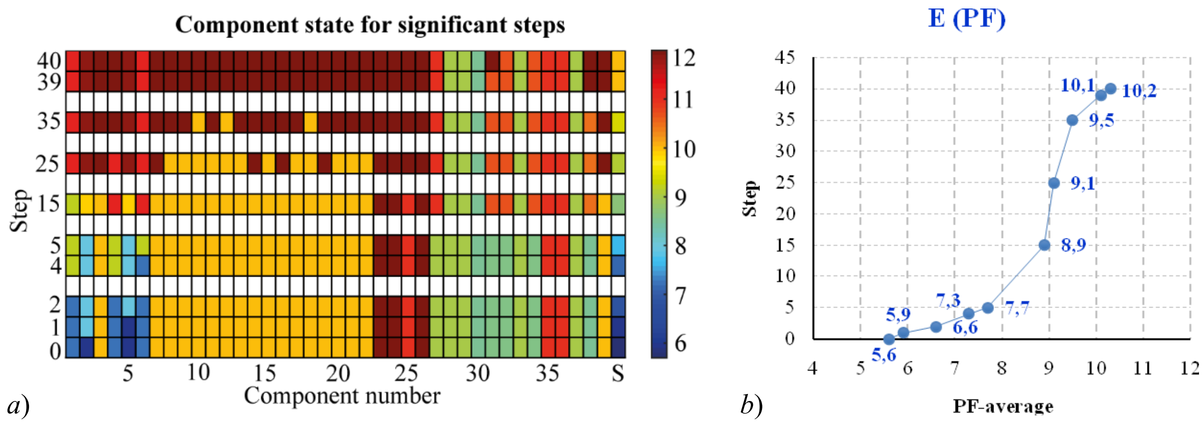

Figure 4. a) MMI failure intensity level; b) Cumulative PF average value, for each component at the most relevant retrofitting steps.

Figure 3a shows the MMI failure level for each component at each retrofitting step; it clearly emerges that the system fragility mainly depends on a few number of components characterized by high fragility levels. It is a priority to retrofit these elements in order to obtain an improvement of the system behavior, i.e. in order to obtain an acceptable Security Level. A retrofitting procedure consisting of 40 steps is herein adopted, leading to a significant improvement of the system safety. The cumulative PF average value (that is PF= 50%) for each component at each retrofitting step is reported in Fig. 3b. It is possible to note that at the end of these 40 steps the mean failure probability (PF = 50%) is reached in correspondence of the more acceptable value MMI $\approx$ 10.20. An important safety level for the Urban System is so achieved by the retrofitting of few components.

Figures 4a,b show the MMI failure intensity level and the cumulative PF average value (PF= 50%) for each component at the most relevant retrofitting steps. It is possible to note that the retrofitting of few particular components strongly affects the SUM security level.

5 CONCLUSIONS

The paper focuses on a new system reliability strategy to assess the seismic safety of a whole historical center. The proposed methodology can be summarized by the following main steps: i) identification of the SUM; ii) selection of the target safety level; iii) definition of the fragility curve for each component; iv) evaluation of the fragility behavior of the whole system; v) identification of an optimal retrofitting strategy.

The application of the method is described with reference to the town of “Montebello di Bertona”. The whole system is simplified by adopting the Urban Minimum Structure concept, which is derived from town planning sciences and adapted to structural engineering.

It is shown that a sensible prioritization and model optimization, even for a complex system like an historical center, is feasible; the results allow to give a clear indication of the priority order according to which system components should be retrofitted. So the main findings of the study underline how retrofitting process has to be well calibrated and fragility hypotheses have to be carefully selected, according to the actual situation that depends on both local seismicity and building maintenance.

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