Vulnerability Methods and Damage Scenario for Seismic Risk Analysis as Support to Retrofit Strategies: an European Perspective

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ABSTRACT: The inherent seismic vulnerability of existing R.C. buildings, designed prior to the introduction of adequate seismic code provisions in the early/mid-1970s, has been dramatically confirmed by the catastrophic socio-economical consequences of earthquake events that have occurred worldwide in the past decade. The urgent need for the development of feasible and efficient structural mitigation strategies, and the implementation of “standardized” retrofit solutions for intervention at urban or territorial scale, has received increasing recognition and attention. Damage scenario and seismic risk analysis, along with the use of a GIS-environment to represent the results, are considered as a helpful tool to support the decision making for planning and prioritizing seismic retrofit intervention programs at large scale. In this paper, after an overview of current vulnerability methods for seismic risk or damage scenario analysis at a territorial scale, tentative suggestions for possible refinements will be provided with particular focus on the vulnerability models for pre-1970 reinforced concrete buildings. Improvements should include the possibility to account for the peculiar alternative damage limit states and collapse mechanisms observed in real earthquakes and further confirmed by recent numerical and experimental investigations. Comparative evaluation of the reduced level of expected damage after alternative retrofit solutions will be carried out and described in terms of fragility curves. A damage scenario analysis, referred to a case study area in Italy, will be provided as further exemplification of the effects of implementing a multi-level retrofit strategy approach at territorial scale.

1. INTRODUCTION

Following recent catastrophic earthquakes, a revitalized interest on seismic assessment methodologies and modelling techniques, as well as on the development of advanced but viable retrofit solutions for under-designed structures, has been observed in the last decade. Several alternative seismic retrofit/rehabilitation solutions have been studied in the past, few of which have been successfully implemented in practical applications on single buildings. Recent developments and numerical/experimental validation of viable and low-cost retrofit solutions for pre-1970 buildings within a multi-level retrofit strategy approach, suggest the possible implementation of “standardized” solutions at an urban or territorial scale. Damage scenarios and seismic risk analysis, devoted to the evaluation of the expected losses for a specific earthquake event or the possible losses in a time period, and the representations of their results in a GIS environment could be considered as helpful tools to support decision making, e.g. planning and prioritizing of retrofit or seismic intervention programs at large scale as well as implementing alternative non structural mitigation strategies and risk transferring through the insurance/reinsurance industry.

In this contribution, an overview of existing and recently proposed procedures for seismic vulnerability assessment at territorial scale will be first given. Suggestions for possible refinements to better represent the seismic performance of pre-1970 reinforced concrete buildings prior and post retrofit will be provided. Comparative evaluation of the efficiency of alternative retrofit solutions in reducing the expected damage will be described in terms of fragility curves. Exemplification of the effects at territorial scale will be provided through a damage scenario analysis on a case study area.

2. ALTERNATIVE VULNERABILITY METHODS FOR EXISTING R.C. BUILDINGS

Comprehensive frameworks for damage scenarios and seismic risk analysis, including GIS-based evaluation tools for end-users, have been developed and proposed as part of major international programmes, e.g. HAZUS (1999); RADIUS (1999), Risk-UE (2004), in addition to private implementations carried out by insurance/reinsurance/risk management companies. Regardless of the common framework, based on the traditionally accepted definition of seismic risk (i.e. convolution of hazard, exposure, vulnerability analyses and cost evaluation), alternative methods have been adopted for the seismic vulnerability assessment of buildings at territorial scale based on: a) actual damage observation b) expert judgment, c) simplified-mechanical and analytical models.

Observed vulnerability methods are based on statistics of past earthquake damage, which can be summarized and represented via DPM *Damage Probability Matrices* (Withman 1973), vulnerability (Figure 1a) or fragility curves (Rossetto and Elnashai, 2003). Due to the inherent difficulty to retrieve reliable and exhaustive observed damage data, referred to all defined building typologies, earthquake intensities and soil conditions, “hybrid” methodologies can be implemented, relying on the combination of the available empirical/statistical data with the results of either numerical analyses (Kappos et al. 1995), neural network systems and Fuzzy Set Theory (Sanchez-Silva and Garcia 2001) or, more directly, expert judgement. Expert-based vulnerability methods apply human judgment to completely replace the processing of observed data, leading to experts-defined DPM (i.e. ATC13, 1987) or score assignment procedures (e.g. ATC21 1988, FEMA154).

Mechanical vulnerability models for territorial scale analysis on classes of buildings can be defined on the basis of either traditional force-based procedures (e.g. capacity spectrum method implemented in HAZUS, 1999 or RISK_UE, 2004) or, according to more recent proposals, displacement–based designed approaches (Calvi et al. 2005). According to force-based procedures, the building performance is identified, within a ADRS (acceleration-displacement response spectra) domain, by the intersection point between the capacity curve of an equivalent non linear SDOF system and the earthquake demand curve, adequately reduced to account for the inelastic behaviour and energy dissipation capacity of the system (Fig. 1b). On the other hand, according to displacement–based approaches, the periods associated to the boundary of different limits states can be evaluated by the intersection between capacity curves, represented in terms of period displacement relationship, and the displacement spectrum demand curves, scaled by equivalent viscous damping factors (Fig. 1c). Other proposals for mechanical-based methods are based on the evaluation of collapse multipliers associated to alternative collapse mechanisms (i.e. Bernardini et al. 1990, Cosenza et al. 2005) or on the derivation of vulnerability or fragility curves from the results of extensive numerical analyses (Elnashai and Jeong 2005).

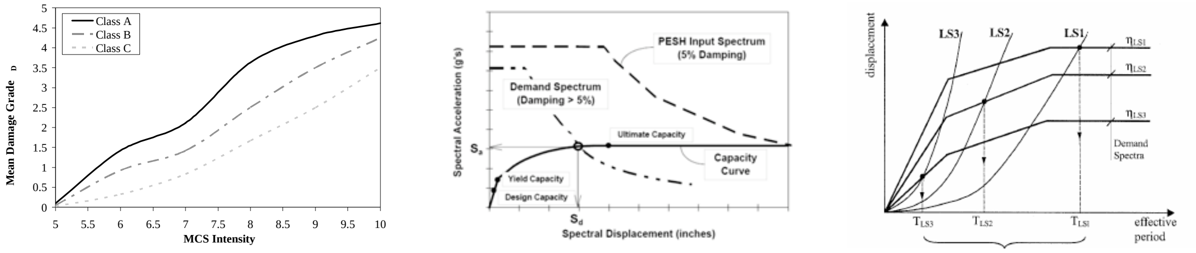

Figure 1.Alternative vulnerability methods: a) Observed-based vulnerability curves (Braga 1983); b) Force-based capacity spectrum method after HAZUS (1999); c) Displacement-based procedure after Pinho et al. 2002

3. RISK_UE VULNERABILITY METHODS

The RISK-UE project (2004), *An advanced approach to earthquake risk scenarios with application to different Europeans towns,* funded by the European commission, involved nine research units and seven European cities with the main objectives of a) developing a general methodology for the seismic risk assessment of European cities, b) increasing the awareness within the decision-makers and c) supporting the implementation of management and action plans. A modular methodology for creating earthquake scenarios was developed based on the available data and knowledge on earthquake hazard, soil conditions and built environment. Hazard scenarios were derived in terms of macroseismic intensity, PGA or spectral ordinates. Two different vulnerability approaches, based on observed-data or mechanical models, were proposed for damage scenario analyses.

3.1 The macroseismic approach

The observed vulnerability approach, employed in the framework of the Risk-UE project and referred to as “macroseismic method” (Giovinazzi and Lagomarsino 2004, Giovinazzi 2005) has been derived from the definitions provided by the EMS-98 macroseismic scale (Grunthal 1998). Based on classical probability theory and on fuzzy-set theory, numerical and complete DPM have been evaluated, in terms of EMS-98 intensities, I_{EMS-98}, and damages grades (D_k k=1-5) for the set of EMS-98 vulnerability classes and building typologies. Fuzzy set theory, herein introduced to associate a numerical value to linguistic definitions of the damage distributions, has also represented an effective tool to cope with the epistemic uncertainties affecting the vulnerability assessment procedures. Upper and lower bounds of the expected damage, as provided by the DPM_{EMS-98}, have been represented in the form of vulnerability curves within a I_{EMS-98}- $_D$ diagram (Fig. 2a), $_D$ being the mean damage grade defined as the mean value of the DPM_{EMS-98}damage distributions. The relationship between the mean damage grade, $_D$, and the Intensity, $I_{EMS-98,}$ has been expressed as:

$$_D = 2.5 \left[1 + \tanh\left(\frac{I + 6.25V - 13.1}{Q}\right)\right] \qquad (1)$$

where Q is a ductility-based index, V= $V^* + \Delta V_m + \Delta V_r + \Delta V_s$ is a vulnerability damage index and function of the building typology, V^*, the behavior modification factor, ΔV_m, the regional vulnerability factor, ΔV_r, and the soil amplification factor, ΔV_s. The latter has been evaluated for each building typology, class of height and soil class according to EC8 prescriptions (2003), while the values of the other factors have been calibrated on the basis of observed damage data and expert judgment. A beta probability density function (Fig. 2b) has been assumed to represent the damage distribution around the mean damage grade $_D$. Fragility curves (Fig. 2c), defining the probability of reaching or exceeding each damage grade $P[D_k|I,(V,Q)]$ can be directly derived. Different scatter can be associated to the beta damage distributions depending on the level of the cognitive uncertainties measured according to fuzzy theory (Giovinazzi and Lagomarsino 2005).

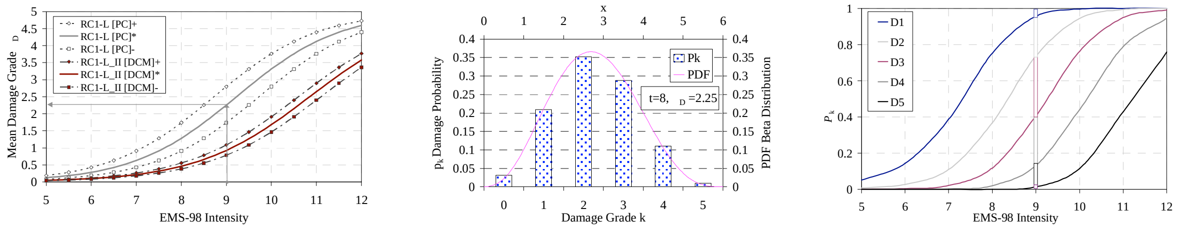

Figure 2. Steps for the macroseismic method: a) medium, upper and lower vulnerability curves for medium–rise pre-code R.C. moment frames ([PC] V=0.62, Q=2.3) or EC8 medium ductility class ([DCM] V=0.36, Q=2.5); b, c) damage probabilities p_k and fragility curves for the pre-code typology for I_{EMS-98}=9 ($_D$=2.25).

3.2 The mechanical approach

The mechanical method proposed in the framework of Risk-UE project is essentially a capacity spectrum-based method, similar to that adopted by Hazus (1999) with few modifications including: 1) the definition of capacity curves for non-designed European masonry typologies, accounting for the prevailing collapse modes, geometrical features, mechanical and dynamic characteristics (Cattari et al. 2004); 2) the definition of capacity curves for seismically designed buildings according to the Eurocode 8 and to older European design codes; 3) the representation of the cognitive uncertainties.

In order to facilitate the operative implementation, the mechanical method was defined with a closed-form solution. Simplified bilinear elastic-perfectly plastic capacity curves were defined, given the yielding acceleration a_y, the fundamental period T and the structural ductility capacity . Constant-ductility inelastic response spectra were derived from a 5% damped elastic response spectrum $S_{ae}(T)$ by means of a ductility-based reduction factor, R . The displacement corresponding to the performance point S_d^* can thus be directly evaluated, without any further iteration (Fig. 3b), as:

$$S_{d*} = \left[1 + \left(\frac{S_{ae}(T)}{a_y} - 1\right)\frac{T_C}{T}\right] d_y \quad \textit{if } T < T_C \textit{ and } \frac{S_{ae}(T)}{a_y} > 1 \qquad S_{d*} = \frac{S_{ae}(T)}{a_y} d_y \quad \textit{if } T_C \le T < T_C \textit{ and } \frac{S_{ae}(T)}{a_y} \le 1 \qquad S_{d*} = \frac{S_{ae}(T_D) T_D^2}{4\pi^2} \quad \textit{if } T \ge T_D$$

where T_C and T_D define the onset of constant spectrum velocity and displacement range within the elastic response spectrum $S_{ae}(T)$ evaluated from deterministic or probabilistic hazard analyses(Fig. 3a).

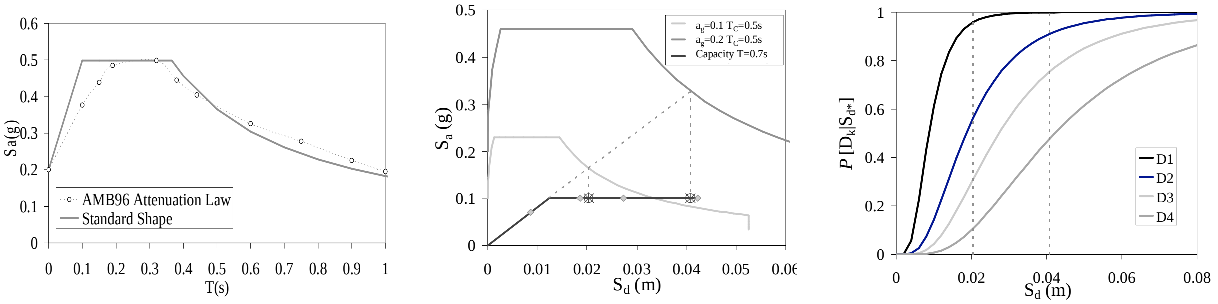

Figure 3. Steps of the mechanical approach a) elastic response spectrum based on spectral ordinates from attenuation laws; b) evaluation of the performance point through capacity spectrum method c) fragility curves

A four damage limit state scale (D_{Sk} k=1÷4) related to performance levels S_{dk} has been adopted for the damage description; the probability of exceeding each damage state threshold S_{dk} is evaluated from the performance displacement S_{d*} by using of a lognormal cumulative function (Fig. 3c).

3.3 Cross validation of the mechanical and macroseimic approaches

Although the proposed macroseismic and mechanical approaches are, in principle, different for derivation and conception, their closed-form formulations allow for a quantitative comparison and reciprocal calibration (Fig. 4). As a useful result, refinements in the definition of the mechanical model definition based on numerical/experimental analysis results can be directly implemented ("translated") into an equivalent macroseismic approach. Concurrently, the reliability of assumed force- or displacement-based capacity curves can be cross-validated on the basis of real observed damage data. The calibration was performed assuming equivalent level of damage resulting from the two approaches and similitude in the damage scales (D_{Sk} k=1-4 and D_k k=1-5, respectively, as shown in Table 1). The correlation between intensity $I_{EMS\text{-}98}$ and the peak ground acceleration a_g was set in the form of $a_g = c_1 c_2 a_g^{(I-5)}$. The relationships between the capacity curves parameters (a_y and , after assuming T) and the macroseismic method indexes V and Q are given by Equation 2:

$$\begin{cases} a_y = 1.43 s c_1 c_2^{(8.1-6.25V-0.95Q)} \\ \quad = 1 - \frac{T_C}{T} + 0.7 \frac{T_C}{T} c_2^{1.35Q} \end{cases} \textit{if} \quad T < T_C \qquad \begin{cases} a_y = 1.43 s c_1 c_2^{(8.1-6.25V-0.95Q)} \frac{T_C}{T} \\ \quad = 0.7 c_2^{1.35Q} \end{cases} \textit{if} \quad T \ge T_C \qquad (2)$$

where c_1 and c_2 are the I-a_g correlation parameters and s is a soil factor (e.g. as per EC8-spectra).

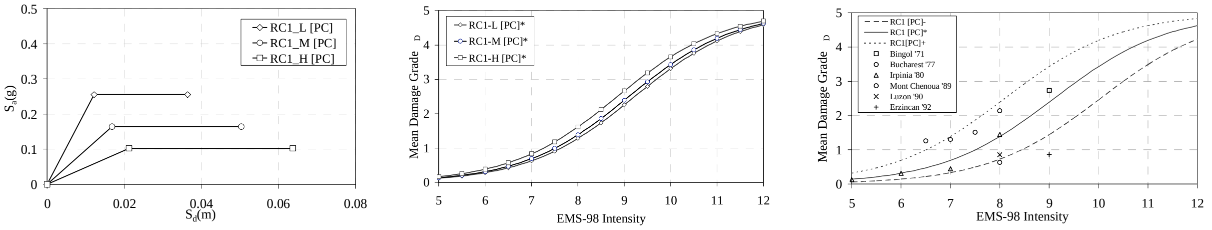

Figure 4. Cross-validation of macro-seismic and mechanical models for pre-code R.C. frame buildings a) capacity curves b) vulnerability curves c) vulnerability curves and observed damage data comparison.

4. IMPACT ASSESSMENT OF ALTERNATIVE RETROFIT STRATEGIES ON PRE-1970'S REINFORCED CONCRETE BULDINGS

4.1 Suggested improvements of existing vulnerability methods

An increased number of experimental and numerical investigations on the seismic performance of pre-1970s RC buildings have provided valuable quantitative evaluation of their inherent vulnerability (Hakuto et al., 2000, Park, 2002; Pampanin et al., 2002), as well as favoured the calibration and further development of simplified analytical methods and assessment procedures (i.e. Pampanin et al. 2003). Due to the poor reinforcing details (including lack of transverse reinforcement in the joint region), the absence of capacity design principle and the use of plain round reinforcing bars, undesirable brittle failure mechanisms can occur. In particular, shear damage and failures in the beam-column joint panel zone can lead to peculiar effects on the overall response (Calvi et al. 2002), leading to more complex inelastic mechanisms, given by the combination of flexural plastic hinge and joint shear hinge in addition to traditional beam-sway and column-sway mechanisms (Fig. 5). Moreover, the presence of infills (e.g. typically un-reinforced masonry) can lead to undesirable, yet controversial, effects due to the interaction with the bare frame (Crisafulli et al., 1997, Magenes and Pampanin, 2004). On one hand, the presence of infills can in fact guarantee higher stiffness and strength, reducing the inter-storey drift demand, thus delaying the formation of a soft-storey mechanism, when compared to the response of a bare frame. On the other hand, the interaction between un-reinforced masonry infills and the bare frame can result in local failures (e.g. short column effects, damage to the joint region) as well as into unexpected soft-storey mechanisms, even in the presence of uniformly distributed infills and not necessarily at the first storey. Deformation- or drift -based limit states associated with the joint and infill panel damage, has been proposed by Pampanin et al. (2003) and Magenes and Pampanin (2004).

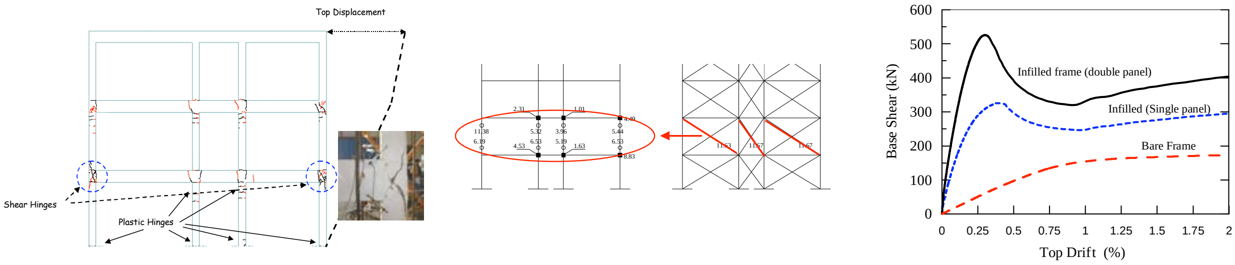

Figure 5. a) Global mechanism of pre-1970 frame: flexural plastic hinges and shear hinges of test- frame (Calvi et al. 2002a). b,c) Numerical response of six-storey frame with masonry infills: b) soft storey at the second floor; c) comparison of pushover curves for different configurations of infills (Magenes and Pampanin, 2004)

Fundamental refinements of the currently adopted seismic assessment procedure, either directed to a single building or to a class of buildings within a territorial scale vulnerability analysis, could be obtained by properly accounting for these damage and collapse mechanisms in the definition of both capacity and demand curves. In addition to a redefinition of a comprehensive set of limit states and related inelastic mechanisms, specific improvements of mechanical vulnerability methods for pre-1970 buildings could include the derivation of more realistic capacity curves to account for the actual strength and stiffness degradation due to joint or infill related damage mechanisms. P-Δ effects should also be considered. Within displacement based vulnerability methods, refinements of the deformed shape associated with alternative global mechanisms are expected.

4.2 Implementation of alternative retrofit solutions and strategies

Several alternative seismic retrofit and strengthening solutions have been studied in the past and adopted in practical applications, ranging from conventional techniques, which utilize braces, jacketing or infills, to more recent approaches, including supplemental damping devices or advanced materials (e.g. Fiber Reinforced Polymers, FRP, or Shape Memory Alloys (SMA). In general, considerations on cost-effectiveness, invasiveness, architectural aesthetics, along with issues related to the socio-economical consequences of excessive damage and related downtime due to a limited or interrupted functionality of the structures after the seismic event, come into the full picture of such a complex decision-making process. A low-invasive and cost-effective retrofit solution for frame systems, which relies on diagonal steel haunches installed locally at the beam-column joints to protect the panel zone and to enforce a more desirable hierarchy of strength, has been recently presented, after numerical and experimental validations, by Pampanin and Christopoulos (2003), as a valuable solution for wide application at large territorial scale with particular interest for under-developed countries.

Alternative advanced retrofit strategies have been recently proposed in literature, providing a clear and correct distinction between the concepts of "retrofit" and "strengthening", too often, and sometimes improperly, associated. Selective upgrading techniques, proposed by Elnashai and Pinho (1998), aim for example to independently upgrade only stiffness, strength or ductility of a single member. More recently, following the developments of high-seismic-performance systems based on a controlled rocking mechanism, a selective weakening approach has been proposed by Pampanin (2005) as a counter intuitive but efficient retrofit intervention for either frames, walls or floor systems. Preliminary applications of a partial or total selective weakening intervention of a wall system are presented in a companion paper (Ireland et al. 2006): the intervention aims to develop a more appropriate flexure-type rocking/dissipating mechanism by a) vertically splitting an existing shear-dominated wall, b) disconnecting the longitudinal reinforcement at the base and c) re-enhancing strength and energy dissipation capacity by adding vertical post-tensioned tendons and external energy dissipation devices (e.g. viscous, friction, Shape Memory Alloys)

As anticipated, damage scenario analysis can be a fundamental tool to assess the impact of alternative retrofit solutions at territorial scale. As an intermediate step of the full procedure, the effects and efficiency of alternative retrofit strategies can be appreciated by comparing fragility curves corresponding to pre-defined levels of damage (D_k). Figure 6 shows, as an example, the effects of three alternative interventions, namely, two selective upgrading (strength only and ductility only) and one selective weakening solution, on a low-rise (three storey) pre-1970 frame building used as a reference for the damage scenario analyses carried out as part of the Risk-EU project.

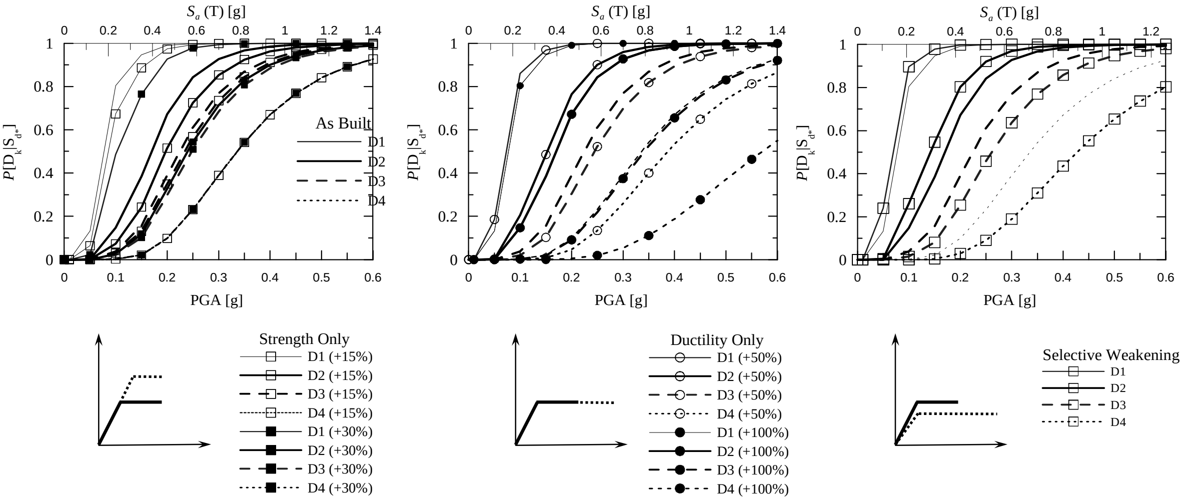

Figure 6. Efficiency of alternative retrofit solutions (strength-only, ductility-only, selective weakening) in terms of fragility curves

It can be noted that each retrofit solution shows a different degree of efficiency at different damage levels, D_k. The selective weakening solution, herein consisting of reducing the strength by 15% and increasing the ultimate displacement by 1.5 times, would be ineffective at low levels of damage (D_1 and D_2), while showing a remarkable efficacy at higher levels (D3 and D4). By introducing (through convolution with the vulnerability curves) the information related to seismic hazard and exposure, as typical of a damage scenario analysis, the actual impact of the implementation of each solution for classes of buildings at a territorial scale, can be properly evaluated.

4.3 Application of multi-level retrofit strategy at territorial scale

According to the concept of multi-level performance-based retrofit strategy, recently proposed in literature (Pampanin and Christopoulos, 2003) and implemented with reference to two alternative retrofit solutions (FRP or steel haunch) for pre-1970 frame systems, a *partial retrofit*, aiming to achieve an intermediate performance objective, could be targeted if a full upgrade (*total retrofit*) is not achievable or impractical from a cost and invasiveness point of view. It could thus be suggested that, based on the results of damage scenario analysis pre and post-retrofit intervention, a quick implementation in critical sub-areas or regions of “partial” retrofit strategies could be favoured, in order to drastically reduce to a manageable level the consequences of the seismic event. A practical example will be given with the case study described in the next section.

5. CASE STUDY – SEISMIC RISK ANALYSIS FOR WESTERN LIGURIA REGION

The vulnerability methods proposed in the framework of the Risk-UE research project, have been operatively implemented and applied within an Italian National research project “Earthquake scenario in Western Liguria, Italy, and strategies for the preservation of historic centres”, promoted and funded by the INGV-GNDT (National Institute of Geophysics and Vulcanology and National Group for Earthquake Defence). In addition to a sub regional scale of analysis, identified with Western Liguria (Fig. 7), an urban study case (Taggia municipality) was selected for more detailed analysis.

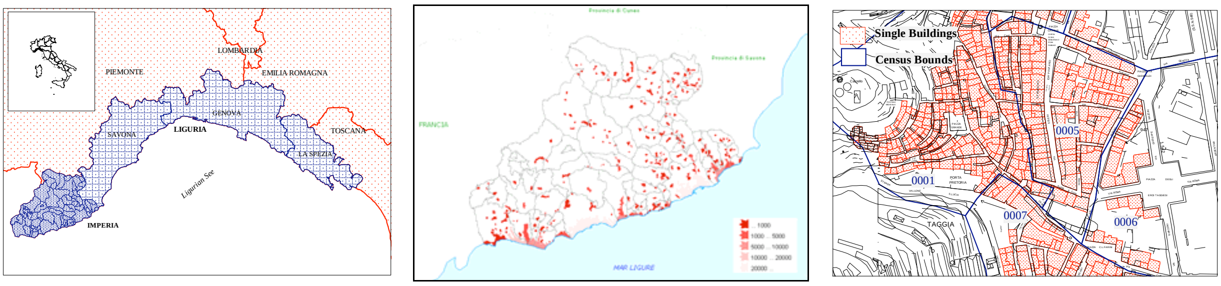

Figure 7. Case study for damage scenario a) sub-regional study area in Western Liguria (Italy); b) number of inhabitants in the sub-regional area; c) comparison between single building and statistical data for the study area.

5.1 Outline of the main steps for the implementation of the seismic risk analysis

The *Exposure* analysis consisted of: E1) defining a classification criterion (URM, RM, RC, timber and steel for a total of 12 building classes); E2) making an inventory of the building stock including number and characteristics (through census statistical data for the regional area and a quick survey for the study area); E3) processing the data and verifying their reliability against surveyed data, geocoding.

Fundamental steps for the *Hazard* analysis were: H1) the identification of the regional seismo-tectonic setting; H2) the identification of an exhaustive historical earthquake catalogue, H3) geotechnical zonation (geology-based approach for the sub-regional area (Fig. 8a,b), or additional validation with in-situ tests for the study urban area of Taggia); H4) a Digital Elevation Model (DEM) of the territory for the investigation of morphological amplification effects (Fig. 8c); H5) the selection of proper attenuation relationships both for the EM98 intensity and acceleration spectral ordinates. Both ground motions for reference earthquake events and constant hazard scenarios were evaluated.

When performing the convolution of *hazard*, *exposure* and *vulnerability* analyses, the minimum area for data availability, i.e. the census tract, was split into portions corresponding to the different soil categories therein identified (Fig. 7b). Centroids of these portions were adopted as reference grid-points for the hazard evaluation. The *Vulnerability* and *Damage* analyses for the macroseimic method required: V1) the evaluation of the vulnerability indexes (V, Q) for each census track, on the basis of the building typology distribution and of their behaviour modification factors; V2) the assessment of the mean damage grade and of the damage distribution for the I_{EMS-98} value resulting from the hazard analysis, according to the procedure described in section 3.1. The *Damage* assessment for the mechanical method required: D1) the evaluation of the performance point (Section 3.2) and damage distribution (assumed tentative limit states $S_{d1}=0.7d_y$; $S_{d2}=1.5d_y$, $S_{d3}=0.5(d_y+d_u)$, $S_{d4}=d_u$), considering soil condition and the hazard value, for all the building typologies included in the census tract; D2) the computation of the damage distribution for each census tract, as weighted average of the damage distributions of the building typologies located in that tract.

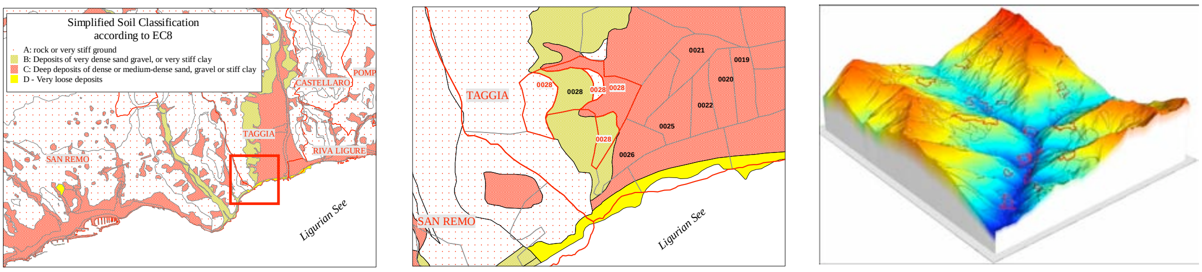

Figure 8. a) Geology-based zonation for the sub-regional area, b) zoom highlighting the analysis units, c) DEM

For the *Losses* and *consequences assessment* structural and non structural damage were converted into percentage of losses through empirical correlations based on observed data. Table 1 shows, as an example, the weight coefficients adopted for the evaluation of a) the Mean Damage Ratio, MDR, defined as the ratio between cost of repairing and cost of replacement b) the number of Unfit for Use buildings (UFU) and c) the number of casualties and severely injured people (S).

Table 1. Correlation between Mechanical Damage States D_{Sk} and Macroseismic Damage Grades D_k and weight coefficient w_k for consequences and loss assessment.

D_{Sk}	D_k	Definition	Structural (S) and Non Structural (NS)	w_k	MDR	UFU	S
D_{S1}	D_1	Slight	S=no - NS=slight	w_1	0.01	0	0
D_{S2}	D_2	Moderate	S=slight - NS=moderate	w_2	0.1	0	0
D_{S3}	D_3	Substantial to Heavy	S=moderate - NS=heavy	w_3	0.35	0.4	0
D_{S4}	D_4	Very heavy	S=heavy - NS=very heavy	w_4	0.75	1	0
	D_5	Destruction	S=very heavy	w_5	1	1	0.3

5.2 Simulation of pre and post-retrofit damage scenario based on the 1887 earthquake event.

For the damage scenario analysis, the maximum historical event in the region has been considered, corresponding to the Western Liguria Feb 23, 1887 earthquake (M=6.3, I_0 = X, Long=8°,1430, Lat = 43°,7480), which claimed over 509 victims and severe destruction in costal towns and villages (Fig. 9a). The current total number of buildings in the selected region is 49372, with RC and URM typologies representing 36% and 64% of the total, respectively, In spite of the higher number of URM buildings, the majority of population lives in RC buildings (60% out of the total 211349 inhabitants living in RC buildings, and 40% in URM buildings), mostly designed prior to 1981, the date of adoption of seismic code provisions in that area (56% pre 1971, 33%, between 1971 and 1981, 12% after the 1981). In general, low-rise buildings are the most common typology regardless of the age class.

In this case study, a damage scenario analysis, under the 1887 event, has been carried out before (Fig. 9b,c) and after simulated retrofit interventions (limited to pre-1970 buildings) according to a multi-level retrofit strategy approach: 1) partial retrofit (+15% strength, +10% stiffness and +150% ultimate displacement, corresponding to ΔV=-0.12, ΔQ=0.6; and 2) total retrofit (+25% strength, +20% stiffness and +200% ultimate displacement, corresponding to ΔV=-0.2, ΔQ=1.0).

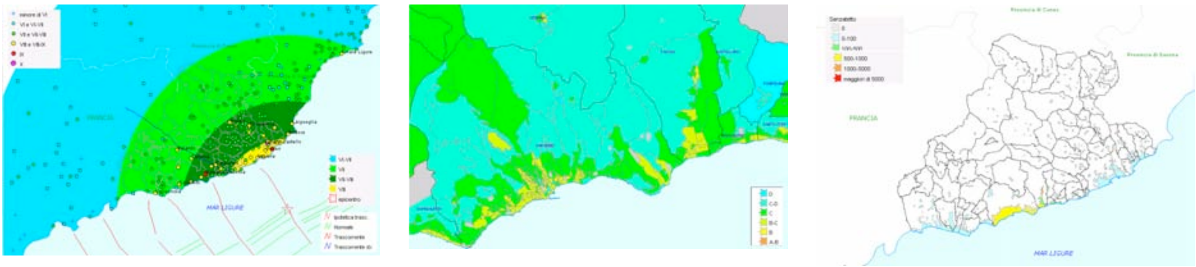

Figure 9. a) $I_{EMS\text{-}98}$ deterministic hazard scenario for the 1887 event and comparison with the observed intensities b) vulnerability map for RC building typologies; c) people needing temporary shelter

The results of the damage scenario simulation, shown in Table 2 in terms of consequences to buildings and people (mean values), confirm the efficiency of a partial retrofit intervention in drastically reducing the effects of the selected earthquake event. Conversely, the additional reduction provided by the implementation of a total retrofit solution might not be justified, from a cost-benefit point of view, in terms of implementation at territorial scale. As an additional advantage of the results provided by a damage scenario analysis within a GIS-environment, a comprehensive and rational risk mitigation strategy can be defined, consisting of alternative levels of intervention (ranging from total retrofit to no action) within a specific unit of analysis, depending on the computed seismic risk.

It is worth noting that, while the results presented in this case-study damage scenario have been referred to a specific event, the whole procedure can be implemented in the form of a complete probabilistic framework, by assuming a probabilistic hazard assessment (e.g. Cornell, 1968).

Table 2. Losses and consequences before and after the application of a partial or a total retrofit intervention.

Damage scenario for the 1887 event		**As Built**				**Partial Retrofit**	**Total Retrofit**
	Building Typology	*URM*	*R.C.*			*R.C.*	*R.C.*
	Class of Age	*All*	*<’71*	*’71-‘81*	*<’71*	*<’71*	*<’71*
BUILDINGS	Unfit for use	3775	480	135	6	242	183
	Collapsed	208	15	3	0	4	2
PEOPLE	Requiring short term shelter	10317	6129	1118	89	2999	2182
	Casualties and severely injured	182	79	9	0	20	10

6. CONCLUSIONS

In this paper, the use of damage scenario and seismic risk analysis as a support to seismic retrofit strategy has been discussed and exemplified, with reference to macro-seismic and mechanical vulnerability models, recently developed as part of European research projects. Positive features of the proposed vulnerability methods and risk analysis tool include: the possibility of being implemented with different levels of data availability, an easy implementation from the computational point of view and the possibility of cross-correlation between the two methods. Based on the experimental and numerical evidence on the seismic response of pre-1970s reinforced concrete buildings with or without masonry infills, tentative suggestions for refinements of the current mechanical model (or equivalent macro-seismic model) to more accurately represent the seismic vulnerability of pre-1970s reinforced concrete buildings with or without infills have also been given. Comparative evaluation of the effects of alternative retrofit solutions, relying on selective upgrading or weakening techniques, have been carried out and presented in terms of fragility curves. In conclusion, an example of a damage scenario analysis prior and after the adoption of a multi-level retrofit strategy, has been given, referring to a case study area in Italy.

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