Evaluation of seismic vulnerability of buildings in Athens and L'Aquila in the framework of the MASSIVE seismic mitigation system

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SUMMARY:
MASSIVE (Mapping Seismic Vulnerability and Risk of Cities) is a GIS-based earthquake mitigation system that was developed in order to provide Civil Protection authorities with accurate and up-to-date maps of seismic hazard, urban vulnerability and risk of buildings at local scale, together with state-of-the-art population evacuation models for two European pilot sites, heavily struck by recent earthquakes in western Athens (GR) and Abruzzo Region (IT). The application of a hybrid methodology developed for the assessment of the seismic vulnerability of the buildings in the two sites is presented. The final results can be given either based on a 'green-yellow-red percent' tagging system, or through a single mean expected damage index at each building block level. The vulnerability models were implemented in the MASSIVE GIS system and the validity of the obtained results was confirmed by comparison with actual damage data of in the two sites under investigation.

Keywords: Seismic vulnerability, seismic risk, GIS, hybrid methodology

1. INTRODUCTION

During the last 20 years or so, a growing interest is observed for seismic risk studies (Bard et al. 1995, Barbat et al. 1996, D'Ayala et al. 1996, Faccioli et al. 1999, Kappos et al. 2002, 2008, Erdik et al. 2003, Dolce et al. 2006) in a number of European cities, particularly those located in its southern part, where the earthquake activity and its consequences are significantly higher. The reason is that it is now widely accepted that seismic risk scenarios and the estimation of the economic and human losses incurred by the earthquake, notwithstanding the inherent uncertainties and practical difficulties involved, are a useful tool for seismic risk management and for prioritizing the pre-earthquake strengthening of the built environment.

Within the framework of the MASSIVE project, researchers from the Aristotle University of Thessaloniki (AUTh) and the Institute of Engineering Seismology and Earthquake Engineering (merged since Aug. 2011 with the Earthquake Planning and Protection Organization – EPPO-ITSAK) were invited by the Institute for Space Applications and Remote Sensing of the National Observatory of Athens, the coordinator of the MASSIVE EU Civil Protection Mechanism project (GA No 070401/2009/540429/SUB/A4, http://www.massive.eu-project-sites.com/) to develop a methodology for the vulnerability assessment of the building stock, taking into account the structural characteristics of buildings and apply it to the cities of Athens and L'Aquila. The AUTh research team, in close cooperation with scientists from EPPO-ITSAK, have been developing over the last decade a methodology for vulnerability and loss assessment of the building stock based on a 'hybrid' approach, combining statistical data from actual earthquakes with the results of inelastic analyses of representative structures and resulting in the derivation of fragility curves for representative building typologies (Kappos et al. 1998, 2006, Kappos 2007). Successive versions of the methodology have been applied to develop damage and loss scenarios for the building stock of a number of Mediterranean cities (Kappos et al. 2002, 2008, 2010).

2. COMPOSITION OF THE BUILDING STOCK

In order to estimate the seismic loss of the building stock in an urban area, the need to assign each structure to one of the typical building classes is essential. Unfortunately, in most cases available data do not include all the necessary information for an unambiguous classification. Depending on the purpose, the scale and the resources of each project, the inventory of the building stock can be more or less detailed. Data gathered during a national census have the advantage of including all buildings but structural information is usually limited since this is not the purpose of a national census; it is also noted that such surveys are usually carried out by people with no civil or structural engineering background. More detailed information is gathered during research programs focusing on the vulnerability of the building stock in a specific area (Penelis et al. 1989, Kappos et al. 2008, 2010). These studies include all required structural information but they are limited to a sample of the existing building stock (that can be adequate and representative for the area under study) but their transferability to other areas can be problematic or needs additional resources.

For the MASSIVE project, data provided by the Hellenic Statistical Authority (EL.STAT.) and the Italian National Institute of Statistics (ISTAT), through the Italian partners of the MASSIVE project (PLANETEK Italia s.r.l.), have been used. Both databases were developed during the corresponding 2001 National Censuses for Greece and Italy. This approach was chosen as the best feasible approach for the two pilot areas studied herein, since it utilizes a large scale available building inventory, requires no extra cost for gathering of new data, and furthermore it is more apt to transferability to other prone areas, at least of the same countries, a feature that was included in the basic scopes of the MASSIVE project.

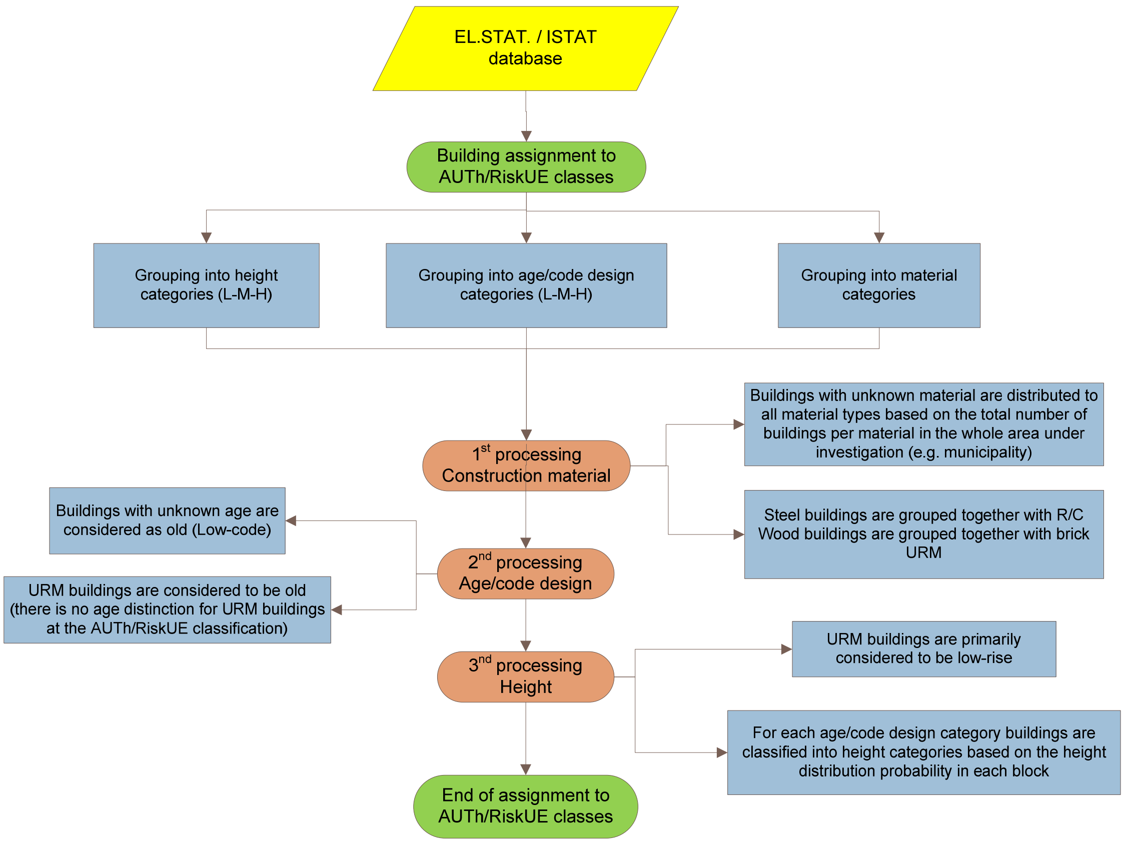

Figure 2.1. Flowchart of the building classification 'algorithm'

As already mentioned, data gathered at the national censuses of both countries include a lot of information concerning the population and the use of the buildings but structural information with regard to their seismic performance is rather limited. Both databases included information related to the height of the buildings (number of storeys), the structural material (masonry, reinforced concrete, steel etc.) as well as the age of the building (correspondence to the seismic codes of that time). No information was available regarding the structural system of R/C buildings (frame or dual) or the presence and the regularity of the infill walls. Another serious drawback was that the data in the databases were available as total values at the building block level and not for each individual building, i.e. the information regarding for example which buildings of a certain material correspond to each age or height level was missing. The only way to overcome these problems was to develop an algorithm through which there would be an implicit assignment of the available data for each particular building, using appropriate assumptions based on the research team's knowledge of typical construction practices in the area under investigation and previous experience from similar studies (Kappos et al., 2006, 2007, 2010). The basic steps of this 'algorithm' are presented in Fig. 2.1. Using the aforementioned assumptions for Athens, the number of R/C building typologies (see section 3) used in this study was finally reduced to 9, while for URM buildings the original 4 classes were retained (13 total). For L'Aquila the corresponding typologies were finally 4 and 4 (8 total). The number of building classes is lower in the L'Aquila case since no high-rise buildings were found in the database and with regards to the age/seismic-code design no moderate-code design was used for the Italian buildings. The entire procedure was integrated into an in-house developed software that was finally incorporated in the MASSIVE GIS system developed by the Greek partner of the MASSIVE project Geoapikonisis SA.

3. VULNERABILITY ASSESSMENT METHODOLOGY

3.1. The AUTH/RiskUE building classification scheme

The building classification scheme initially proposed within the framework of the Risk-UE European project (Kappos et al. 2006, 2008, Lagomarsino and Giovinazzi 2006) has been adopted, as the authors believe that it establishes a common basis for vulnerability studies in Europe, in a similar fashion that HAZUS (FEMA-NIBS 2003) classification is currently considered as a reference for North America. The structural types are generally classified into a total of 72 R/C and 4 URM building typologies (Kappos and Panagopoulos 2010). R/C buildings are classified on the basis of the level of code design and detailing used (no-, low-, moderate-, or high-code), the height of the building (low-, medium-, or high-rise), the structural system (frame or dual) and the configuration of masonry infill walls (i.e. bare, regularly infilled and irregularly infilled). Unreinforced masonry (URM) buildings are classified according to their structural material (stone or brick), and their height (low- and medium-rise).

3.2. Adaption of Greek fragility curves to the MASSIVE building typologies

Fragility curves in terms of peak ground acceleration (PGA), were developed for all these building classes in previous studies by the authors using a hybrid approach that combines available statistical damage data from actual earthquakes with the results of inelastic dynamic analyses (Kappos and Panagopoulos 2010, Kappos et al. 2010). These curves (given for the damage states shown in Table 3.1) were further refined and adapted for the needs of the MASSIVE project with regard to the particular characteristics of the buildings presently under investigation (Athens and L'Aquila) as well as the available information in each case.

Table 3.1. Damage state definition for both AUTh and Pavia fragility curves

Damage State	Description
DS0	None
DS1	Negligible to slight
DS2	Moderate
DS3	Substantial to heavy
DS4	Very heavy
DS5	Destruction

As noted in section 2, since data for several building classes were not included in the EL.STAT./ISTAT databases (e.g. regarding the presence of infill walls), it was decided to use weighted median and standard deviation values from the hybrid fragility curves derived using the aforementioned procedures. For example, with regard to the infill wall pattern of R/C buildings it was decided to use weighted median and standard deviation values from the fragility curves of the corresponding regularly (≈85%) and irregularly (≈15%) infilled typologies as they appear in the building stock of Ano Liosia, Thessaloniki, and Grevena (Kappos et al. 2007, 2008, 2010). The number of bare frame buildings is usually very low in residential areas and has been neglected in the present study. Some examples of the finally derived fragility curves are given in Fig. 3.1.

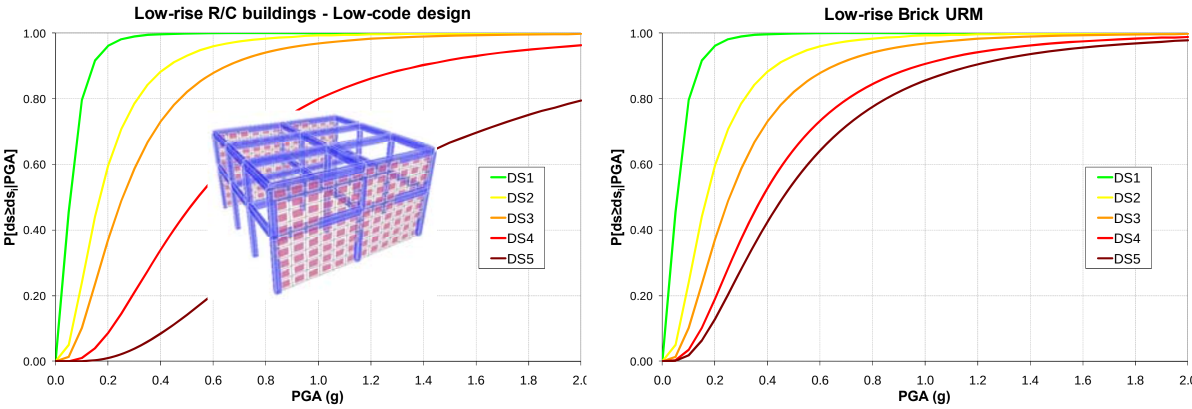

Figure 3.1. Fragility curves in terms of PGA for low code, low rise with frame system (left) and low rise, brick URM buildings (right)

3.3. Use of Italian fragility curves for the L'Aquila case-study

With regard to the specific characteristics of the building stock in L'Aquila, it was decided, along with the application of the Greek vulnerability functions, to also make use of fragility curves derived by Italian researchers specifically for Italian buildings, since the number of URM structures in L'Aquila is significantly higher compared to Greek cities (where reinforced concrete is the dominant material).

Within the framework of the Risk-UE (2001-2004) project Lagomarsino & Giovinazzi (2006) proposed vulnerability functions for most common Italian building typologies adopting a classification close to the EMS-98 approach. Two methods were proposed, namely a macroseismic model, to be used with macroseismic intensity hazard maps and a mechanical model, to be applied when the hazard is provided in terms of peak ground accelerations and/or spectral values. The macroseismic model was deemed inapplicable for loss estimation of the building stock in L'Aquila since the available seismic scenario was in terms of PGA (see section 4.1) and it is well known that the correlation between macroseismic intensity quantities and PGA is characterised by huge scatter and imposes significant uncertainties. Fragility curve parameters were available to the research team only in terms of spectral displacement (S_d) but not in terms of PGA, for them to be used in the L'Aquila scenario. As a result, due to the lack of the required data the Lagomarsino & Giovinazzi fragility curves were finally not used in this study.

The second method was carried out in the University of Pavia as a part of a recent PhD thesis (Rota, 2007, Rota et al. 2008) and subsequent information herein presented comes from this source. In this thesis building typologies have also been identified with reference to the RISK-UE (2004) building typology matrix, and modified on the basis of the information from all available Italian databases of post earthquake surveys. In all, 23 building typologies were identified although data for some of them were insufficient. Buildings have been firstly subdivided by the material of the load-bearing system : reinforced concrete, masonry, steel and mixed (masonry and reinforced concrete). A very detailed classification is given for unreinforced masonry wall buildings, taking into account the regularity of wall distribution and in- plane floor rigidity for masonry buildings. Empirical fragility curves have been derived after the processing of a set of approximately 163,000 building survey records from the main recent Italian earthquakes; namely Irpinia (1980), Abruzzo (1984), Umbria-Marche (1997), Pollino (1998) and Molise (2002).

Since the ISTAT database does not include detailed information to assign the L'Aquila building stock into all building classes developed in Rota's thesis (especially for masonry structures), the following additional assumptions have been adopted, after personal communication with Prof. D. Galeota of the Engineering Faculty of L'Aquila University and in-situ inspection of the L'Aquila building stock by members of the research team. All masonry buildings are assigned to the irregular typologies of the Rota et al. classification. Old masonry buildings (pre-1919) are considered to have flexible floors and no tie-rods or tie-beams, while newer masonry buildings (post-1919) are considered to have rigid floors and tie-rods or tie-beams.

4. APPLICATION – VALIDATION OF THE RESULTS

4.1. Loss estimation scenarios

The aforementioned approach has been applied to the case studies of Athens (Greece) and L'Aquila (Italy) and loss estimates have been derived for both cities using PGA-based seismic scenarios that correspond to the Athens 1999 and the L'Aquila 2009 earthquakes, developed by other researchers within the MASSIVE project. In particular, for Athens the attenuation law of PGA published in Skarlatoudis et al. (2003) was applied based on earthquake magnitude M, epicentral distance d, hypocentral distance h (km), the type of the seismic fault F, and the type of soil S as follows:

$$\log PGA = 0.86 + 0.45M - 1.27 \log(d^2 + h^2)^{0.5} + 0.10F + 0.06S\ (\pm 0.286),\ \text{where: } d \leq 30\text{km} \tag{4.1}$$

$$\log PGA = 1.07 + 0.45M - 1.35 \log (d + 6) + 0.09F + 0.06S\ (\pm 0.286),\ \text{where } d > 30\text{km} \tag{4.2}$$

A similar empirical formula (Sabetta and Publiese, 1987) was selected for the test site of L' Aquila (G. Papadopoulos; personal communication 2010):

$$\log PGA = -1.562 + 0.306M - \log (d^2 + 5.8^2)^{0.5} + 0.169S \tag{4.3}$$

The whole procedure has been integrated into an in-house developed software that includes:

- the classification of the building stock data to representative building typologies and the adoption of the corresponding fragility curves
- the application of the PGA values from the seismic scenario and the estimation of damage probabilities for each building typology
- the prediction of the seismic damage expressed either in terms of the typical Green-Yellow-Red tagging approach or the 5 damage state scales presented in section 3
- the estimation of a weighted loss index defined as $\Sigma(MDF_i \cdot N_i)/N_{tot}$, where the number of buildings for each typology *i* in a building block is used to weigh the mean damage factor MDF for this type

The software can run as a stand-alone application but it was also integrated within the MASSIVE ArcGIS system, as a dynamic link library (.dll) in order to automate the loss estimation procedure.

The geo-information company GEOAPIKONISIS SA, partner of MASSIVE project, designed the MASSIVE GIS system architecture (Fig. 4.1) which accommodates a user interface, adequate environment for the applications run and a database component. The design and implementation of the GIS system assures optimized functionality and robust models handling for PGA assessment, building vulnerability, and building damage estimations and models output mapping at census block level. The integrated GIS system was designed as a custom add-in module for the ArcGIS ArcMap GIS software version 9.3.1. The user Interface of the MASSIVE custom module consists of the MASSIVE Risk toolbar and the MASSIVE Evacuation toolbar, the latter consisting a special application to highlight the risk for uncontrolled evacuation of the area at risk. The great profit for emergency planning authorities is that the system provides the user with capability to run any earthquake scenarios he needs, select the area for the model to run, calculate the seismic risk parameters, as well as the evacuation risk based on the road network characteristics. Therefore, the user can create “What if” scenarios for prevention and planning. The final outputs are thematic maps depicting the results of the risk and evacuation models. The architecture of the MASSIVE GIS system is depicted in the following figure.

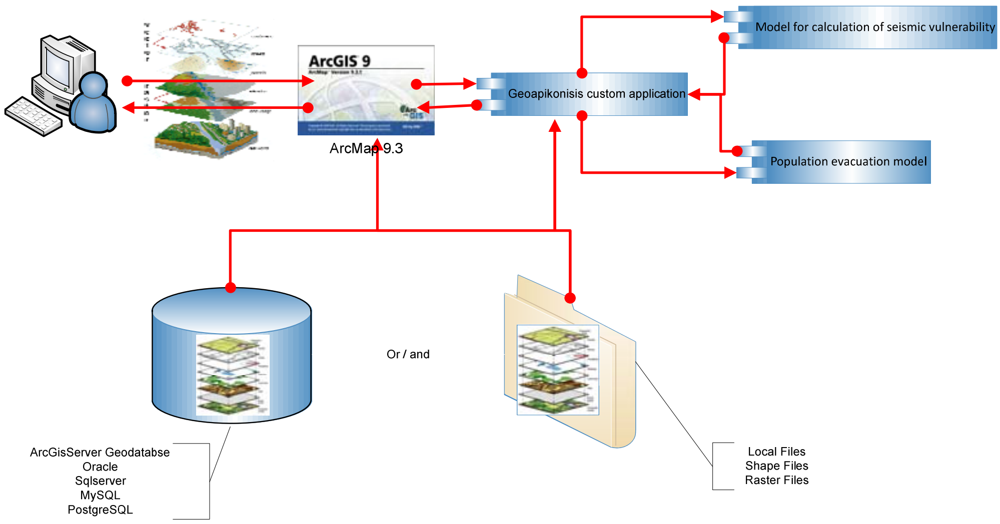

Figure 4.1. The structure of the GIS – RDBMS solution

Results can be obtained in terms of a 5-scale damage state definition (Table 3.1) or the common Green-Yellow-Red post earthquake tagging approach (Fig. 4.2, left) or even in terms of an appropriate mean damage factor (MDF) that provides a good insight into the most vulnerable parts of the city when projected on a GIS map (Fig. 4.2, right).

Figure 4.2. Predicted distribution of post-earthquake damage distribution in terms of green-yellow-red tagging for Athens (left) and Mean Damage Factor for L’Aquila (right)

4.2. Validation of the results

Table 4.1 summarizes the results for the Athens scenario and compares them with actual damage data recorded after the 1999 earthquake, as collected by the Greek Seismic Rehabilitation Agency (YAS). It can be seen that estimates are generally in good agreement - for most municipalities as well as for the whole case-study area - with the statistical data collected by YAS, considering all the uncertainties existing in such studies,.

Table 4.1. Predicted tagging of buildings for Athens (MASSIVE damage assessment approach) vs On-site reported (validation) data by YAS

Municipality	ITSAK/AUTh (MASSIVE damage assessment approach)			YAS (Damages reported on site)		
	Green	Yellow	Red	Green	Yellow	Red
Ag. Paraskevi	92.9%	7.1%	0.0%	99.0%	1.0%	0.0%
Ano Liosia	71.9%	26.8%	1.3%	77.1%	17.0%	5.9%
Acharnes	76.6%	23.0%	0.4%	78.8%	17.1%	4.1%
Zefyri	71.4%	28.0%	0.6%	73.8%	23.5%	2.7%
Kamatero	70.4%	29.0%	0.6%	87.1%	11.4%	1.5%
Kifisia	89.3%	10.2%	0.5%	92.7%	6.5%	0.8%
Metamorfosi	79.2%	20.6%	0.2%	82.1%	16.2%	1.6%
Chalandri	89.0%	10.9%	0.1%	95.4%	4.5%	0.2%
Thrakomakedones	81.8%	18.2%	0.0%	58.5%	36.3%	5.1%
Total	80.6%	19.0%	0.5%	85.0%	12.4%	2.6%

Although satisfactory from an engineering point of view, it should be noted that the losses predicted by the AUTh model underestimate the percentage of actually incurred heavy damage (‘Red tag’), while predicting higher percentages of moderate damage (‘Yellow tag’) (see Table 4.1). This can be at least in part be attributed to possible underestimation of the actual PGAs (a fact also acknowledged by the colleagues that developed the seismic scenario in the framework of the MASSIVE project) due to - difficult to model-predominant directivity effects in the meisoseismal region during the 1999 Athens earthquake. It must be stressed in this respect that in a previous study by Kappos et al. (2007) concerning this region but using other earthquake scenarios characterised by PGA values substantially higher than those assumed herein, higher losses were predicted. Near-field phenomena can increase the acceleration in Municipalities like Ano Liosia or Thrakomakedones that are close to the epicentre of the 1999 earthquake.

Furthermore, given the inherent probabilistic nature of the methodology, it should be noted that it is more appropriate to consider the results on a larger building conglomeration unit (e.g. neighbourhood) since damage states associated with low probability are missed if the number of buildings is very limited. On the other hand, it should be taken into account that the ‘actual’ results correspond to the first degree inspections carried out after the 1999 earthquake which always suffer from the over-conservatism typical to emergency situations, tending to increase the recorded level of damage; as a result during the 2nd, more comprehensive, degree of the survey, a portion of the ‘Red’ tagged buildings are typically moved to the ‘Yellow’ tag.

In order to validate the results for the L’Aquila case study, building damage data of the 2009 earthquake were used. The data was available from the post -earthquake usability evaluation carried out by SGE - Struttura per la Gestione dell'Emergenza adopting the following scheme (Fig. 4.3) and provided to us by the partner PLANETEK Italia.

A) USABLE	Building can be used without measures. Small damage, negligible risk for human life.
B) USABLE WITH COUNTERMEASURES	Building is damaged, but can be used when short term countermeasures are taken
C) PARTIALLY USABLE	Only a part of the building can be safely used
D) TEMPORARILY UNUSABLE	Building to be re-inspected. Unusable until the new inspection.
E) UNUSABLE	Building cannot be used due to high structural, non structural or geotechnical risk for human life. Not necessarily imminent risk of total collapse.
F) UNUSABLE FOR EXTERNAL RISK	Building could be used, but it cannot due the high risk caused by external factors (heavy damaged adjacent or facing buildings, possible rock falls, etc.)

Figure 4.3. Post-earthquake usability scheme in Italy

It has to be noted that no straightforward comparison can be made between structural (fragility curves) and usability (statistical) damage states. For example, when trying to correspond the Italian usability scheme to the familiar Green-Yellow-Red tagging scheme, it can be seen that the last category (F. Unusable for external risk) actually corresponds to a building with no damage in itself but which cannot be used due to external factors (e.g. damaged adjacent buildings); therefore, this is actually structurally "green-tag" building. Based on this remarks, it is reasonable to assume that usability categories A and F correspond to structurally "green" buildings, categories B, C and D to "yellow" and category E to "red" (leading to a 44.1% "green" – 18.3% "yellow" – 37.6% "red" distribution, as shown on Table 4.2). Use of the Italian fragility curves in the developed methodology predicts a 66.3% "green" – 18.5% "yellow" – 14.6 % "red" distribution, see Table 4.3, while use of the AUTH/EPPO-ITSAK curves leads to a 26 % "green" – 43.4% "yellow" – 30.5 % "red" prediction, as seen on Table 4.4. Noting once more that the comparison between the percentages of buildings assigned to each damage or usability state can only lead to indicative conclusions, it is nevertheless noted that use of the AUTh/ EPPO-ITSAK fragility curves lead to an overall better prediction of the anticipated damage, especially for the high-damage ("red-tag") state.

Table 4.2. Statistical usability damage data (SGE)

	A	B	C	D	E	F
Number of buildings	4031	1661	217	33	3943	585
Percentage	38.5%	15.9%	2.1%	0.3%	37.6%	5.6%

Table 4.3. Predicted tagging of buildings using the Italian (Rota et al.) fragility curves

	DS0	DS1	DS2	DS3	DS4	DS5
Number of buildings	3547	4213	1085	1057	641	1060
Percentage	30.6%	36.3%	9.4%	9.1%	5.5%	9.1%

Table 4.4. Predicted tagging of buildings using the Greek (AUTh/EPPO-ITSAK) fragility curves

	DS0	DS1	DS2	DS3	DS4	DS5
Number of buildings	333	2686	2241	2802	858	2683
Percentage	2.9%	23.1%	19.3%	24.1%	7.4%	23.1%

5. CONCLUSIONS – DISCUSSION

It should be emphasized that since the building stock data gathered from the 2001 national censuses in Greece and Italy were used, the transferability of the model to other areas of these two countries is straightforward, assuming that the required data is available in the same format. In order to use this model for other case studies, it is essential to verify that data for the building stock are provided in a compatible format and that the building classification adopted herein is able to describe the seismic performance of the existing building typologies; otherwise a new set of fragility curves has to be added.

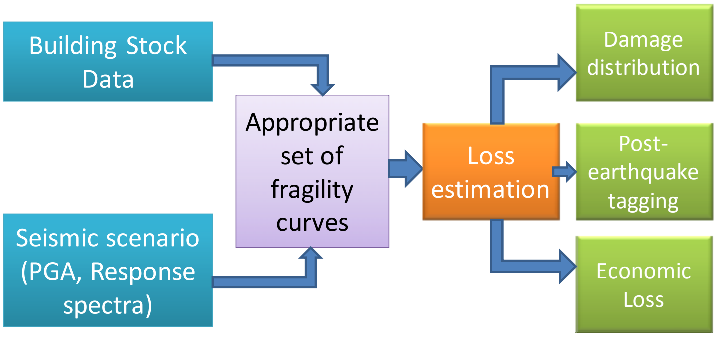

Figure 5.1. The AUTh/ EPPO-ITSAK loss estimation procedure scheme

The overall scheme of the applied procedure is presented in Fig. 5.1. One of the strengths of the proposed methodology is that its algorithms can easily be integrated into a software application that can automate the procedure and furthermore can be implemented within the ArcGIS environment, as it was actually done in the MASSIVE project. Among possible improvements of the methodology one can mention the further calibration of the fragility curves based on future data of observed seismic damage in the various structural types, as well as use of more sophisticated finite element building models (eg. 3D models that take into account torsional effects) for the analytical estimation of the fragility curves. A follow-up of the implemented methodology may include its use for the estimation of expected economic loss and of expected injuries or deaths during an earthquake, and the combination of its results with other methodologies for identifying critical evacuation or emergency routes etc. In conclusion, the developed methodology can be a valuable tool for all local or national authorities that are responsible for the mitigation of earthquake effects on the citizens and the built environment.

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