REPAIRABILITY DECISIONS: SIMPLIFIED PROCEDURES FOR POST-EARTHQUAKE RECONSTRUCTION POLICIES OR SCENARIO BASED DAMAGE ASSESSMENT AT TERRITORIAL SCALE

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Abstract

Decisions on the fate damaged buildings after severe seismic events is largely influenced by a number of factors including damage level, post-earthquake safety, stakeholder willingness to repair, social and political context, economical convenience. Among those factors, the technical feasibility to repair may not be the key aspect while final decision is often driven by monetary constrains. In this framework, the use of simplified procedures to estimate expected capacity loss and associated costs for repair as well as demolition probability as a function of buildings main characteristics may strongly help decision makers for establishing post-earthquake reconstruction policies.

Based on statistical treatment of the L'Aquila 2009 post-earthquake reconstruction data, a simple methodology for assessing reparability of RC damaged buildings is herein presented. The method relies on the scenario-based simulation of building damage state and expected repair costs; moreover, the building age and the initial safety level are considered. The procedure allows to consider building typologies distribution at the territorial scale based on suitably assembled building inventory, example starting from the information reported in census returns integrated with the information provided by an the interview-based form (Cartis) that collects typology-based vulnerability data for town compartments. On the other hand, if post-earthquake data on building tagging are available, an alternative evaluation approach can be applied that uses real costs statistics towards estimation of demolition probability.

Keywords: Repairability, performance loss, reconstruction policies, Demolition probability; expected losses;

1. Introduction

The assessment of opportunity to repair a building after a damaging earthquake is not a trivial issue; several factors need to be accounted for such as that the damage state, the economic convenience to repair, the building's residual capacity and post-earthquake safety [1]. Considering other alternatives like repair and strengthening, or demolition and reconstruction of damaged buildings, several other factors can influence the decisions on reparability, as pointed out in different studies before (e.g. [2]-[3]).

Starting from the analysis of the database on damaged buildings after 2009 L'Aquila earthquake, and considering final decision on the post-earthquake action for those buildings (repair, repair and retrofit or demolish and rebuild), different studies proposed simplified approaches for evaluation of building reparability [4]-[5] and showed their applicability in large scale scenarios [6].

This paper describes the simplified tools that were developed towards reparability decisions linking them to the different kind of data and instruments that are available in the post-earthquake environment.

2. Post-earthquake recovery phases

The timeline of engineering activities in the *post-earthquake* is such that greater efforts towards building tagging and damage *reconnaissance* are generally concentrated in the first months after the event (see Fig. 1). After the first chaotic phases, the *short-term recovery* continues in the few months following the earthquake, with the setting of temporary housing, more organized activities related to damage inspection and the issuing of regulations and/or policies for reconstruction.

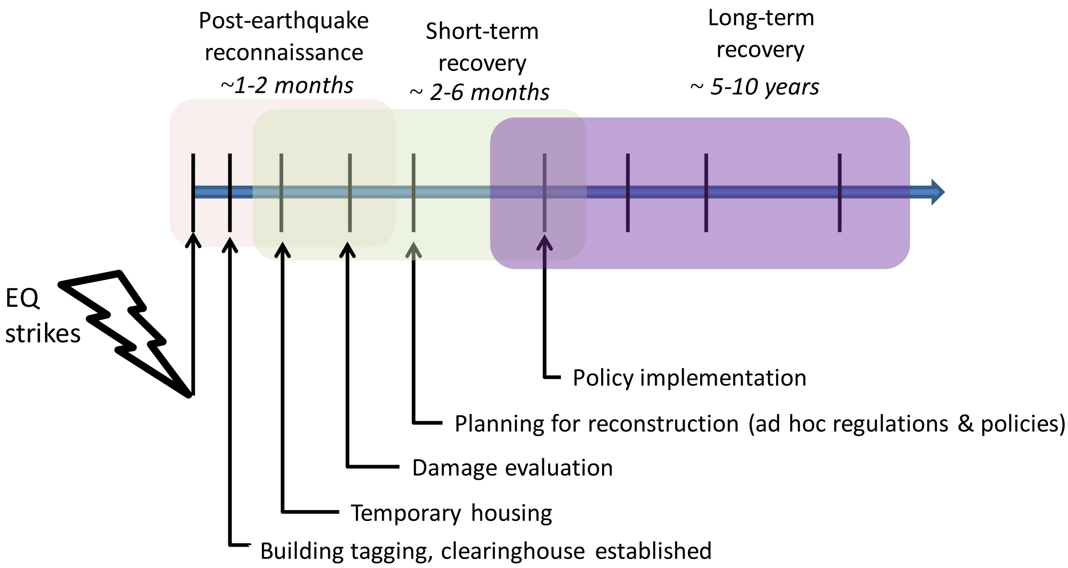

Fig. 1 – The timeline of post-earthquake activities

On the other hand, the *long-term recovery*, including the reconstruction process of damaged buildings and re-settlement of homeless in place or delocalized, starts few months after an earthquake and may last several years. Often, due to the lack of clear repair standards and criteria for re-occupancy after a damaging earthquake, this post-earthquake phase may be quite controversial and significant delays can elongate the time to complete recovery.

3. The L'Aquila experience

The M_w 6.3 earthquake, that on April 6th 2009 L'Aquila struck the town of L'Aquila and the surrounding areas, caused collapses, structural and nonstructural damage to thousands of buildings, leaving approximately 67,000 homeless people and sadly determining 308 fatalities.

3.1 Short-term recovery

The visual inspection of buildings finalized to evaluate the usability and damage started immediately after the earthquake [7]. According to the AeDES survey form [8], that is filled based on the visual in situ inspection of the building, 6 categories from A to F can be used for building tagging (see first two columns in Table 1). By the end of August 2009, more than 72,000 buildings had been inspected, and more than 50,000 resulted damaged to structural parts or nonstructural infill elements. Fig. 2 shows usability rating distribution by the end of August 2009 [7].

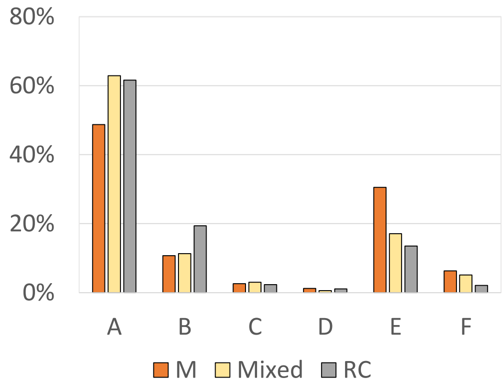

Fig. 2 – Usability rating distribution by the end of August 2009 [7]

Concerning reconstruction policies, the following Ordinances of the President of the Council of Ministers (OPCM) were issued in the first months following the earthquake: OPCM no. 3779 (June 2009) [9], OPCM no. 3790 (July 2009) [10], and OPCM no. 3881 (June 2010) [11]. The financial support given by the Italian government to private owners intended to cover entirely the costs of repairing the building, while additional funds were given for strengthening interventions based on the building usability rate [12], see Table 1. Note that the buildings with an E usability rating but with high non-structural risk and slight structural damage were termed as E-B in the reconstruction approval process [10]; this was a special funding class for which a higher amount was granted for local strengthening interventions (€250/m^2 vs €150/m^2 that was granted for slightly damaged buildings). The grant for strengthening of severely damaged buildings (those with E usability rating) was intended to cover the strengthening at least up to 60 % (and no more than 80 %) with respect to the new building standard NBS according to new design code [13]-[14].

As evident from the funding principles of the ordinances, the results of short-term activities such as building tagging may have a strong impact in the management of the emergency and reconstruction phase. Moreover, damage data collected in this phase [15] are fundamental for the development of empirical-based fragility curves (see e.g. [16], or more recent works [17]).

3.2 Long-term recovery

The management of the reconstruction process outside the historical center of L'Aquila, following the issued ordinances, was performed by a team (Filiera) formed by three groups with different responsibilities: FINTECNA, a company totally owned by the State through the Italian Ministry of Economics and Finance, ReLUIS, an interuniversity consortium with the purpose of coordinating the university laboratory activity of seismic engineering, and CINEAS, a university consortium for Insurance Engineering. In particular, ReLUIS had to evaluate the consistency between repair intervention and damage and the compliance between designed local (or global) strengthening interventions and current seismic code provisions and ordinances issued after the L'Aquila earthquake. The Filiera activities started in August 2009 and ended in March 2013. To speed the recovery process, the buildings with less damage (B or C usability rating) were examined first, leading to the so-called "light damage" reconstruction [12].

The approval process and the relevant grant allocation for "light damage" reconstruction was almost completed by the end of September 2010. On the other hand, the examination and approval process for severely damaged or collapsed buildings (E usability rating), the so called "heavy damage" reconstruction, started later and by September 2013 about 74% of the applications were completed [18].

Table 1 – Usability ratings according to AeDES and reconstruction contributions

<table>
<tr><th>Usability rating</th><th>Definition</th><th colspan="2">Strengthening</th><th>Repair</th></tr>
<tr><td></td><td></td><td>Local str.</td><td>Retrofit</td><td rowspan="8">Repair costs are fully covered for primary residences</td></tr>
<tr><td>A</td><td>Usable</td><td></td><td></td></tr>
<tr><td>B</td><td>Usable only after short term countermeasures</td><td rowspan="2">€150/m² [9]</td><td></td></tr>
<tr><td>C</td><td>Partially usable</td><td></td></tr>
<tr><td>D</td><td>To be re-inspected</td><td></td><td></td></tr>
<tr><td>E</td><td>Unusable due to high structural or non-structural risk, high external or geotechnical risk</td><td></td><td>€400-600/m² [10]</td></tr>
<tr><td>(E-B)*</td><td>buildings with an E usability rating but with high non-structural risk and slight structural damage</td><td>€250/m² [10]</td><td></td></tr>
<tr><td>F</td><td>Unusable building from external risk alone</td><td></td><td></td></tr>
</table>

* specific classification introduced in the reconstruction approval process [10], not defined in [8]

The reconstruction process of buildings in historical centers of L'Aquila and other municipalities were dealt by specially instituted offices. Due to the historical value of the buildings and the complexity of the urban environment, often comprising aggregate type buildings and/or constraints posed by the Cultural Heritage Soprintendenza, the reconstruction process in historical centers is much slower and currently ongoing. It mainly involves masonry buildings in aggregates and according to data provided by Special Offices for reconstruction of L'Aquila and other municipalities historical centers (https://usra.it/; http://www.usrc.it/), the end of the process is possibly expected in 2024.

4. Performance-based reconstruction policies

Table 2 summarizes guidelines and/or relevant international policies related to post-earthquake assessment and reconstruction for reinforced concrete RC buildings.

The FEMA 308 document [19] introduced a Performance-Based Policy Framework (PBPF) for assessment of reparability of damaged buildings; the framework relies on safety level of the building, in its intact and damaged state, with respect to new building standard (%NBS) and on the relative performance loss PL as significant indicators for repair and/or upgrade decisions. Practical rules for applicability of such kind of framework may be found in the San Francisco Building Code and related documents [20]-[21]. According to [21], the buildings not complying with new design standards are usually not considered adequately resistant and, if "sufficiently damaged", must not only be repaired, but also retrofitted to a standard defined by code. Sufficiently damaged buildings are those buildings where the loss of lateral load capacity exceeds given thresholds (see Table 2, where performance loss PL is defined as the complement to one of the variation of lateral load capacity).

In the Japanese Guideline for Post-earthquake Damage Evaluation and Rehabilitation [22] the post-earthquake condition is evaluated as a function of a normalized residual capacity index R. The guidelines directly link different R-index values to corresponding damage states: $R \geq 95\%$ slight damage; $80\% \leq R < 95\%$ minor damage; $60\% \leq R < 80\%$ moderate damage and $R < 60\%$ severe damage. The value of $R = 60\%$, corresponding to severe damage, is considered as a significant threshold for reparability decisions [23]-[24].

Table 2 – Example of post-earthquake policies and/or guidelines for RC buildings

Policy	**Code compliance**	**Typology**	**Post Earthquake condition**	**Action or indication**
San Francisco Building Code ([20]-[21])	Complying YES/NO (1973 S. F. Building code)	Not complying RC buildings	PL≤5%	Cosmetic repair
			PL = 5%÷20%	Restore to pre-EQ capacity
			PL >20%	Upgrade
Japanese Guideline for Post-earthquake Damage Evaluation and Rehabilitation ([22]-[24])	-	RC buildings	R≤60%	Repairable
			R>60%	Not repairable
NZ Building Act + rules issued by the Christchurch City Council [25]- [26]	<33% NBS	RC buildings	-	Upgrade from 34% to 67% NBS
Ordinance after L'Aquila [10]	<60% NBS	all	Slight damage	Repair or (repair + local upgrade)
			Heavy damage	Repair + retrofit
	≥60% NBS		Slight damage	Repair or (repair + local upgrade)
			Heavy damage	Repair + Retrofit or (repair + local upgrade)

The New Zealand Building Act [25] applied with the rules issued by the Christchurch City Council [26], requires that sub-standard buildings, i.e. those having a safety level lower than 33% of NBS, should be upgraded up to 67% of NBS.

The ordinance issued in the aftermath of L'Aquila earthquake [10] impose to strengthen buildings having a safety level lower than 60% with respect to NBS; as explained in §3.1, funds are granted to private owners for strengthening up to 80% of NBS.

5. Simplified tools for evaluation of Residual Capacity and Costs

By examining the post-earthquake rules and policies reported in Table 2, it is evident the importance of performance loss PL as a key factor ruling the possible actions to undertake. Also the policies issued after L'Aquila indirectly consider the variation of seismic capacity as an important parameter, albeit not specifically introduced in [10]; indeed, the rules are given depending on usability rating, that is directly connected to damage level and hence to the capacity loss.

In addition to PL, also repair costs C_r constitute a relevant parameter for reparability decisions. Indeed, when dealing with post-earthquake assessment, key decisions need to be taken regarding if it is more convenient to repair and retrofit or to demolish and rebuild the building.

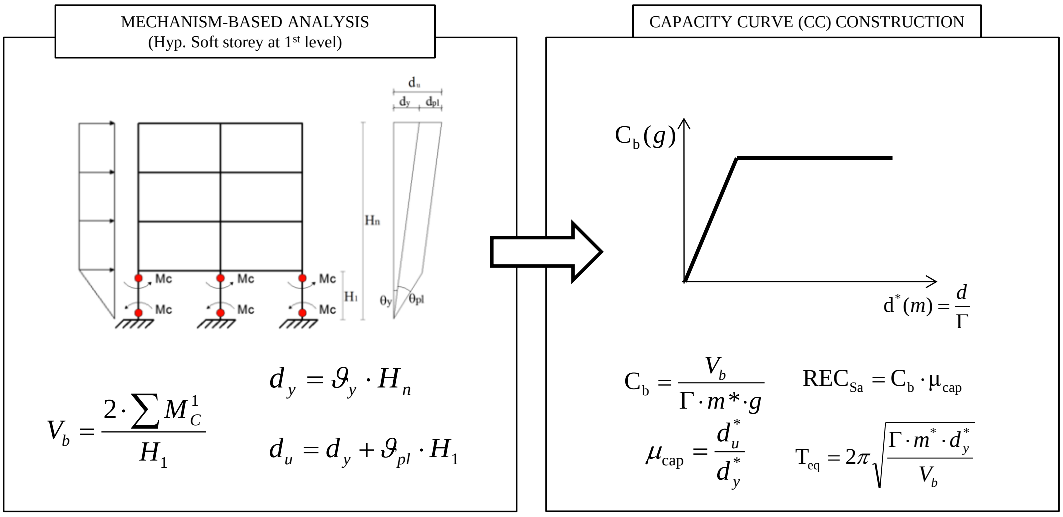

Fig. 3 – Calculation of REC via mechanism-base analysis

In [4] simple tools for rapid assessment of expected PL for damaged RC building classes representative of existing European Mediterranean constructions and a relationship of PL with expected repair costs (C_r) were presented. The PL can be determined as a function of the (REsidual) Capacity of intact and damaged buildings. Fig. 3 and Fig. 4 resume the process for simplified estimation of PL. As proposed in [27], the REC_{Sa} for the intact structure can be estimated starting from the capacity curve CC representing the nonlinear response of the equivalent SDOF system of the real structure (see Fig. 3).

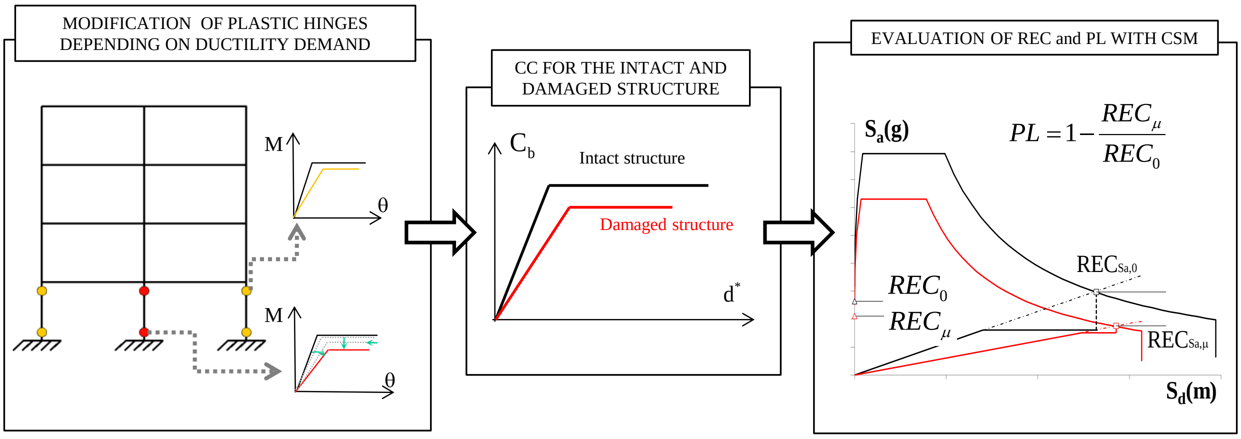

Fig. 4 – Modification of plastic hinges and calculation of capacity curve and REC for damaged structure

CC may be obtained with mechanism-based analysis. After suitable modification of plastic hinges of the considered mechanism, depending on local ductility demand [28], see left and central panels in Fig. 4, also the REC_{Sa} of the damaged building can be evaluated with the same approach. Finally, applying the Capacity Spectrum Method CSM [29], the REC for intact and damaged structure are obtained and the performance loss is calculated as $PL=1-REC_{\mu}/REC_0$ (see right panel in Fig. 4).

Notably, the variation of residual capacity, and the corresponding PL, depends on global ductility demand μ for the system. The latter can be derived with CSM, once the CC for the equivalent SDOF and the elastic demand spectra are available.

In [4], relying on a simulation based approach [30], the CC as well as curves relating the potential ductility demand μ to the expected PL are built for 30 considered RC building classes (from 2 to 7 storeys and with construction age from 46's to post '91 of the past century).

A catalogue of CC and PL-μ curves is included in [4]. Moreover, based on a calibration on a large cost database available after the 2009 L'Aquila earthquake in Italy, a relationship of PL with expected Costs for Repair (C_r) was proposed, reported in Eq. (1):

$$C_r(PL)=0.21+1.25\cdot PL \quad (1)$$

6. Reparability decisions

As a result of Reluis activities in the aftermath of L'Aquila earthquake, a large database comprising data on nearly 3000 RC damaged buildings was collected. Considering only severely damaged buildings (those classified with E rating) and for which repair costs recognized after the reconstruction approval process were available, in [5] a study on the most influential factors for demolition decisions was performed. In particular, the final database consisted of 472 RC buildings; 122 out of those 472 buildings where demolished and rebuilt.

Considering that the outcome of the decision on the fate of a building is binary (demolish and rebuilt, or repair), a logistic regression was performed to evaluate the probability of demolition as a function of relevant parameters between the data available in the database. In particular, the study was initially performed adopting as predictors the following standardized variables: x_1= *age* (construction age); x_2= N_s (storey number); x_3= $Area_{FP}$ (Mean footprint area); x_4= *%NBS* (pre-earthquake safety level expressed as % of New Building Standard); x_5= C_R (repair cost). Two models were considered in the regression study, namely a first model (a) including only predictors available in "peace time" (x_1 to x_4) and a second one (b) including the whole set.

It was found that for model (a) the most influential parameter is the construction age and the expected demolition probability p_{dem} could be calculated with Eq. (2):

$$p_{dem}(x_1) = \frac{1}{1+e^{-(-1.09-0.72\cdot x_1)}} \quad (2)$$

On the other hand, for model (b) the best prediction can be obtained considering contemporarily three variables, namely *age*, *%NBS* and C_R, and p_{dem} can be obtained with Eq. (3):

$$p_{dem}(x_1, x_4, x_5) = \frac{1}{1+e^{-(-0.49\cdot x_1-0.57\cdot x_4+4.66\cdot x_5)}} \quad (3)$$

Note that p_{dem} calculated with Eq. (2) or (3) is the percentage of buildings that are expected to be demolished among the severely damaged ones. As mentioned before, the x_j are standardized variables obtained for the relative parameters; the limit values used for standardization are 1953.5 and 2005.5 for *age*, 0.30 and 0.59 for *%NBS* and 85.4 and 1810.9 for C_R [5].

7. Scenario based methodology for assessing reparability of damaged buildings

The simplified tools and formulations developed in previous studies can be applied for rapid preliminary estimation of the number of buildings N_{dem} that are expected to be demolished at the territorial scale.

Fig. 5 resumes the methodology that could be adopted for an earthquake scenario. Two kind of approaches may be used: first one, indicated as simulation-based assessment and with blue arrows in Fig. 5, fully relies on the simplified tools developed in [4]-[5], while second one, indicated as empirical-based assessment and with green dashed arrows in Fig. 5, requires the availability of data on post-earthquake building tagging. The starting point for computation of N_{dem} is the availability of a suitable building inventory for the study area. Depending on if simulation-based or if empirical-based assessment is performed, and if the model (a) or (b) for evaluation of p_{dem} is applied, different building classifications are required.

For simulation-based assessment the building inventory should give the number of RC buildings belonging to relevant classes defined in terms of storey number *Ns* and construction *age*. Indeed, simulation-based assessment needs to use the catalogue of CC and PL-μ curves included in [4], that were developed for RC building classes defined in terms of *age* and *Ns*. Given the building inventory the number of "severely damaged" buildings SDi for each class i is firstly derived for the earthquake scenario considered. To this end, relevant seismic fragility curves for the considered building classes can be applied; as proposed in [5], the buildings exceeding damage level D2 of the EMS98 scale can be considered to be severely damaged. Given SDi, the p_{dem} can be computed with model (a) using Eq. (2) for each age class. For using model (b) and Eq. (3), in addition to age, also *%NBS* and C_R are needed; the latter two parameters can be calculated as briefly explained in Fig. 5 (more details may be found in [6]). By summing over the classes the expected number of buildings to be demolished within each class, $n_{dem,i}=SDi\cdot p_{dem,i}$, the total expected number of buildings to be demolished N_{dem} in the study area is obtained.

For empirical-based assessment, building classification can be based solely on construction *age*. If post-earthquake survey data are available, the SDi, i.e. number of severely damaged buildings for each age class, can be directly retrieved from building tagging statistics and the p_{dem} can be computed with model (a) using Eq. (2) for each age class. Once $p_{dem,i}$ is calculated for each class, the rest of the procedure is applied in the same way as for simulation-based assessment to compute the expected value N_{dem}.

Concerning the building inventory, the easiest approach is to organize it based on census data, which are cheap sources of information available over a large scale generally including information on construction age and in some cases including also the storey number.

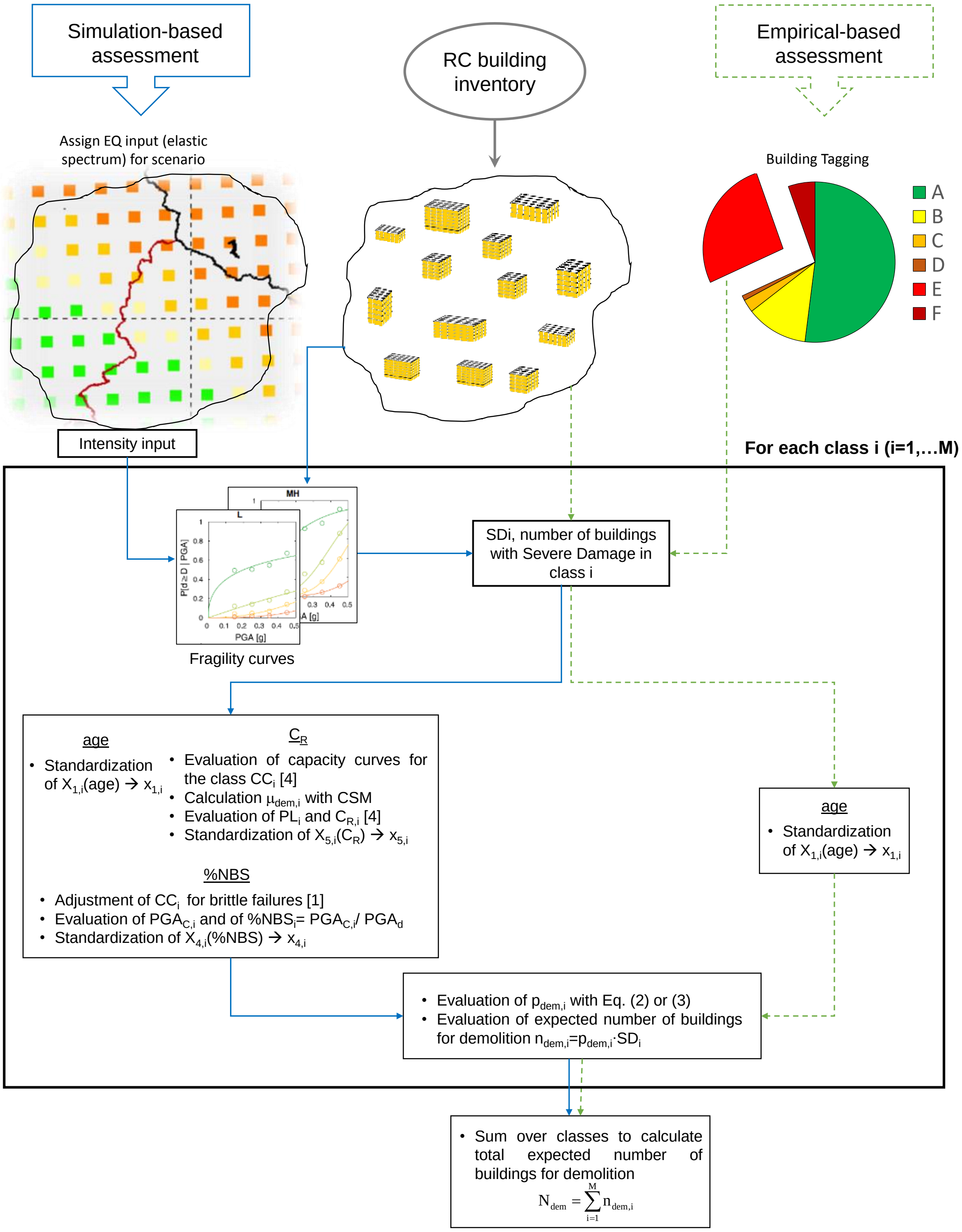

Fig. 5 –Scenario-based methodology for evaluation of expected number of buildings to demolish

Depending on the vulnerability model adopted to compute the severely damaged buildings, additional information on vulnerability may be needed. For example, with the RISK-UE vulnerability model [31] a classification refinement is possible considering sub-typologies defined by additional vulnerability factors VF, such as, e.g. regularity in plan or elevation for RC buildings. As shown in [32], by integrating the information reported in census returns with the information provided by an the interview-based form

(Cartis), that collects typology-based vulnerability data for town compartments, it is possible to rapidly obtain more refined building inventory for territorial scale applications. Other relevant data included in the Cartis form for RC building typologies are the infills consistency and disposition. Notably, local frame-infill interaction effects and the possible negative consequences, such as brittle failures in columns, can be more relevant in case of stiffer infills [33]. Hence, such kind of additional information provided by the Cartis form can be very useful to adjust estimation of %NBS in existing buildings.

8. Conclusions

A simple methodology for assessing reparability of RC damaged buildings is presented. It can be applied for preliminary evaluation, at the large scale, of expected number of buildings to be demolished N_{dem} among the ones that are severely damaged SD. In particular, N_{dem} can be calculated as a function of an estimated probability of demolition p_{dem} that, as found in previous studies [5], depends on relevant factors such as building *age*, the building safety level with respect to new building standard *%NBS* and unit repair costs C_R. Given building inventory, that is the starting point for large scale assessment, two kind of approaches can be used for calculating p_{dem} (and eventually N_{dem}). First "simulation-based" approach considers an earthquake of a given intensity assigning the elastic demand spectrum. Adopting suitable fragility functions it estimates SD buildings and next employs the tools previously developed by the authors in [4]-[1] to determine *%NBS* and C_R for building classes defined in terms of storey number and construction age. Next, the parameters *age*, *%NBS* and C_R are used to calculate p_{dem}. The second "empirical-based" approach hypothesizes the availability of building tagging in a post-earthquake environment, and hence the number of SD buildings are directly derived from the building tagging data. In this second case a simpler model for estimation of p_{dem}, depending only of building *age*, may be applied.

The data and statistics used to derive the formulations recalled in this study are based on the information collected after the L'Aquila 2009 earthquake. Therefore, such models are strictly applicable only to building typologies that are similar to the local ones, e.g. referring to gravity load design or low-code design RC moment frame buildings in Italy or European Mediterranean regions. Moreover, damage and cost data used to calibrate p_{dem} functions refer to a specific earthquake, legal policy framework and reimbursement rules. Therefore, the formulations cannot be used indiscriminately worldwide. Nevertheless, the methodological approach is general, and it can be employed for preliminary assessment at the large scale, given basic information on building typologies and additional required data are available.

9. Acknowledgements

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