Use of seismic assessment methods for planning vulnerability reduction of existing building stock

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SUMMARY:
Reducing building stock vulnerability is an essential step towards reduction of seismic risk. Large-scale assessment methods are praised by decision-maker for assessing building stock as they are not expensive and easy to use. However their employment is still controversial in France as their primary objective is frequently forgotten. Some methods are herein tested on two seismic databases by comparing predicted to recorded building damage. In that way, decision-maker can perceive the balance between assessment method accuracy and their final decision on a building stock. The first database is quite homogeneous, with two typologies of reinforced concrete structures. The second one is less complete but more varied which gives the possibility to adopt a building manager viewpoint.

Keywords: vulnerability assessment, damage databases, L'Aquila earthquake, Düzce earthquake

1. INTRODUCTION

With the noteworthy exception of the Guadeloupe and Martinique islands in the Caribbean region, France is a low to moderate seismic country. The last damaging earthquake took place in 1909 in the Lambesc region of South of France. With time going by without major earthquake, vigilance towards seismic risk can easily decrease, although vulnerability of the building stock remains high. Moreover, human and financial resources employed to reduce seismic risk cannot be as high as in some high seismicity regions. Global seismic assessment methods thus seem to be of particular interest to determine at a lesser cost global vulnerability and even try to set priorities for intervention.

In France, national authorities can contribute to reduce risk at municipality level through the enforcement of "seismic risk prevention plan". This regulation tool not only defines local hazard at a smaller scale than the national zonation map (microzonation) but also has an existing building section which can enhance national regulation, prescribe seismic assessment of individual or groups of buildings and even prescribe actual reinforcement within some financial limits. However, this section is still very controversial, in particular with the emerging use of vulnerability assessment methodologies to define which building should be primarily assessed. A similar situation arises for the State which has begun to prioritize assessment within its own building stock.

To help national authorities better understand the possible uses, aims and limits of global assessment methodologies, a dozen international methodologies have been dissected, looking for similarities and differences in terms of building typologies, vulnerability characterization, uses, scale levels… Some common methods are then tested on two post-earthquake damage databases. Predicted and recorded damages are each time compared.

2. SEISMIC ASSESSMENT METHODOLOGIES

The professional is confronted with dozens of seismic assessment methodologies which differ in objectives, application field, etc. Study of the hypotheses and parameters taken into account to evaluate vulnerability or damage shows that the main classical methodologies are often connected to their development context, in particular building typologies and intended purpose (Chever, 2010). Several classifications of vulnerability assessment methods have been proposed in literature. Italian GNDT suggests four distinct classifications according to vulnerability expression form (vulnerability index, damage estimate without intermediate variable), typology of result (literal expression of damage, value of mean damage, probabilistic method), method development (created from earthquake damage databases, expert opinions, analytical studies) or description of building (GNDT, 1993). Calvi *et al.* (2006) suggest a first classification between empirical and analytical methods before focusing on the result type.

Looking exclusively from an operational way, building managers mainly see assessment methods as a mean for an objective often directly related to an analysis scale, roughly:
- large-scale vulnerability assessment as in an earthquake scenario or a vulnerability analysis on a whole town,
- screening of buildings or prioritization on a medium-size building stock for a property manager,
- first estimate of an individual building vulnerability (the method then often provides with a simple analytical evaluation).

Boundaries between these three objectives are sometimes quite vague and temptation is strong to use a global assessment methodology for another purpose that the one it was originally created for. Methodologies using vulnerability index are often concerned because of their simplicity and their low cost. Table 2.1. gives the most common methods used in practice according to scale analysis and objective of the property manager. Methodologies coming with a small star * are those used out of their initial objective.

Table 2.1. Damage assessment methodologies according to their analysis scale and objective

Analysis scale	Thousands of buildings	Few hundred to few dozens	Individual building
Objective	Large-scale vulnerability, earthquake scenario	Screening, prioritizing into a building stock	Rough first estimation of individual vulnerability
Methods	ATC13 EMS98 DBELA GNDT level I GNDT level II HAZUS vulnerability model Risk-UE LM1 Risk-UE LM2 Vulneralp	AFPS (2001) ATC21 FaMIVE FEMA154 GNDT level II* IEB New Zealand JBDPA Japan NRC-CNRC OFEG level 1 Risk-UE LM1* VC/VM procedure Italy Vulneralp* Vulnus	JBDPA Japan FaMIVE* FEMA310 VC/VM procedure Italy Vulnus*

To give to the decision-maker an estimation of the adequacy of a method to meet his purpose and link the inherent level of uncertainties to the impact of the political decision, some methods are compared to damages observed after two earthquakes. The first damage database contains buildings from a very homogenous typology. The second one, smaller, contains buildings with mixed typologies. The methods tested out are those for which sufficient data are available without need of excessive approximation. Large-scale vulnerability assessment and screening of buildings are the two objectives tested for.

3. SEISMIC ASSESSMENT OF AN HOMOGENEOUS BUILDING STOCK

3.1. Seismic event and associated database

In November 1999, a powerful M_W 7.1 earthquake struck the city of Düzce (Turkey). Peak ground accelerations were closed to 0.5 g in the city centre as measured by the DZC station (PEER database). Three months earlier, a devastating M_W 7.4 earthquake had occurred in Izmit, approximately 100 km west of Düzce, weakening some buildings in the latter city. The cumulative effects of the two earthquakes correspond to a macroseismic intensity IX-X in Düzce, without possibility to clearly uncoupled consequences of each event (Lekkas, 2000).

The structural engineering research unit of Middle East Technical University (Ankara, Turkey) created a comprehensive database of 484 buildings damaged to various degrees in Düzce. Two building typologies are represented making the database quite homogeneous:

- Reinforced concrete frames with masonry infill (77% of database), mainly 3 to 5 stories structures built between 1975 et 1996,
- Reinforced concrete dual systems (33% of database), higher and built more recently.

The database includes various parameters as the number of stories or irregularity types both in plan and in elevation according to the classification adopted by the Turkish seismic specifications for structures (Republic of Turkey, 1998).

3.2. General hypotheses

Building damage level is estimated on the state of the reinforced concrete frames and walls with no information on the behaviour of masonry infill. Table 3.1 gives the equivalence adopted between the database and EMS 98 damage scales.

Table 3.1. Equivalence between damage scales

METU damage scale	ATC13 scale	EMS 98	Building ratio
N – none	None	Grade 1 + no damage	12.6%
L – light	Slight + light	Grade 2	31%
M – moderate	Moderate	Grade 3	31.2%
S – severe	Heavy	Grade 4	12%
C/R – collapsed or removed	Major + destroyed	Grade 5	13.2%

All seismic assessment methods take into account seismic codes being in force at the time of construction. This parameter has to be adapted to local context as progress in seismic design can be different from the country where the method has been developed. In Turkey, three main dates punctuate seismic codes progress. In 1940, seismic action is taken into account in structural design for the first time. In 1975 seismic detailing requirements are improved to achieve better ductile behaviour. Seismic code based on capacity design is implemented since 1997.

Soil consistency is always a difficult parameter to assess in vulnerability evaluation. In Düzce town centre, damages are widespread and quite homogeneous, which would indicate a rather uniform soil (Ramirez *et al*, 2000). Inspections on two sites reveal deep deposits of stiff clays with interbedded layers of dense sands and gravels. Shear wave velocity $V_{s,30}$ in the upper 30 m of soil measured at DZC station categorized the soil as a ground type C according to Eurocode 8 classification (category D according to FEMA 302, NEHRP Recommended provisions for the seismic design of new buildings and other structures).

The macroseismic intensity according to EMS 98 scale has been re-evaluated on the database with vulnerability class estimation of the buildings inspected by the METU teams. The sample turned out to be representative of a macroseismic intensity IX-X, in spite of a large proportion of collapsed or removed buildings. This large proportion may be explained in two ways: the removed buildings could have been initially partly destroyed (initial Grade 4 instead of Grade 5) or the first earthquake could have weakened some buildings, which would have more probably collapsed during the second earthquake. Consequently, the proportion of R/C damage buildings is quite high compared to severely damaged buildings.

3.3. Large-scale vulnerability assessment

Large-scale vulnerability assessment is carried out on the database using four different vulnerability assessment methodologies and, if needed, taking into account an intensity IX and an intensity X.

The ATC 13 methodology (ATC 13, 1985) gives damage probability matrices based on expert judgments for 40 Californian structural typologies. Three typologies are used to describe the Düzce database: reinforced concrete dual system, ductile frame for structures built after 1975 and non-ductile frames for the others. The additional parameter, namely the number of stories, is directly available in the database. Risk-UE LM1 methodology (Milutinovic and Trendafolsky, 2003) developed within the European project "An advanced approach to earthquake risk scenarios with application to different European towns 2001-2004" is derived from the European macroseismic scale, where vulnerability assessment is refined. A building vulnerability matrix consistent with European building stock is defined and known vulnerability factors must be checked. The Düzce database buildings are ditributed among three typologies: regularly infilled RC frames for buildings witout any of the irregularities pointed out by the Turkish seismic code, irregular RC frames and RC dual systems. The database does not account for all the parameters of Risk-UE LM1. Bad maintenance, insufficient aseismic joint, soil morphology or foundation typology are left blank. Vulneralp method (Guéguen, 2007) is an adaptation of Italian GNDT methodology level II (GNDT, 1993) to assess seismic vulnerability of typical metropolitan French typologies. Like its Italian counterpart, Vulneralp 1.0 takes into account the structural type, time of construction, soil morphology and constitution, number of stories, irregularities in plan and in elevation, roof type and aggregate building. Some of these parameters are not present in Düzce database and are consequently not accounted for in the predicted distributions.

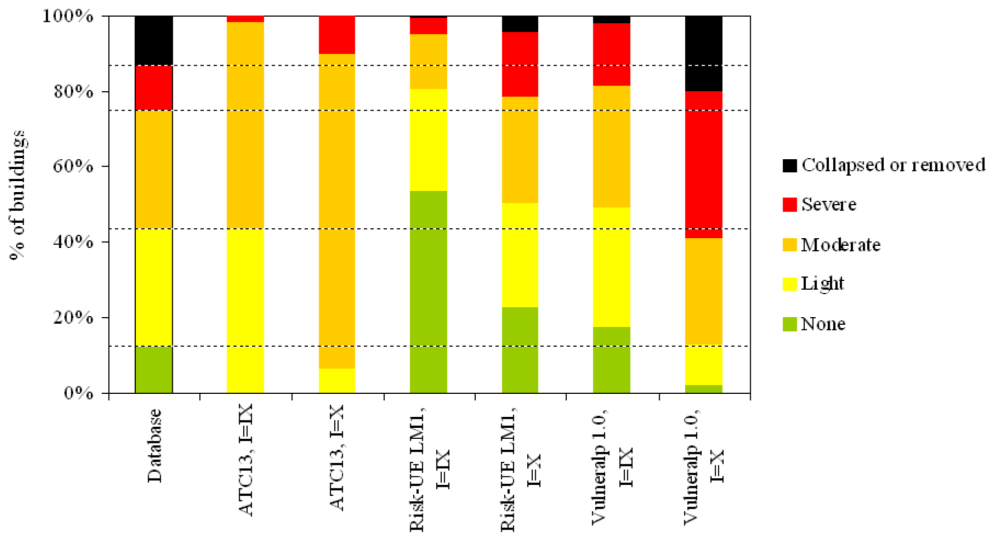

Figure 3.1. Comparison between database, ATC13, Risk-UE LM1 and Vulneralp damage distributions

Risk-UE LM2 is the second assessment methodology developed within the Risk-UE project. Unlike the first, Risk-UE LM2 follows HAZUS conceptual framework (FEMA, 2003) deriving capacity and fragility models from analytical studies. Unfortunately, the models have not been derived for the entire European building typology matrix. Only the reinforced concrete moment frames, with a level of seismic protection defined as moderate code or high code, are available for complete calculations. Therefore, the database considered has been reduced to the 299 – 4 to 7 stories frame structures built after 1975. The moment frame typology is not the best suited for this truncated database but is still quite close to the real typology. The spectrum taken into account is the regulatory spectrum for the

Düzce region given by the Turkish seismic code (Republic of Turkey, 1998).

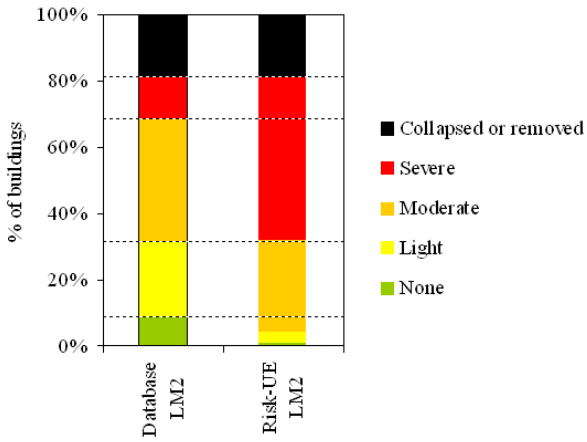

Figure 3.2. Comparison between database and Risk-UE LM2 damage distributions

As seen in Fig. 3.1., the damage distribution of Düzce database cannot be satisfactorily estimated by ATC13 neither considering an intensity IX nor X. The standard deviation is too low to account for the dispersion of the distribution. Risk-UE LM1 gives satisfactory results considering an intensity X, with less than 15% error on the predicted distribution. The number of collapsed buildings is underestimated, which is coherent with the first analysis of the collapsed-removed part of the database. Vulneralp gives also a good estimate of the damage distribution but for an intensity IX. This discrepancy in intensity has already been mentioned by (Guéguen, 2007). Considering Fig. 3.2., Risk-UE LM2 overestimates the damages by one level of damage, considering the Turkish code spectrum. However, the relative distribution remains quite correct.

3.4. Screening possibilities

Some methods are specifically designed to screen the existing building stock so as to identify the safest buildings or, on the contrary, the ones which need immediate detailed seismic assessment because of a high risk. FEMA 154 is one of these methods: it is a parametric test with the parameter S "final structural score" being an estimate of the probability that the building is a threat to human life (threshold S=2). For data analysis, it has been considered that a building with severe damage (S) or collapsed (C/R) is a realization of the hypothesis. The assessment method is considered successful if the error of the first kind is minimum (all buildings classified as risk free are correctly built) and if the error of the second kind is kept quite low (a structure correctly built is not classified as dangerous).

Dual systems are not taken into account in FEMA 154 typologies, consequently two hypotheses have been made to describe the database. The first hypothesis is that all buildings are considered as reinforced concrete frames with masonry infill. The second one states that the frames with masonry infill are simple frames and that the dual systems are reinforced concrete shear wall structures.

Table 3.2. Screening with FEMA 154 methodology

	Data		First hypothesis		Second hypothesis	
	Evaluation needed (S<2)	Acceptable risk (S>2)	Evaluation needed (S<2)	Acceptable risk (S>2)	Evaluation needed (S<2)	Acceptable risk (S>2)
Risk for human life (S or C/R)	25.2%	0%	25.2%	0%	17.4%	7.8%
No risk (N, L or M)	0%	74.8%	74.8%	0%	59.7%	15.1%

In the first hypothesis, the test is not discriminant at all and all buildings would have to go through a detailed analysis. Actually, in the FEMA 154 method, the score S of RC frames with masonry infill are always be below the threshold, whatever the score modifiers, for high seismicity zones. In the second hypothesis, the error of the first kind is limited but 71.7% of the database would need a detailed analysis. The test is not discriminant enough, consequently not adapted to the Turkish context.

Prioritizing detailed assessment of buildings using the predicted mean damage or the vulnerability index from the Risk-UE LM1 or the Vulneralp methodologies is also not conclusive. For example, 40% of buildings without any structural damage after the Düzce earthquake receive a mean damage between Grade 3 and Grade 4 on EMS 98 scale when applying Risk-UE LM1. Moreover, nearly 19% of buildings which actually collapsed or were removed end up with a mean damage grading of 1 or 2. It is not thus possible to screen an homogenous database with these large-scale methods.

4. SEISMIC ASSESSMENT OF AN HETEROGENEOUS BUILDING STOCK

4.1. Seismic event and associated database

Following the April 2009 L'Aquila earthquake, a reconnaissance team from the CETE Mediterranée created a small database of buildings in the area affected by the earthquake. Description of the structure and its environment consists of the usual parameters such as global geometry, nature of vertical elements, regularity in plan and elevation, topography etc. 68 forms were enough detailed to be usable for vulnerability assessment. Unlike the Düzce database, the Italian database is quite heterogeneous: a wide range of building construction time is represented as well as various construction material (28% masonry, 66.2% reinforced concrete and, to a lesser extent, 2.9% steel and 2.9% wood structures). Damage distribution, estimated on EMS 98 scale, is shown in Fig. 4.1.

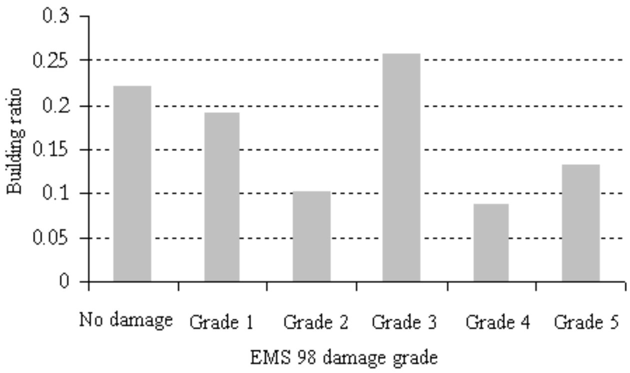

Figure 4.1 L'Aquila database damage distribution

Considering the sample size, the stock cannot be considered as statically representative of the global damage suffered by the region. A large-scale analysis cannot be carried out like for the Düzce database. However, the sample is large and varied enough to look at it from a property manager perspective, who wants to prioritize his action for seismic risk reduction. In the French regulation context, it can also be representative of the necessary screening of buildings when establishing the existing building section of a town seismic risk prevention plan.

4.2. General hypotheses

Soil consistency knowledge is essential to correctly use seismic assessment methodologies. This element is really essential in the L'Aquila database as many authors have mentioned site effects in the alluvial Aterno valley. Macroseismic intensity estimates have been taken as established by the INGV and the Italian civil protection (Galli et al, 2009). Seismic intensity on the MCS scale reached IX in some villages of the Aterno valley. Finally, seismic code progress has been studied to draw periods with globally known seismic performance of buildings. L'Aquila region is identified as seismically active since the beginning of last century. Seismic regulation and zonation maps have been updated frequently, often following large earthquake events.

4.3. Comparison with Vulneralp method

Vulneralp methodology is here not employed as first intended by its author but to try to set priorities within the sample. Comparison with observed damage is made on the vulnerability index as it has been done in some French field studies and on the estimated mean damage. Fig. 4.2. gives for each observed damage grade the maximum, minimum, upper quartile, lower quartile, median and mean values of the calculated vulnerability indices and of the estimated mean damage.

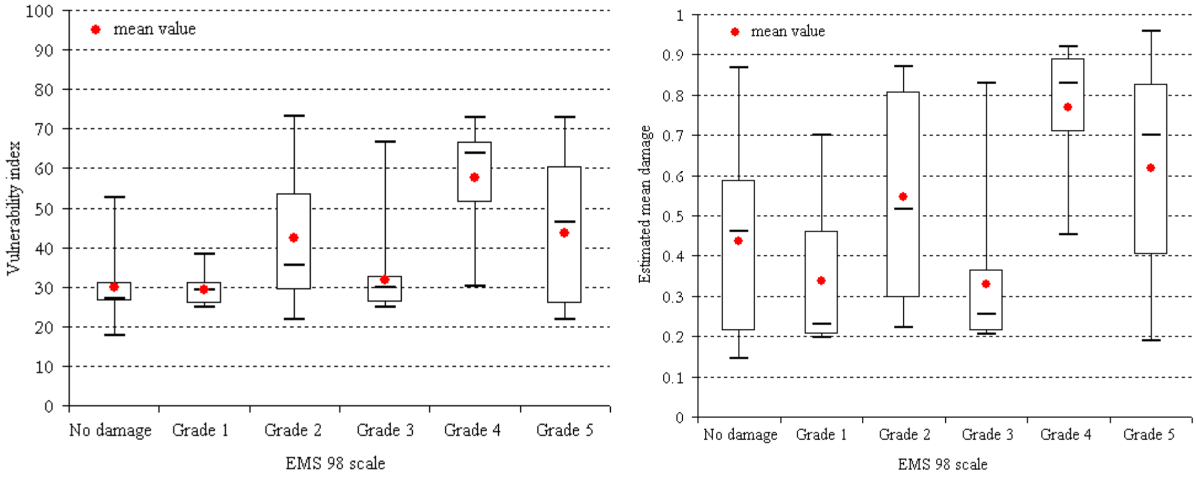

Figure 4.2. Distribution of calculated vulnerability index and mean damage according to observed damage (Vulneralp methodology)

Contrary to what could be expected, vulnerability index mean values do not clearly increase with observed damage levels. Similarly, when looking at estimated mean damages, the results are even more disparate although the hazard is better taken into account through modulation of macroseismic intensities. These discrepancies, in particular on Grade 5, are not compatible with a prioritization of buildings on this only criterion.

Detailed analysis of results show that estimated damage of weakly damaged buildings is often surestimated whereas Grade 2 and Grade 4 are correctly predicted. The majority of hazardous buildings is however not detected which prevents from using Vulneralp methodology for screening.

4.4. Comparison with Risk-UE LM1 method

Like Vulneralp methodology, Risk-UE LM1 is tested for its capacity to set priorities in a building stock. In the same manner as Fig. 4.2., Fig 4.3. compares vulnerability indices, predicted mean damage and observed damage.

Vulnerability index means roughly increase with observed damages. The dispersion is low for Grades 0, 3 and 4. Adequacy of observed damage with predicted damage is less effective. Damage of Grade 3 buildings is largely underestimated and dispersion for Grade 5 buildings is high. However, unlike Vulneralp methodology, Risk-UE LM1 seems to allow for small level of damage, making perhaps screening for the safest buildings possible. To confirm this hypothesis, the estimated vulnerability indices are classified into three priority classes with the aim of screening out Grade 1 and undamaged buildings. Two vulnerability threshold values are chosen. The low priority class is defined as the group of buildings with a vulnerability index implying no damage or Grade 1 damage for an intensity IX (V_I=0.401). The high priority corresponds to a Grade 4 or Grade 5 damage level for an intensity IX (V_I=0.731).

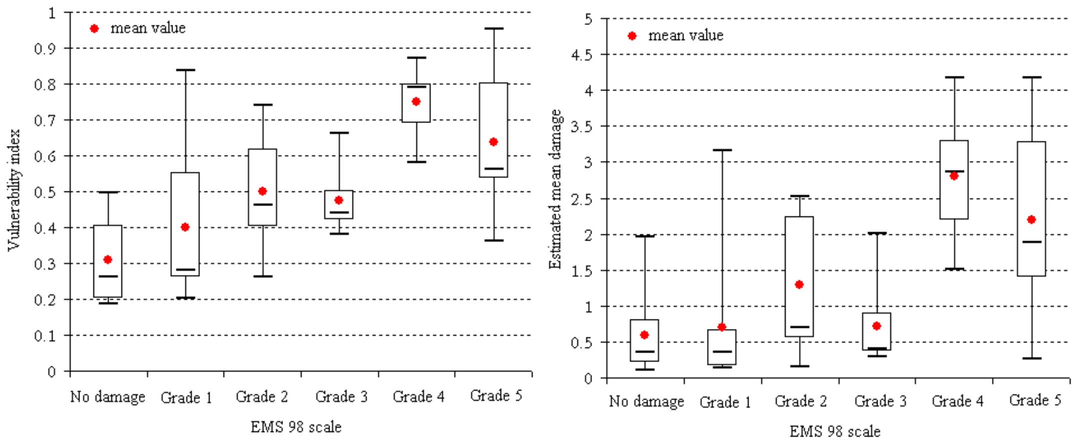

Figure 4.3. Distribution of calculated vulnerability index and mean damage according to observed damage (Risk-UE LM1 methodology)

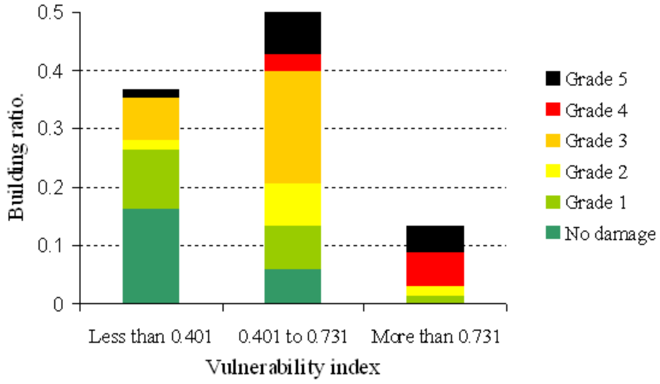

Figure 4.4 Building prioritization with thresholds values V_I = 0.401 and V_I = 0.731

The low priority class sorts only 73% of observed undamaged buildings and 54% of Grade 1 buildings. One Grade 5 building shows up in the low priority class. Risk-UE LM1 is consequently not designed for screening.

4.5. Comparison with FEMA 154 method

In the same way as for Düzce database, unsafe buildings are considered to be Grade 4 and Grade 5 buildings. They should be pointed out by screening through FEMA 154 methodology. Two hypotheses have been tested out. In the first, all Italian reinforced concrete frame buildings with masonry infill are considered as typology C3 in FEMA 154 i.e. their actual typology. In the second hypothesis, the buildings are considered as simple frames (typology C1 of FEMA 154).

Table 4.1. Evaluation of the Italian database with FEMA method

	Data		First hypothesis		Second hypothesis	
	Evaluation needed (S<2)	Acceptable risk (S>2)	Evaluation needed (S<2)	Acceptable risk (S>2)	Evaluation needed (S<2)	Acceptable risk (S>2)
Risk for human life (S or C/R)	22.1%	0%	20.6%	1.5%	20.6%	1.5%
No risk (N, L or M)	0%	77.9%	52.9%	25%	36.8%	41.1%

In the first hypothesis, the error of the first kind is kept low but the error of second kind is too high:

detailed assessment would be necessary for nearly 73% of the sample, although the actual observed damage calls for 22.1% of detailed seismic analyses. The second hypothesis tries to minimize this error: false positive are reduced but 57.4% of the stock would have to be checked. FEMA 154 methodology indicates that it is possible to use final scores for drawing intervention priorities. Classifying by increasing S is not conclusive, as two collapsed buildings would have a low priority.

4.6. Comparison with OFEG level 1 method

The objective of OFEG level 1 method (OFEG, 2005) is to classify buildings into four groups of decreasing priority, taking into account not only structural vulnerability but also associated losses (building facilities and uses, economical loss).

When keeping the threshold values recommended by OFEG (WZ=65 related to collapse probability and RZPS=500 related to seismic risk), 46% of buildings are ranked in the top priority group, nearly all the other ones being in priority groups 3 and 4. Discrimination of priority 4 is very well done as it comprises 75% of undamaged or Grade 1 buildings. However, more than a third of Grade 3, 4 and 5 buildings are not in the top priority group. Looking more precisely into the database, it appears that this sorting is not due to a poor seismic vulnerability evaluation but to lower issues at stake. The RZPS threshold value has consequently been modified to RZPS=200 to achieved a better distribution of buildings within the four priority classes. 84% of Grade 3, 4 and 5 buildings are now in the top priority class. However, the discriminatory power of the method is lessen, as 58% of the buildings are in priority 1 compared to 46% in the first hypothesis.

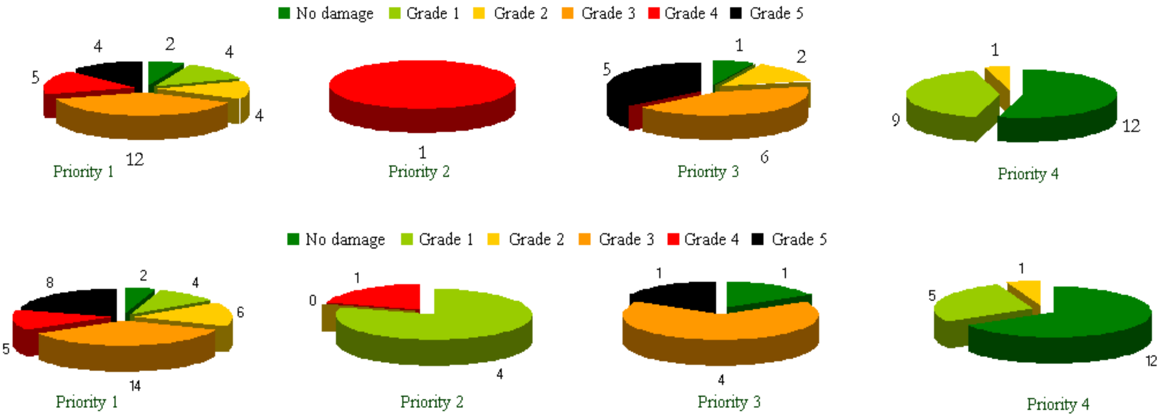

Figure 4.5 Observed damage level according to priority class for threshold WZ = 65 (up) and threshold RZPS = 200 (down)

5. CONCLUSION

Comparison between observed damages from two seismic databases and predicted damages from commonly used global assessment methodologies allows to point out precautions to be taken when using them for decision-making.

Four global assessment methods and one screening method have been tested on the Düzce earthquake database (SERU, 1999). United-States typologies taken into account in ATC 13 or FEMA 154 do not entirely match the behaviour of Turkish buildings. Risk-UE LM1 seems to be the most suitable method to predict the damage distribution in the sample. No method has been able to perform a correct screening. The need of building typology adaptation to local context is thus a major issue. Numerous methods are indeed specifically developed on the typologies represented in Düzce database, like the discriminant function analysis performed by Özcebe et al (2003) showing that the most important factor to explain damage is in fact the number of storeys.

The Italian database was studied exclusively from a decision-maker standpoint, who would be responsible for a limited number of buildings and who would have to draw priorities on his stock. The methods which use vulnerability index have shown their limits as screening methods. In the present state, they cannot prioritize between buildings with enough reliability to plan massive field operational use. OFEG level 1 method draws attention to other possibilities for building manager i.e. taking decisions not only on simple vulnerability but also into on potential functional and economical losses.

This study allows the decision-makers to grasp the degree of precision that can be expected from the different uses of global assessment methods and the impact of taking into account more than simple structural vulnerability to set priorities on an existing building stock. Such conclusions are of particular interest for the first seismic assessment of French State buildings, which has begun in 2011.

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