Seismic prevention and mitigation in historical centres

Prevenzione e mitigazione del rischio sismico nei centri storici

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ABSTRACT: After recent seismic events, the topic of seismic prevention and mitigation in historical centres is become very important, in particular for a seismic prone areas, like Italy, Greece, Portugal, in which a lot of historical towns, for high quantity of old buildings and for their urban structure, suffered a lot of damages. In the past, for this reason, the Authors described and discussed a strategy for seismic prevention and mitigation of historical centres, analyzing them in terms of structural safety. This approach was 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 is the analysis of a complex system aiming to individuate 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 will be discussed, i.e. how different typologies of buildings, that coexist in historical towns, could influence the reconstruction strategy. In fact, when one thinks to an old building isn't only a masonry historical building, an old building could be a more recent r.c. building 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 a lot of damages and deaths, an efficient procedure to approach the impact of r.c. structures on seismic prevention and mitigation in historical centres has to be considered a fundamental goal to reach.

Dopo i recenti eventi sismici l'argomento della prevenzione e mitigazione del rischio sismico nei centri storici è diventato particolarmente rilevante, soprattutto in quelle aree sismicamente attive, Italia, Grecia, Portogallo, in cui un numero significativo di centri storici ha subito danni rilevanti sia negli edifici che nella sua struttura urbana. Nel passato gli Autori hanno descritto e discusso una strategia di intervento in cui il sistema centro storico è stato analizzato in termini di sicurezza strutturale. Questo approccio era basato su due fasi significative: la prima lo studio del cosiddetto Rischio Urbano, la seconda la programmazione a priori dell'attività post-sismica. La prima attività si sostanzia nell'analisi del sistema complesso con l'intento di individuarne le fragilità nodali. La seconda tende a valutare la coerenza delle attuali procedure per la verifica della sicurezza e delle condizioni di occupabilità degli edifici dopo l'evento sismico.

In questo lavoro si affronta un particolare aspetto del problema e cioè come differenti tipologie di edifici, che coesistono nei centri storici, possono influenzare le strategie per la ricostruzione. Infatti è chiaro come pensando agli edifici storici non si debba far riferimento ai soli edifici in muratura, ma si debbano considerare anche più recenti strutture, o porzioni di strutture, in cemento armato che sono state realizzate senza previsioni sismiche e, spesso, con materiali di qualità molto scarsa. Considerando l'elevato numero di datti e vittime che il crollo di edificio in cemento armato ha provocato all'interno di centri storici, la definizione di un'efficace procedura per la valutazione dell'impatto di tali strutture sul rischio sismico di tali centri è sicuramente un argomento di notevole portata.

KEYWORDS: AeDES Classification Method, Damage Survey, In-situ Survey, Reconstruction Plans, Urban Minimum System, Urban Risk Assessment / Metodo di Classificazione AeDES, Analisi del Danno, Analisi In-Situ, Piani di Ricostruzione, Sistema Urbano Minimo, Valutazione del Rischio Urbano

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 buildings, urban vulnerability depends not only on the structure characteristics but also on the functional systems that compose a city. Urban prevention, therefore, has a wider vision as compared to a single building and is designed to maintain the vita 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 settlement strategic role as compared to the surrounding area and with due consideration of the different elements that compose it. This approach, i.e. selection of some elements only, is justified by the fact that it is impossible to protect the entire settlement, for reasons of costs and time. It is therefore natural to make a choice: which structures, and to 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 minimum urban structure is linked to the strategic role, of the different elements, on the ordinary life of a city.

One needs to understand which are, at any given time, components of the Urban Minimum System (UMS), with the final goal of identifying the set capable of having a city work after an earthquake.

The Authors discussed in the past of this topic. In particular after a lot of papers dealing with vulnerability analysis of structures and infrastructures (Nuti et al. 2001, Nuti & Vanzi (2005), Vanzi et al. 2005, Nuti et al. 2007, Nuti et al. 2010), they focused their attention on Urban vulnerability analysis both in structural and in urban-planning point of view (Biondi et. al 2011, Biondi & Vanzi (2012), Sepe et al. 2016, Vanzi et al. 2016).

After the 2009 Abruzzo earthquake, they were involved, under supervision of an Italian Government Department, in the reconstruction phases. The Abruzzo municipalities characteristics, with low population density and low property values, but important historical and aesthetic values, were the focus of the public intervention policy. In this activity the idea of the Urban Minimum System (UMS) was improved in order to define a strategy for the reconstruction (Biondi & Vanzi (2011), Biondi et al. 2012).

The main initial choice was to co-ordinate reconstruction activities among different towns and necessities (economic, urban, artistic, historical, structural) in a geographical and functional coordination. The work consists mainly in preparation of reconstruction plans and in definition of the main guidelines, together with the preparation of pilot retrofitting projects on important structures (mainly public) having an exemplary character. With a special view on the current regulations, the attention is focused on the main structural design approaches, in synergy with all the other design specialties (i.e. architectural and urban planning), in order to implement design criteria that are both safe and respectful of history and aesthetics.

The principal goals of this past activity were to carry out a multi-disciplinary approach considering both structural and urban-planning point of view and to test the reliability of the post-seismic rehabilitation and seismic improvement procedure as defined in the Italian Code.

The first procedure, capable to define the most efficient structural improvement strategy within a urban centre, has been set up. The system (a portion of a municipality) is modelled via its cut sets and at each element is assigned a fragility curve specifically computed. An optimization procedure, aiming at maximizing the global system safety and minimizing retrofitting costs, is then set up. Results clearly indicate the best seismic retrofitting strategy.

The second aspect tends to evaluate the coherence of the damage survey obtained by means of a simple abacus (AeDES chart) with the local earthquake effects (in terms of maximum peak ground acceleration for example); to define a code of practice for the assessment of historical patrimony. For this aim regional attenuation relationships (Sabetta & Pugliese (1987), Zonno e Montaldo (2002)) have to be taken into account and to be compared with damage survey results.

These activities pointed out a different approach regarding the old existing buildings. When these buildings were built with masonry, the original architectonic characteristics have to be preserved. This goal is prevalent and taking into account this idea the structural material characterization is carried out in a parametric approach according to Seismic Code, Biondi & Vanzi (2012).

When these buildings were built with reinforced concrete, the original architectonic characteristics have a little relevance and the preservation goal has an attenuation. So in this case a complete and severe structural restoration has to be considered and a more detailed characterization of structural materials has to be carried out. The in-situ concrete strength assumes a fundamental role (Breysse et al. 2016) and these uncertainties have to be taken into account in the vulnerability approach.

2 A STRATEGIC APPROACH TO HISTORICAL CENTRES

An historical centre 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 one of the system components fails, the entire system fails. Conceptually, a series system is one that is as weak as its weakest link. A parallel system is a configuration such that, as long as not all of 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 conceptual approaches have to be redefined for the historical centres, above all if little towns in marginal territories are considered, like those of previous Abruzzo Region experiences. In this case historical centres show low inhabitant density, a great part of uninhabited or partially inhabited buildings, a poor maintenance of those buildings.

In this case is not possible to define if a building is a part of a series system or is a part of a parallel system: probably those buildings are out of any system from the functional point of view and it isn't so clear how manage their failure.

On the contrary these buildings have a great value from urban point of view. They may be particularly relevant in terms of architectural content, may be particularly interesting in terms of touristic use, may be particularly usefulness in terms of avoiding the soil use. Finally it could be extremely complex to individuate the owners of this existing estate patrimony, so it could be extremely complex to characterize these buildings in terms of fragility.

Generally these old, masonry, buildings are now uninhabited buildings without any maintenance effort. Their inhabitants live or in a greater town or in a neighbour place of the same town. They live in more recent, r.c.?, building that it isn't sure that guarantee higher structural security level.

For this complex of reasons a strategic approach to urban historical centers needs an additional level of analysis.

In a historical center it isn't mandatory to investigate the actual security level according to the actual functional distribution, in a historical center could be mandatory to investigate how to reactivate the original use of buildings, despite of the actual security level. Practically in a historical center the choice if restore or not a building (or if seismically improve or not) could be devoted to urban or architectonical considerations and not to economical or purely structural evaluations.

Often in the past structural difficulties caused uncorrected urban choices. For example, if a primary school was located in an old friar building, it was difficult to create a gymnasium in this complex. So the gym dome was built in the suburbs. Now it is mandatory to reunify those two functions, school and sport, and surely the prevalent issue is to rebuilt the gymnasium dome near the school and not the contrary.

Again a urban planning that provides to rearrange the residential building position could prefer to relocate those buildings in the historical center, could prefer to restore old existing buildings and to abandon more recent (r.c.?) buildings designed without any seismic provisions.

For these reasons when an engineering approach to urban safety has to be carried out for a historical (minor) center an accurate evaluation of the historical evolution of urban pattern can be avoided.

In this case the population size trend could be a fundamental parameter. As shown by the recent experiences in post L'Aquila Earthquake Reconstruction Planning, population size trend is linked to damage response for historical center.

In fact population size determines both building construction and building maintenance. 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 case of an earthquake this town will be more fragile than another town with constant population size trend.

A comparison between population trend and post-earthquake damage survey will be shown in following chapters.

3 URBAN RISK ASSESSMENT AND REDUCTION

A particular relevance assumes the analysis of urban seismic vulnerability; such kind of analysis has been developed in the past by the Authors. In particular a procedure for safety evaluation was improved for network systems like electric power, road, water, hospital regional systems or for hospitals, bridges or strategic buildings as a single structure, Nuti, C., Rasulo, A. and Vanzi, I. (2010).

In the specific case of Urban Risk Assessment and Reduction a new system is considered: the so-called Urban Minimum System (SUM) i.e. an urban system composed of buildings, open spaces and public ways [Biondi & Vanzi (2011), Biondi et al. (2011)]. If this system is composed with infrastructural networks and external risks (environmental and geological risks) it is possible to analyze a complex system. From a mathematical point of view, considering that aleatory quantities are involved, as structural strength, the approach has to be probabilistic; on the other hand if a Urban Plan has to be approved, practical and operational decisions have to be assumed.

Generally when a seismic safety evaluation is carried out a procedure to maximize safety of selected nodes and minimize economic expenses has to be constructed, allowing identification of which components, within each part of the system, have to be upgraded to obtain the maximum economic convenience. In the case of a Urban System the approach has to be revisited in order to take into account functional, and social, role of the different part of a city.

So, as above discussed, the evaluation of urban vulnerability doesn't only depend on the constructive characters of each structure but it is strictly connected with city identity. So, for example, in a historical towns isn't only important that inhabitants will be safe during an earthquake but it's important that they will remain in the historical center, that shops and public offices will be re-open, that schools will guarantee their lessons, that monumental buildings will not damaged and touristic activity will continue.

Or it could be preferable that at the end of Reconstruction Period many people abandon the suburbs in order to repopulate the historical center.

Again when a Urban Minimum System (UMS) is analyzed, it has to be clear that it generally plays a fundamental role not only in municipal range but also in territorial range. For example if some public or private services are located in every municipality (as town office, postal service, primary school, Pharmacia or food store), other services are territorial (as hospitals, police stations, fire departments, superior schools). This territorial approach was deeply discussed in previous papers. In this approach attention is paid on a smaller portion of territory: a historic centre of a little town or of a small village with its social life and its necessity of safety. In this centre often buildings have low maintenance, inhabitants are generally older and poor and, in some cases, the building owners are unknown and a large part of estate patrimony is abandoned. For these reasons fragility assumptions have to be more conservative than for similar building that have a regular and continuative maintenance; i.e. when a fragility curve is selected for these buildings, a more probable lack of capacity has to be assumed and population size trend has to be kept in mind.

The logical scheme for an Urban Minimum System is shown in Figure 1 (a). This scheme, for Montebello di Bertona (Vanzi et al. 2016), 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 if global safety has to be preserved, Figure 1 (b). So if a strategic building is considered, for example a primary school, it is safe if open spaces near the school are accessible, if electric power is at disposal, if water network is operative, if eventual ground sliding remains in a quiescent stage, if public ways preserve their accessibility to the entire community and, above all, by ambulances or civil protection and fire trucks.

On the other hand when an element class shows some redundancy, the component can be assumed as arranged in parallel. So if the same primary school can be reached by means of two different road ways, these two ways are in parallel and one of these can collapse if the other remains full efficient. In order to guarantee this equilibrium a probabilistic approach has to be carried out. Fragility curves of each component have to be selected, fragility behavior of the system has to be defined via Montecarlo and target safety level has to be selected. That it is with drastic decisions too: if a building can collapse on an important way, it would be better if the building could be demolished. Any macro sub-system has to be in series with the others while a punctual analysis permits to decide what element of the subsystem is in series and what in parallel, Figure 1 (c).

In previous papers the case of Montebello di Bertona was discussed basing on both sub-systems and components arrangement (in series or parallel).

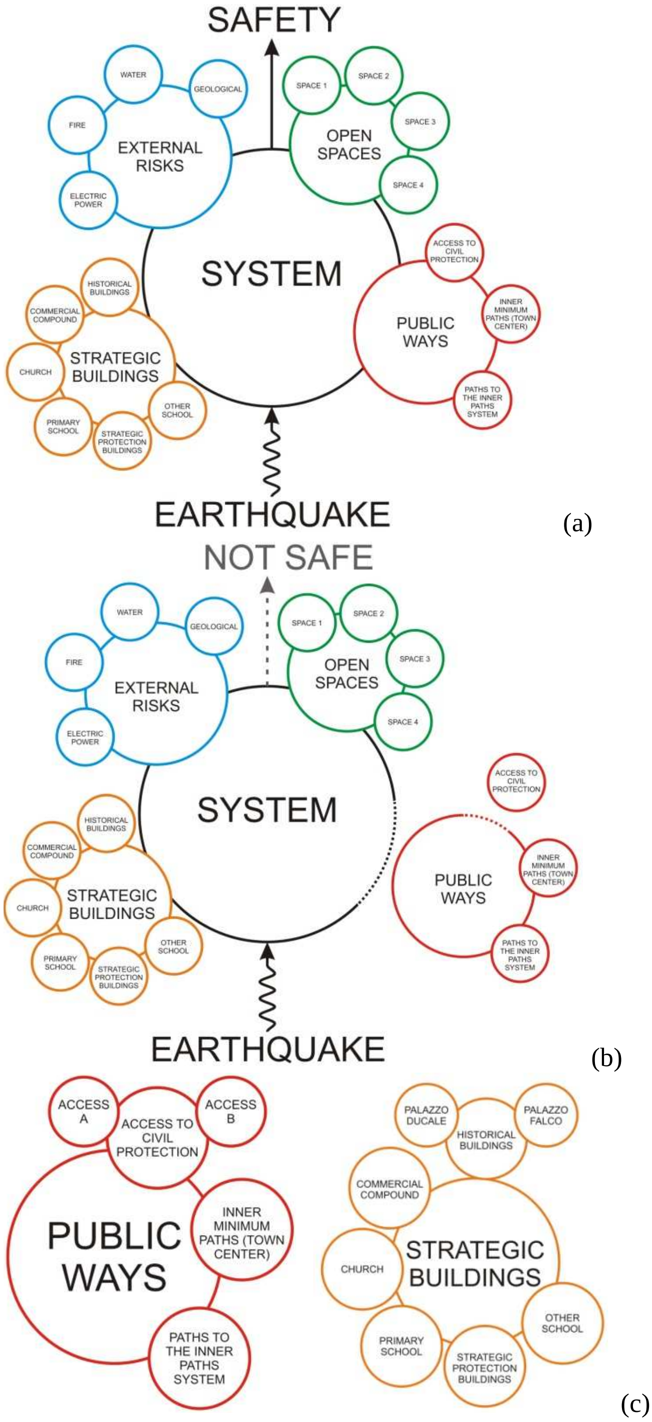

Figure 1. Logical schemes for Montebello di Bertona Urban Minimum System with different hypothesys for sub-systems / Differenti schemi logici del sistema urbano minimo di Montebello di Bertona

The fragility curves for the study Urban Minimum System are shown in Figure 2. Almost 40 elements are considered and red thick line is the actual fragility curve of the system. It is possible to note that actual failure probability is PF = 50% for MMI ≈ 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 with masonry building as a prevalent building typology, a MMI = 10 level can be assumed as acceptable Risk Level target.

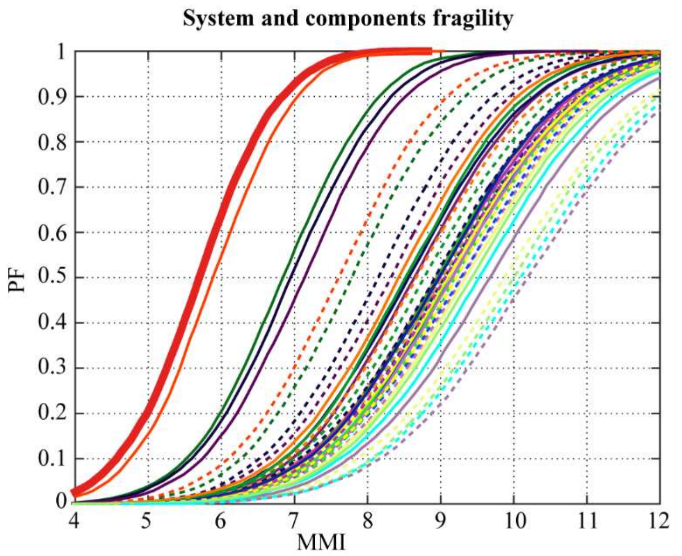

Figure 2. Fragility curves for Montebello di Bertona Urban Minimum System / Curve di fragilità della Struttura Urbana Minima di Montebello di Bertona

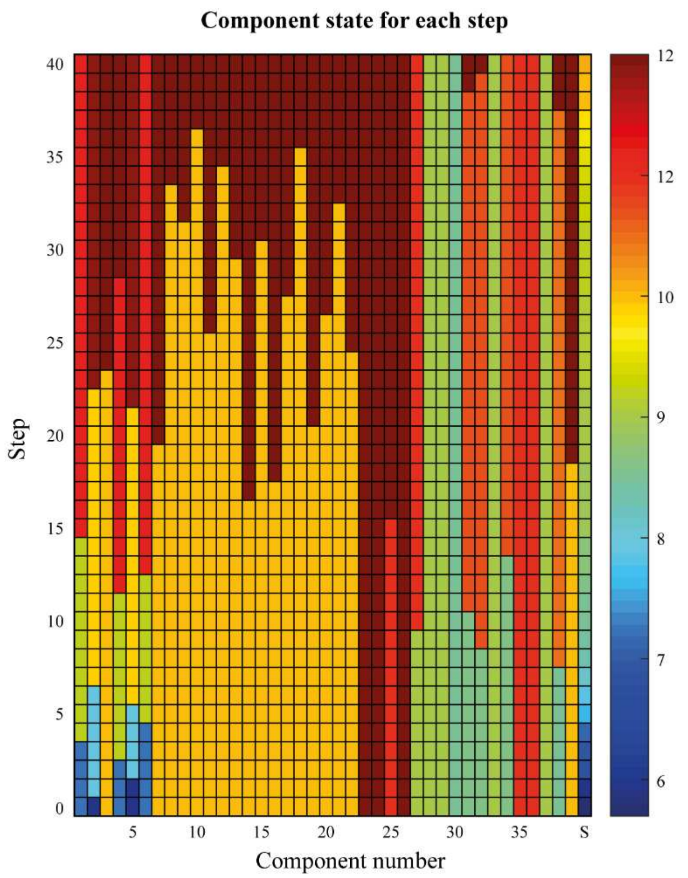

Figure 3. MMI failure intensity level for each component at every retrofitting step procedure / livello di intensità MMI di collasso per ogni componente a ciascun passo della procedura di retrofitting

It is possible to study the MMI failure level for each component at every retrofitting step procedure, Figure 3, and it is possible to note that system fragility depends mostly on a few number of components that show high fragility levels. It is a priority to retrofitt these elements in order to obtain an improvement of system behavior i.e. in order to obtain an acceptable Security Level.

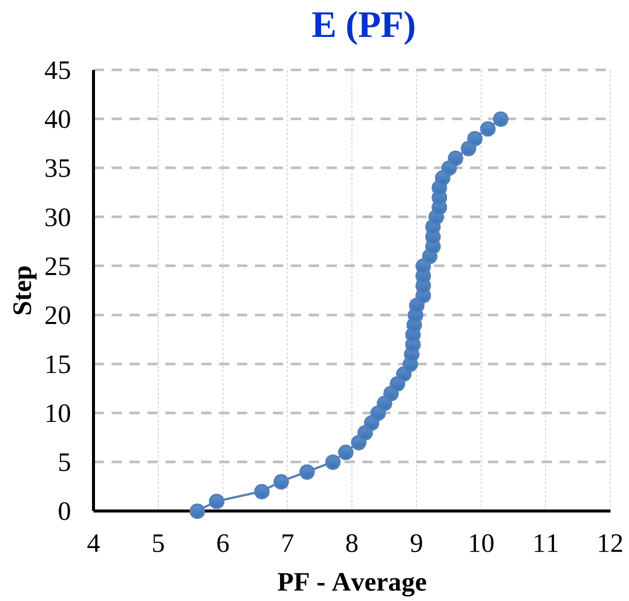

Figure 4. Cumulative PF average value for each component at every retrofitting step procedure / Valore medio della probabilità cumulativa di collasso a ciascun passo della procedura di retrofitting.

If a retrofitting procedure is carried out, it is possible obtain that, in about 40 steps of a single element independent improvements. In Figure 4 cumulative PF average value for each component at every retrofitting step procedure is shown.

It is possible to note that at the end of those 40 steps the average failure probability (PF = 50%) reaches a more acceptable value: MMI ≈ 10,20.

An important safety gain for the Urban System due to the retrofitting of some particular elements.

In Figure 5 the MMI failure intensity level for each component for the most relevant retrofitting steps is shown while in Figure 6 the cumulative PF average value for each component for the most relevant retrofitting steps is depicted. It is possible to note that the retrofitting of some particular elements (i.e. some particular retrofitting steps) have a greater influence on system security level.

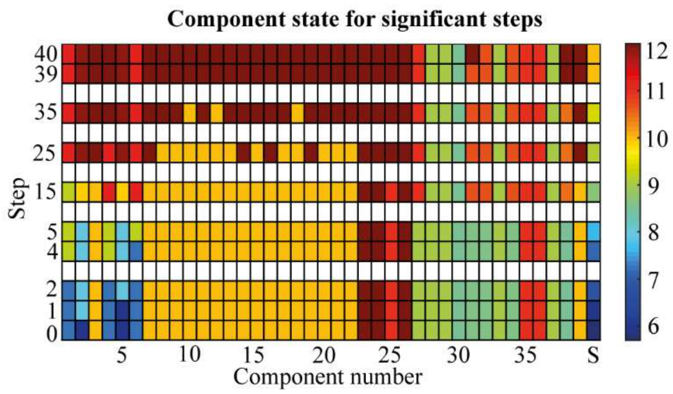

Figure 5. MMI failure intensity level for each component for the most relevant retrofitting steps / livello di intesità MMI di collasso per ogni componente ai principali passi della procedura di retrofitting

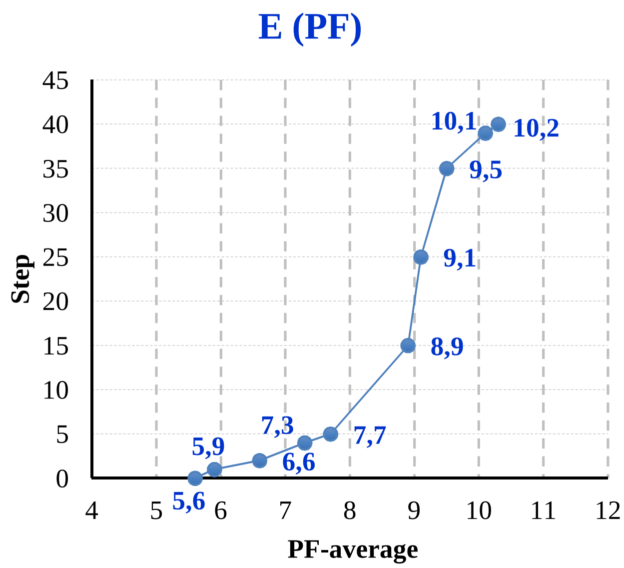

Figure 6. Cumulative PF average value for each component for the most relevant retrofitting steps / Probabilità cumulativa media di collasso per componente nei principali passi

3.1 *Post-Earthquake Safety Survey: the case of 2009 L'Aquila Earthquake*

As discussed in previous papers the Post-Earthquake Building Safety Survey and Occupancy Evaluation after the 2009 L'Aquila Earthquake represented a good occasion to test the coherency of proposed Urban Minimum System (UMS) procedure.

In fact after the Main-Shock, a lot of professional teams, composed by structural engineers and architects, are created in order to evaluate structural damages and to report occupancy situation in each town. This judgment was obtained by means of a simple abacus (AeDES chart) that considers few parameters in order to evaluate structural damage. After a review of general data (location, construction type, age, height and plan area, occupancy type) a risk evaluation is carried out in terms of structural, non structural, external and geotechnical risks, Figure 7. In terms of structural configuration both masonry buildings and framed (r.c. or steel) buildings are considered in the AeDES chart. Structural (on vertical and horizontal elements) and non-structural damages have to be combined in order to obtain the occupancy judgment finally.

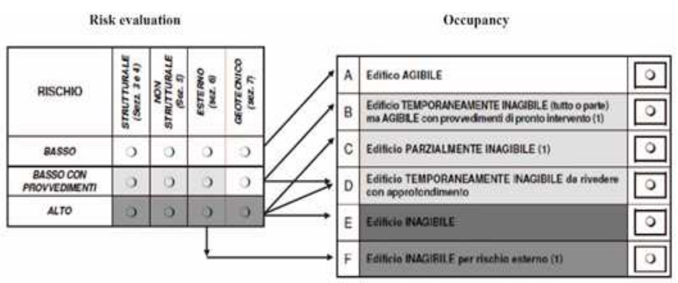

Figure 7. Risk evaluation (left) and occupancy judgment (right) in the AeDES chart / Valutazione del rischio (sinistra) e esito di agibilità (destra) nella scheda AeDES

Figure 8. Damage survey plans for Civitella Casanova, Montebello di Bertona e Ofena / Mappe del danno per Montebello di Bertona, Bussi sul Tirino ed Ofena

Six categories of occupancy judgment can be selected: -A- immediate occupancy without temporary measures, -B- immediate occupancy with temporary measures, -C- partial unoccupancy due to damage, -D- partial unoccupancy due to insufficient structural information, -E- full unoccupancy for building strong damage or collapse, -F- full unoccupancy for external risk.

Basing on this data base, damage survey plans have been drawn for different little historical centers, Figure 8, (red buildings are those whit E occupancy judgments).

In Figure 9 cumulative frequencies of these different occupancy judgments (A-B-C-D-E-F) are shown. These frequencies are collected considering, for every town, the ratio between the number of building having an occupancy judgment to the total of buildings (up) or the same ratio if the gross area of each building is considered (down).

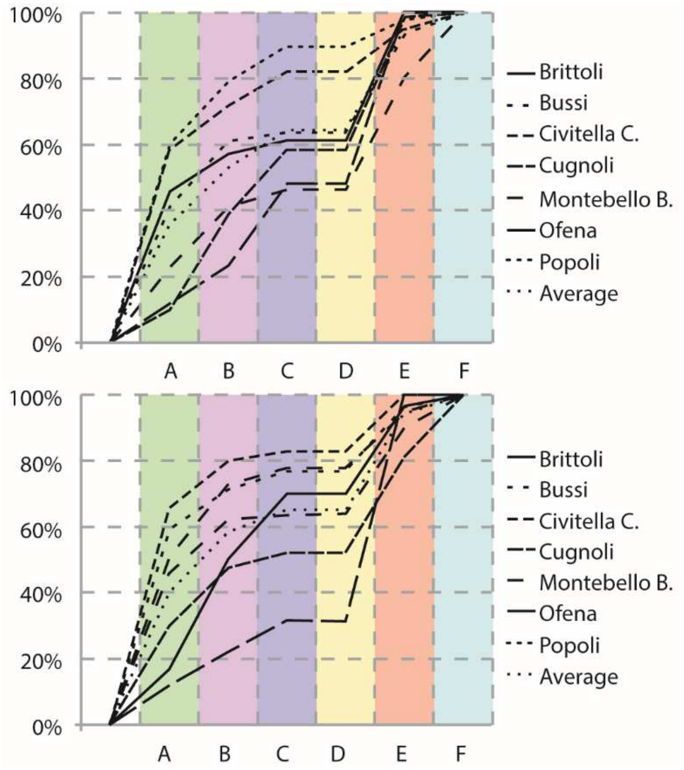

Figure 9. Cumulative frequencies of building number (up) or building gross area (down) for different occupancy judgments (A-B-C-D-E-F) / Frequenza cumulativa del danno (A-B-C-D-E-F) per numero di edifici (sopra) o per area totale (sotto)

As previously discussed [Biondi et al. (2012), Biondi & Vanzi (2012)], in order to evaluate the AeDES Chart availability the ratio $S_{aBV/SLD}$ (1) between the maximum local peak ground acceleration estimated via the original Biondi-Vanzi attenuation relationship, $\alpha|_{BV} = a_g/g\ |_{BV}$, and the design peak ground acceleration at SLD limit state as determined for each site, $\alpha|_{dSLD} = a_g/g|_{dSLD}$, is considered.

$$S_{aBV\,/\,SLD} = \frac{a_g\,/\,g\big|_{BV}}{a_g\,/\,g\big|_{d(SLD)}} \tag{1}$$

It was possible to note a good fitting, in terms of increasing E frequency, between AeDES Chart responses and spectral ratio defined in (1). In fact Ofena showed the highest ratio $S_{aBV/SLD}$ and it suffered an high level of damage (the second place in terms of E judgment).

So the AeDES Chart approach can be assumed as both a good operative procedure in post-earthquake activity and a good basis for Urban Minimum System (UMS) procedure in order to calibrate actual fragility. On the other hand, historical center that suffered highest level of damage (the first place in terms of E judgment) was Brittoli [Biondi et al. (2012)], despite a medium spectral ratio $S_{aBV/SLD}$. Brittoli spectral ratio in fact was similar to Civitella Casanova ratio while Brittoli population size trend showed a greater population loss than Civitella Casanova, Figure 10. For these reasons the highest level of damage in Brittoli could be expected: a Urban Minimum System (UMS) procedure approach has to take into account population size trend (or another building maintenance parameter) in order to define building fragility.

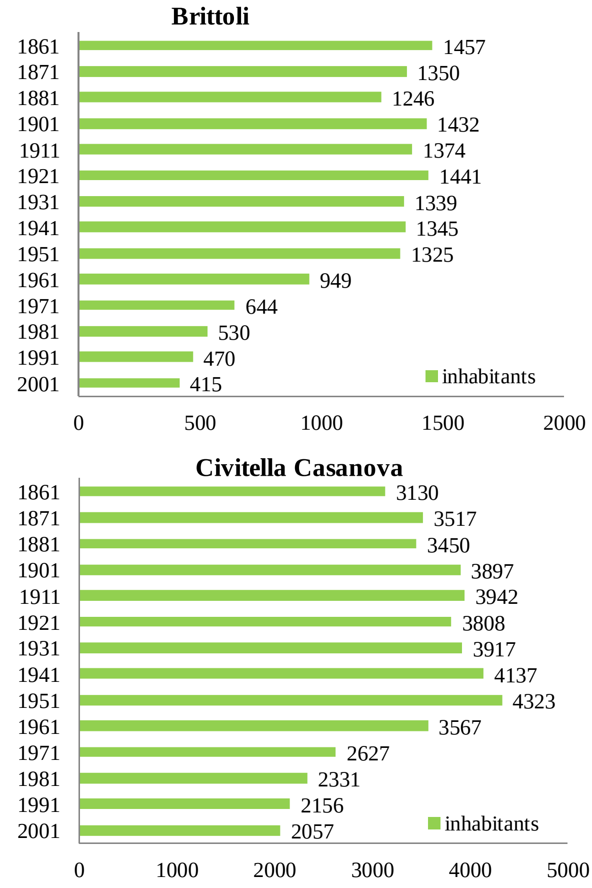

Figure 10. Population size trend according to official census / Andamento demografico sulla scorta dei censimenti ufficiali

4 IMPACT OF R.C. STRUCTURES

In order to define hypotheses for fragility curves of structures selected in an Urban Minimum System (UMS) procedure, both structural behavior of buildings and retrofitting activities according to Seismic Code have to be kept in mind.

In Biondi & Vanzi (2012) a so-called Code Flow-Chart was presented and discussed for old masonry building according to 2008 Italian Code Chapter 8.

This Flow-Chart focused its attention on stiffness (elastic modulus) and strength (compressive) values derived from Code provisions, structural Model, Sectional analysis and material Tests, respectively $_C$, $_M$, $_S$ and $_T$ in (2) and (3).

$$E_d(X_C, X_T, \sigma) = E_m(X_T) \cdot g_0(\sigma) \cdot g_2(X_C) \tag{2}$$

$$f_d(X_M, X_C, X_T, X_S) = \frac{f_m(X_T) \cdot g_3(X_C)}{FC(X_T, X_S) \cdot g_1(X_M)} \tag{3}$$

For masonry design values, $_d$, can be defined basing on average test values, $_m$, and using different Code parameters, $_1$, $_2$, $_3$. For r.c. structures the procedure is quite different and a little bit complicated.

First of all (2) and (3) relationships have to be defined for two different components: concrete and steel. But steel characteristics are stable and depending only on steel class (FeB24k, FeB38k ... and so on according Italian Code). So this dependence isn't very relevant.

A second aspect is more significant: for an r.c. structure both regularity in structural arrangement and non structural element behavior can influence global response and define structural fragility. On this regard experiences of recent earthquakes show how r.c. structures designed without or with older seismic provisions behave worse than old masonry buildings.

For these reasons, more conservative hypotheses have to be taken into account if an Urban Minimum System (UMS) procedure is carried out considering the r.c. structures impact too.

5 CONCLUSIONS

The paper shows a system reliability model to assess the seismic safety of a whole historical centre. Applications are given for typical Italian cases, making reference to Abruzzo, which has been recently hit by the major L'Aquila earthquake. The whole system is simplified using the Urban Minimum Structure concept, which is excerpted 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 system component to retrofit first. So retrofitting process has to be well calibrated and fragility hypotheses have to be selected according to actual situation that depends on both local seismicity and building maintenance. The first could be evaluated basing a post-earthquake survey, the second keeping in mind population size trend in the past.

Il lavoro illustra un modello, nell'ambito dell'affidabilità strutturale, di un intero centro storico italiano. Viene fatto esplicito riferimento al caso dell'Abruzzo, recentemente colpito dall'evento di L'Aquila. Il sistema è semplificato utilizzando il concetto, mutuato dalle discipline urbanistiche ed adattato all'ingegneria strutturale, di Struttura Urbana Minima.

L'applicazione mostra la fattibilità di studi di ottimizzazione, anche per sistemi complessi come un intero centro storico. I risultati permettono l'individuazione dei componenti del sistema su cui intervenire con precedenza rispetto agli altri.

Sia il processo di adeguamento che la definizione delle curve di fragilità debbono essere condotte in modo accorto e tenendo conto del reale stato di fatto del sistema urbano che si considera. A tale proposito si deve far riferimento alla sismicità locale ed alla manutenzione degli edifici. Nel primo caso posso considerarsi i risultati di esiti di agibilità sismica, se disponibili, mentre nel secondo caso può essere un parametro significativo l'evoluzione della popolazione urbana nel tempo.

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