Assessing the residual capacity of buildings for post-earthquake asset management at urban scale

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key words: seismic vulnerability assessment, urban-scale vulnerability mapping, post-earthquake assessment, damage distribution, seismic resilience

Abstract

Among the various natural hazards, earthquakes remain a major source of human casualties and economic losses. It is a well-known fact that earthquakes do not kill people; buildings that collapse during earthquakes kill people. Thus architects, civil engineers and urban planners should work in the way of transforming existing cities into resilient systems that are able to withstand seismic events with the least possible losses. Two main challenges regarding seismic resilience at urban scale are related to determining seismic vulnerability prior to earthquakes as well as real damage suffered and residual capacity following a seismic event.

Ambient-vibration measurements (AVM) are a non-destructive data source that, together with standard visual inspections, have potential to improve the efficiency and the accuracy of seismic vulnerability assessment of towns. In the pre-earthquake phase, AVM can help in the detection of the real seismic behavior of structures and in the modeling of existing building classes especially in regions with very limited observational data after significant damaging earthquakes. In the post-earthquake phase, AVM can provide information about the real damage suffered and the future damage in case of an aftershock. A methodology for the up-scaling at urban scale of data collected on the various building classes and their damage assessment is proposed and the applicability of clustering buildings is assessed, showing high potential.

1. INTRODUCTION

Earthquakes are natural hazards that continue to cause a high number of casualties and important economic losses (UNISDR, 2013). Earthquakes do not kill people, buildings do. Transforming existing cities in earthquake-resilient systems should be the main objective for researchers in the field of seismic analysis and assessment of entire towns and cities. Providing means for realistic disaster risk scenarios can help decision makers in planning proactive and/or reactive action schemes to improve the resilience of urban systems and save lives and goods. Two main challenges regarding seismic resilience at urban scale are related to determining seismic vulnerability before earthquakes and residual capacity following a seismic event.

In this context, ambient-vibration measurements (AVM) present an interesting and non-destructive tool to address the two main challenges. Such a data source can help in the identification of the real seismic behaviour of structures in regions with very limited construction data prior to an earthquake. Additional measurements – after the seismic shock – provide information related to the extent of damage and thus, the safety for occupancy of damaged buildings.

The recent seismic events that hit Italy in 2016 underlined once again the importance of some relevant issues: the earthquake management, the assessment of damages suffered by buildings and the assessment of the related safety for occupancy. Combined, these issues carry a primordial importance, especially in case of seismic sequences that are characterized by a series of violent events (shock followed by several aftershocks) rather than in the case of seismic sequences characterized by a main shock followed by much less violent events.

In the case of the Central Italy Earthquake in 2016, from the 24th of August 2016 (the date of the first shock, epicenter Accumoli and Magnitude equal to 6.0) to the 28th of April 2017, around 65 500 events have been recorded (of which 3 500 with Magnitude greater than or equal to 2.5). In this timeframe, nine events were greater than or equal to a magnitude of 5.0. During the aftershock of the 30th of October 2016, epicenter Norcia, a magnitude equal to 6.5, greater than the first shock, was recorded[1].

In the case of considerably important aftershocks, the post-earthquake management plays a highly important role and concerns both the first aid and the assessment of safety for occupancy of damaged buildings (followed by a possible reconstruction phase).

During the 2016 Central Italy Earthquake, even though many buildings resisted to the first shock on the 24th of August 2016, they were unfortunately destroyed during the October aftershock. In this context, a sad example is the San Martino Church in the hamlet of Moletano (Amatrice). After the first shock, the church was seriously damaged; especially in the main façade, in the wall of the altar and in some roof elements (Figure 1). The presence of tie rods avoided the overturning of longitudinal walls and the related collapse of the wooden roof. Unfortunately, despite the in-depth inspection set up by the National Board for Cultural Heritage[2] few days after the first shock, the classification of the church and the design of temporary safeguard interventions (that were never realized), the church collapsed during the aftershock.

This underlines how, after a first event, shocks of the same amplitude (or even higher as in the case of Centre Italy Earthquake) could result in further damages and worsen already critical situations.

Determining the intensity and the frequency content of an aftershock in advance is undermined by the unpredictable nature of seismic hazard. The case of the seismic event of the 30th October 2016 in Norcia is a clear evidence. The frequency content of the seismic event recorded in the station in the historical center of Norcia was largely different from the frequency content recorded in the station outside the town. In the city-center, the frequency content was particularly high in the low frequency range (between 0.5 and 2.0 Hz). Therefore, low-frequency buildings (with a high period of vibration, characterizing flexible buildings) have been hit the most. Indeed, the cathedral (often, monumental buildings have high periods of vibration) has been one of the few buildings in the historical center that was destroyed. The rest of the historical center, composed of low-rise masonry buildings (with a high frequency) reinforced during the 70s' (by welding slabs to vertical walls, by adding reinforced-concrete (RC) slabs, and by constructing RC roofs), suffered no damage. A different frequency content has been registered out-of-town. Here the most prominent frequency range was in the high frequencies (between 1.5 and 5.0 Hz). Accelerations and displacements for high-frequency structures were particularly high if compared to the city center. This fact caused the collapse of several standard residential buildings.

This short focus concerning the frequency characterization of the Norcia aftershock of the Central Italy Earthquake underlines once more how unpredictable earthquakes are. Consequently, safety-for-occupancy assessment of damaged buildings cannot be automatized and cannot be independent or decoupled from visual inspections and expert judgments. In a similar way, post-seismic danger is not only linked to structural failure. Non-structural elements (such as chimneys, roof elements and facades) are potential sources of danger for people in the vicinity of buildings. In a similar way, heavy furniture and non-structural walls can be dangerous for inhabitants of buildings. The overturning of a secondary element, such as a partition between two rooms, may have the same catastrophic consequence for humans as the collapse of a primary element. Such sources of danger, which may kill people as much as the structural collapse, are hard to be identified by automated approaches based on structural measurements such as vibrations or crack detection. This explains the reason why a process of visual inspection cannot be automatized and easily widespread towards large scales.

The process of visual inspection after a seismic event is a key phase for the evaluation of the occupancy of buildings (Rossetto *et al.*, 2010). This process, especially in Italy, follows a clear procedure. A specific form (AeDES) is available (Baggio *et al.*, 2007) and engineers involved in the survey campaign are trained to classify the damaged buildings in different classes (from A to F) in relation to the damage reached. Other national code, as in Switzerland, introduced similar tools (D'urso *et al.*, 2015).

[1] INGV data.

[2] Sovrintendenza per i Beni Culturali.

Figure 1 - *Damages at the altar wall in the San Martino Church (Moletano, Amatrice) after the first shock of the 24th August 2016 [Photo credit: Diana L.]*

A building classified in class A is a building that is considered safe for occupancy while a building classified in class E needs in-depth interventions to recover its original state and to be (re-)considered safe.

However, visual inspection may be prone to subjectivity in the assessment (Galloway *et al.*, 2014; Sheng-Lin *et al.*, 2017) and is a task that involves intensive time demands (Marquis *et al.*, 2017; McEntire and Cope, 2004). Indeed, current approaches of post-earthquake visual inspection generally involve a one-by-one building campaign. All buildings hit by an earthquake are supposed to be surveyed. It is clear that this process is time demanding. Several elements are evaluated for a final judgment: the main structural elements like walls and girders as well as non-structural elements. In addition, after each major aftershock, additional inspections may be required.

Moreover, the final judgment remains a subjective judgment that is highly influenced by uncertainties. The real state of some structural elements often cannot be evaluated in detail. Destructive in-situ tests are time-demanding and not always allowed. In this way, buildings sometimes risk to be misjudged as "safe" for occupancy due to misunderstanding of its real behavior. It is clear that such an error may also be committed the other way round. Furthermore, especially in post-seismic management, this error can afflict entire areas and villages – having important consequences in the reconstruction phase. Finally, it has to be said that visual inspection mainly provides an estimate of how well a building behaved under the earthquake. Thus, few indications can be obtained on how well a deteriorated building will behave under subsequent earthquake actions (Marshall *et al.*, 2012).

Slowness and subjectivity of visual inspection that have been described are incompatible with the need of rapid and accurate decision-making that are required in the aftermath of earthquakes. The perspective of aftershocks adds to the need for quick and informed decision-making. Performing visual inspection of every building requires important time and money resources, and may lead to important needs of temporary housing as well as to reduced economic activities. In addition, cascading effects, such as reduced traffic flows and scarcity of necessary goods that may result from slow inspection rates, reduce the resilience of communities with respect to earthquakes.

Applications of structural-identification techniques have the potential to reduce the subjectivity of post-earthquake assessment as well as to reduce the time between an earthquake and decision-making regarding safety for occupancy of deteriorated buildings. Structural identification leads to a better understanding of model parameters by comparing model predictions and measured behavior (Behmanesh *et al.*, 2015; Goulet and Smith, 2013; Smith, 2016). In case of post-earthquake assessment, structural models that are obtained using structural-identification techniques have potential to provide precise and accurate predictions regarding building behavior under subsequent earthquakes or aftershocks (Reuland *et al.*, 2019a, 2019b).

In this way, ambient-vibration measurements (AVM) present an interesting non-destructive data source to support engineers and complement techniques involved in the survey process. The main goal of AVM is to derive modal properties from acceleration or velocity measurements (vibrations) that result from environmental excitation (such as trains or vehicles and other human activities and natural excitation sources such as wind and micro-tremors). Several techniques exist to derive modal properties from AVM, such as the frequency-domain decomposition (Brincker *et al.*, 2001; Ren *et al.*, 2004).

As AVM are a non-destructive source of information, this tool has encountered increasing interest from the structural health monitoring community (Brownjohn, 2007; Catbas et al, 2013). The link between stiffness and modal parameters resulted in a wide-spread application for damage detection (Dorvash *et al.*, 2014; Fan and Qiao, 2011; Özer and Soyöz, 2013; Roeck, 2003).

In post-earthquake assessment, AVM campaigns cannot replace visual inspection. However, they can be a tool for supporting the final judgment as they provide information related to the overall structural behavior of buildings such as the natural frequencies of vibration. The determination of the real damage grade suffered by a building (e.g. damage grade 2 instead of grade 3) can have important consequences in the final "occupancy" judgment and in the guidelines provided for the reconstruction. It has been shown in the past, that modal properties derived from ambient-vibration measurements are sensitive to structural damage and are thus an indicator of the building condition (Clinton *et al.*, 2006; Vidal *et al.*, 2013; Foti *et al.*, 2014; Trevlopoulos and Guéguen, 2016; Mirshafiei *et al.*, 2017).

Combining AVMs and visual inspection using structural-identification techniques has the potential to improve structural resilience with respect to seismic hazard. Earthquakes are catastrophic events that may occur in seismic regions as well as in areas with a moderate seismicity. Human casualties and economic losses or production interruptions may afflict for several years the economy of entire countries. Urban managers and developers should be provided with tools able to evaluate the resilience of a system. All municipalities should have a clear post-earthquake procedure to be activated if needed. Pro-active or reactive actions should be planned with the optic of a catastrophic event. In this way, in the post-earthquake phase, a clear procedure should be applied. The use of AVMs together with visual inspection may provide also at urban scale a clear information regarding the possible future damage reached by buildings hit by an aftershock, thereby reducing the time lapse and the risk of wrong evaluations. Considering that an automatized evaluation of safe buildings cannot be set, structural identification may help in the assessment of the current behavior as well as in the evaluation of the future damage that buildings hit by an earthquake will reach.

The goal of this paper is to enlighten the reader about how AVM can help the evaluator in the understanding of the real structural behavior of buildings both in the pre-earthquake and in the post-earthquake phase. A clear framework of the various tasks that engineers are asked to complete is presented. In detail, an application for up-scaling from building to city scale the evaluations for reliable urban post-earthquake maps will be shown.

2. METHODOLOGY

Seismic risk assessment at large scale is a very sensitive subject since multiple domains are involved: seismic hazard, exposure and seismic vulnerability (Carreño *et al.*, 2007). In the specific evaluation of seismic vulnerability, several elements should be evaluated and the framework is structured in different phases and goals. As can be seen in Figure 2, the work of engineers in seismic assessment is structured in two separate phases: a pre-earthquake assessment and a post-earthquake assessment.

In the pre-earthquake assessment, the role of the engineer (the evaluator) is to define the damage that buildings are expected to suffer. In the post-earthquake phase, engineers are needed to define the real damage suffered as well as the residual capacity of buildings hit by the earthquake. The residual capacity can be defined as the predicted damage that earthquake-hit buildings are expected to suffer in the case of an aftershock or any future seismic action. In this multiple-objective framework, the work of the engineer during both phases is assisted by structural measurements, such as ambient-vibration measurements (AVM). Indeed, AVM allow engineers to determine some structural features that cannot be directly detected by the means of visual inspections or by behavior-model reconstructions. By applying for instance the Frequency-Domain

Decomposition (FDD) (Brincker *et al.*, 2001), modal properties of a building can be derived from ambient vibrations. Modal properties, such as frequencies and mode-shapes, give insights into the global behavior of structures.

In the following part, we will focus on the different tasks that engineers are face with and have to complete, especially at urban scale, to provide reliable seismic evaluations. The innovative part is related to the use of AVMs for both the determination of structural behavior of building classes (in the pre-earthquake phase) and of the expected damage that already-damaged buildings can suffer during an aftershock (in the post-earthquake phase). Of particular relevance and novelty is the use of selected sample buildings in order to widespread post-seismic evaluation to urban scale. As stated before, time in the post-earthquake management represents a major factor. Developing a methodology for clustering buildings in a rapid way in order to define a small set of representative buildings that can be used to wide spread results at the urban scale can significantly speed up the evaluation process and provide trustworthy maps for expected damage distribution in the case of an aftershock in a short lapse of time. Clustering buildings and then wide spreading the obtained results reduces efficiently the time demand for evaluation at urban scale. The support provided by AVM reduces the subjectivity of the expert judgment as well as the time needed for the judgment since uncertainties concerning damage grade and structural performances may be reduced using data collected by sensors.

2.1 The pre-earthquake phase

The accurate detection of building classes is a key step towards seismic vulnerability assessment at an urban scale. Knowing the real nature of resisting structures helps in determining the possible damage that towns can suffer under seismic events. At global scale, a main

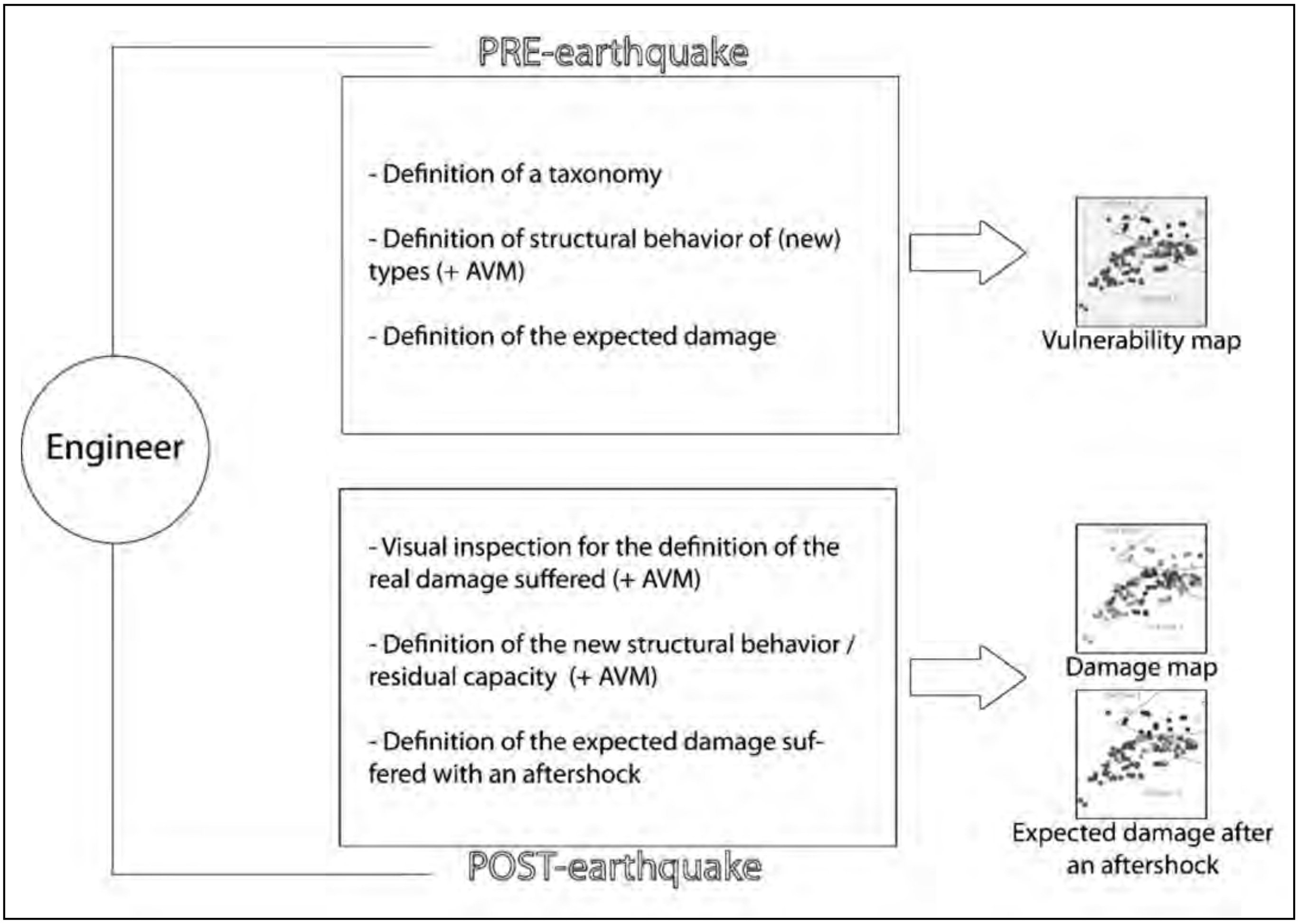

Figure 2 - *The framework of seismic pre- and post- evaluations [credit: Diana L.]*

challenge is related to the variety in building types and construction methods. Several studies have been proposed all over the world in order to assess seismic vulnerability at an urban scale in the pre-earthquake phase (GNDT, 1993; FEMA 178, 1997; Otani, 2000; Onur *et al.*, 2005). Some of them have been proposed in Europe (Lagomarsino and Giovinazzi, 2006). A summary of seismic vulnerability assessment tools can be found here (Diana, 2017).

The first step for reliable seismic vulnerability assessments at urban scale is the classification of the building classes composing the urban system. It is clear that towns are complex systems composed of thousands and thousands of buildings. At territorial scale, the one-by-one evaluation is time and money demanding. Therefore, some simplifications are needed. As a consequence, the definition of a clear taxonomy is an important starting point. Based on the material types, the architectural and load-bearing system of a building, it can be attributed to a given class. All the classes composing the urban system should be introduced and listed. Once the taxonomy and all the classes described by different structural models are defined, a single class should be attributed to each building composing the system. This attribution process is a key phase for pre-earthquake seismic evaluation at urban scale. Also, this classification is the starting point for all kind of evaluations that follow.

In Europe, a taxonomy of existing buildings has been introduced by EMS 98 (Table 1) (Grünthal *et al.,* 2001). Within the framework of Risk-UE project, Lagomarsino and Giovinazzi (2006) have proposed an upgraded version of the original taxonomy. All the structural classes here introduced are adequate to describe the structural behaviour to horizontal loads in seismic prone regions (i.e. southern Europe). However, these classes are not optimal to describe features of other building stocks (e.g. in central and northern Europe) (Diana *et al.,* 2018). An example of building classes that has been introduced for the Swiss building stock can be seen in Figure 3 (on the right). A detailed study on the city of Sion (Switzerland) has shown how the introduction of new classes for the Swiss building stock results in a damage distribution that is clearly moved towards lower damage grades (Diana *et al.,* 2019), as shown in Figure 3 (on the left).

In the pre-earthquake phase, the use of AVM may help in the definition of new structural classes composing the existing building stock. The elaboration of data collected concerning building vibrations under the excitation generated by the nearby environment (no need for any form of actuation) allows the determination of some important structural characteristics. For instance, AVM can lead to an estimate of the mode shapes related to natural vibration modes, which can help the engineer to understand the load-bearing system of a building (Reuland *et al.,* 2015) and the quality of construction materials (Reuland *et al.,* 2017a).

Table 1 - *Differentiation of structures (buildings) into different structural classes (Grünthal* et al.*, 2001)*

Type of the structure
MASONRY
M1 - Rubble stone, fieldstone;
M2 – Adobe (earth brick);
M3 – simple stone;
M4 – Massive stone;
M5 – Unreinforced, with manufactured stone units;
M6 – Unreinforced, with RC floors
M7 – Reinforced or confined
REINFORCED CONCRETE (RC)
RC1 – Frame without earthquake-resistant design (ERD)
RC2 – Frame with moderate level of ERD
RC3 – Frame with high level of ERD
RC4 – Walls without ERD
RC5 – Walls with moderate level of ERD
RC6 – Walls with high level of ERD
STEEL
S – Steel structures
WOOD
W – Timber structures

Collecting structural drawings (of the as-built situation) and generating refined 3D numerical models, together with the information gathered from AVM, allows the identification of real structural behavior of existing building. Methods used at the design stage are often over-conservative and therefore, cannot be used to assess existing structures.

Finally, the structural behavior of the structure under horizontal loads can be described by a capacity curve, where horizontal spectral displacement at the top of the structure is related to the horizontal shear strength at the base, expressed in terms of spectral acceleration (Figure 4). As can be seen in Figure 4, every point of the capacity curve defines a well-defined damage grade (DG). DGs range from 1 to 5, as stated by EMS98, where DG 1 characterizes slight damage and DG 5 is for the collapse.

The definition of capacity curves is one of the main factors for reliable damage predictions in seismic vulnerability analysis at territorial scale. When applied on a large scale, capacity curves should be representative of a wide range of buildings in the classes where material parameters, geometry and drift capacity of bearing elements are random variables. Therefore, several buildings of the same class should be surveyed and measured. Dispersion of random variables is compatible with the variability of characteristics of buildings in the

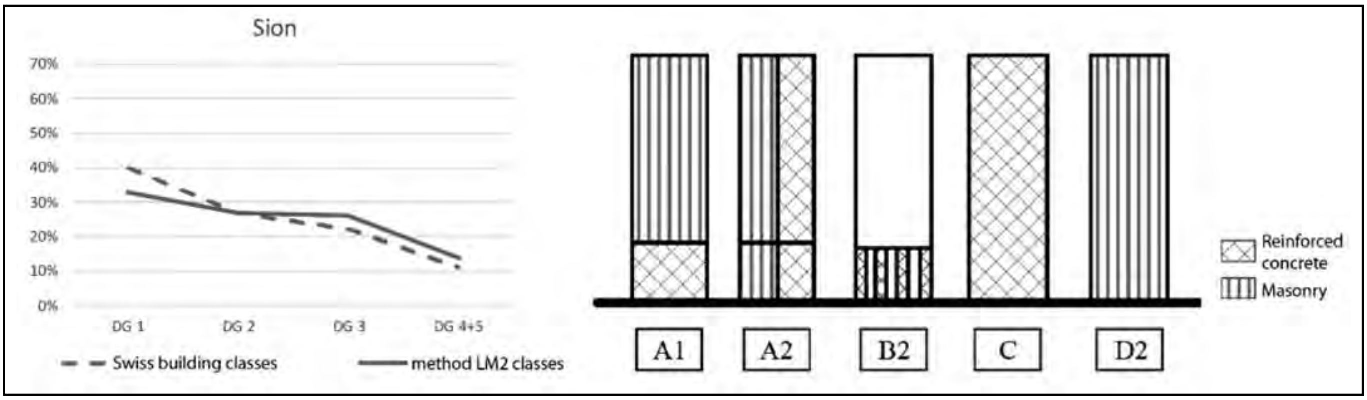

Figure 3 - *Comparison of the damage distribution obtained for Sion using the standard classes of Risk-UE project (Lagomarsino and Giovinazzi, 2006) and after introduction of new Swiss building classes (on the left); The five new Swiss building classes introduced for the city of Sion (Diana et al., 2018a and 2018b) (on the right)*

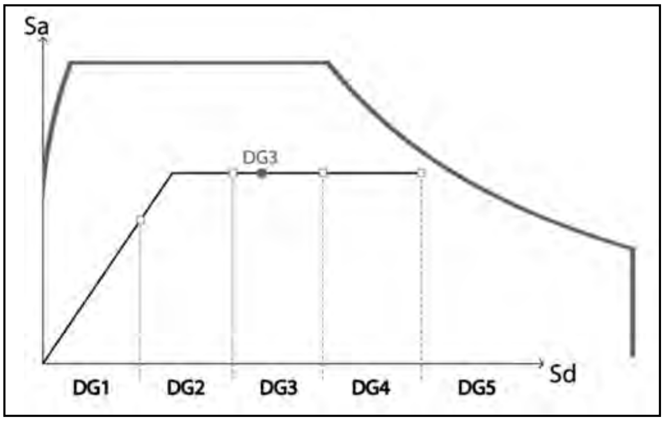

Figure 4 - *Generic capacity curve where the horizontal spectral displacement at the top is express in function of the base shear, expressed as spectral acceleration. To each point of the curve corresponds a damage, ranging from 1 to 5. The red dot represents the seismic performance reached by the structure (performance point). In this case, the performance point determines a damage grade 3 for the analyzed structure. In red the response spectrum [credit: Diana L.]*

class (Lestuzzi et al. 2017; Luchini 2016). Different capacity curves are therefore developed for the same class in accordance to the dispersion obtained: minimal, average and maximal curve (Figure 5). AVM may be useful to gather additional information on specific buildings if needed.

A different capacity curve is developed for every structural class and every building composing the studied urban system is attributed to a specific class. At this stage, the vulnerability analysis at urban scale can be performed and vulnerability maps can be drawn. The term "seismic vulnerability" refers to the tendency of a structure, subject to possible seismic events, to suffer damage (Calvi *et al.*, 2006). In other words, it is the expected damage suffered by structures (under a given seismic excitation that is often defined by national codes).

For urban pre-earthquake assessment, the expected damage is evaluated on the base of the mechanical approach. The expected seismic performance of buildings hit by an earthquake, called performance point, provides the expected damage grade suffered. The performance point is determined by the comparison between the above-mentioned capacity curve and the response spectrum. The capacity curve describes the structural behavior of the building to horizontal seismic actions while the response spectrum is defined as the earthquake demand curve (Cattari *et al.*, 2004). All the buildings analyzed in the pre-earthquake vulnerability phase are subject to the same kind of earthquake (returning time 475 years, corresponding to an event of 5.5 magnitude and an epi-central distance of 7.5 km for

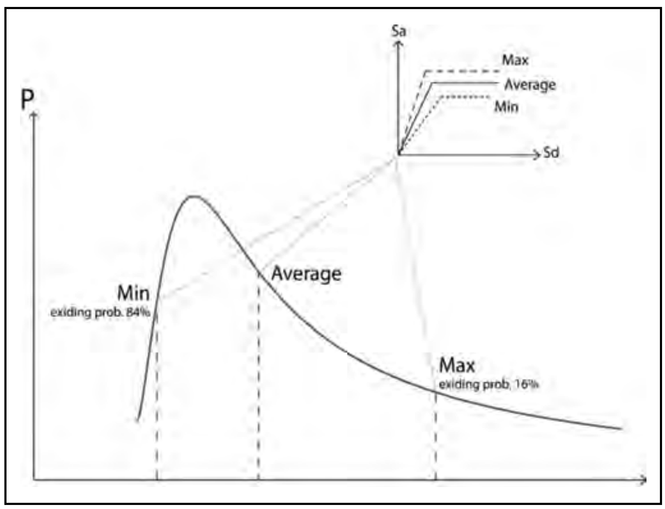

Figure 5 - *Dispersion of a certain property into the same class and thresholds for the definition of the different (min, mean, max) capacity curves [credit: Diana L.]*

every building). Response spectra differ only due to the changing soil conditions into which buildings are anchored.

2.2 The post-earthquake phase

Urban-scale approaches for seismic vulnerability assessment are useful for two main goals: determining urban maps of the expected damage prior to a seismic event (vulnerability maps) as well as concluding on real damage suffered and residual capacity of buildings in the aftermath of a seismic event.

In the post-earthquake assessment, the introduction of measurement devices (such as vibration sensors) to complement visual inspections has the potential to reduce uncertainties and consequently the time needed to express the judgment regarding the safety of buildings. Reducing the time between a seismic event and decision making regarding residual seismic capacity without compromising safety is a major step towards earthquake-resilient cities (Figure 6).

Furthermore, AVMs provide an estimate of the global stiffness of a building and therefore, information on the residual capacity to withstand an aftershock since a reduction of the stiffness of the structure can be identified and linked with structural damage. Thus, taking AVM on an earthquake-hit building can help to assess the real damage suffered by structure as well as the residual capacity in an objective manner and in a short lapse of time (10 minutes of measurement data are usually enough to derive natural frequencies of a structure in a stable manner).

It has been shown that structural identification strategies using modal properties prior to and after earthquakes help to identify the nonlinear behaviour of buildings (Reuland *et al.*, 2017b). If model bias and epistemic uncertainties are taken into account explicitly, the prediction range of displacement demand can be efficiently reduced for a single building.

In case of the post-earthquake assessment of a single building, in absence of AVM for the initial (undamaged) building state, refined three-dimensional models can be used to derive the residual capacity of earthquake-hit structures. The outcome of visual inspection, in the form of an ESM98 damage grade (Grünthal *et al.*, 2001; Lagomarsino and Giovinazzi, 2006) is used alongside the post-seismic AVMs in order to perform structural identification using nonlinear static predictions (pushover curves) of three-dimensional models. Unlike many other applications, no information of the initial building state is necessary to identify nonlinear parameters of buildings (Reuland *et al.*, 2018). In absence of information regarding the seismic signal, such static nonlinear approaches are more efficient than dynamic nonlinear approaches. In conclusion, for a single building, the visual inspection together with AVM provide insights on the real damage suffered and on the damage that it could be suffered in the case of an aftershock.

A building hit by an earthquake shows a degradation of the structural properties. Structural models defined in the pre-earthquake phase and described by capacity curves change widely after a shock. Indeed, information collected by AVM together with the visual inspection

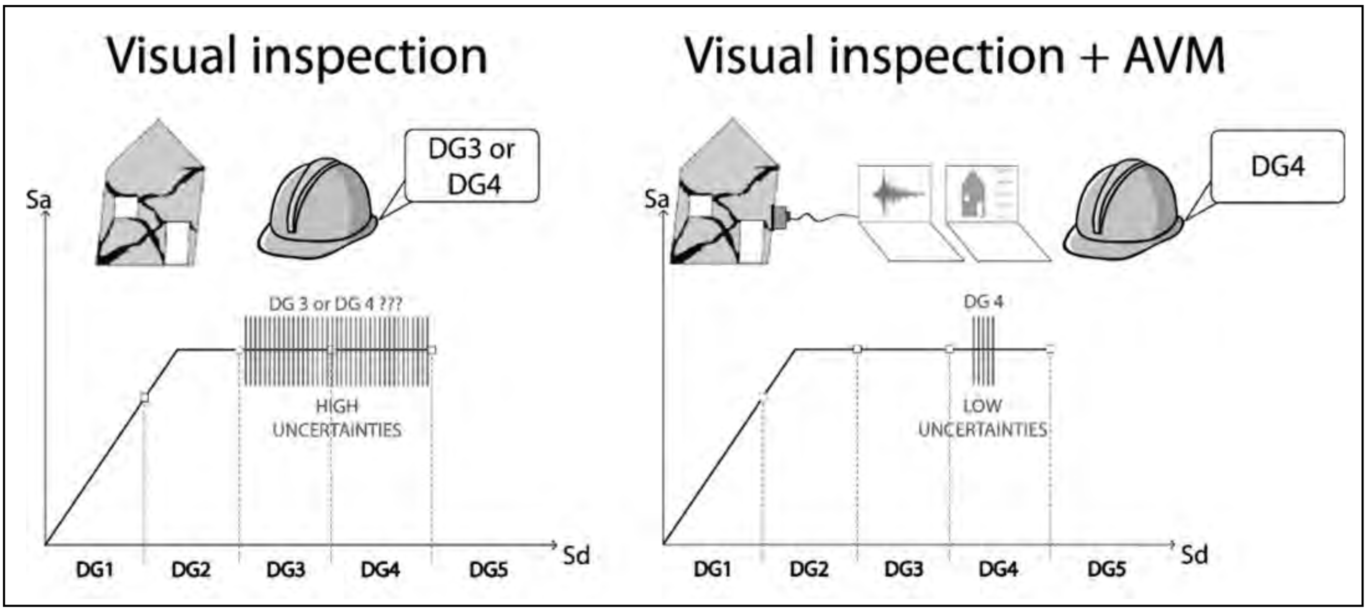

Figure 6 - *The use of AVM to support visual inspection reduces the uncertainties related to the damage reached by a structure hit by an earthquake [credit: Diana L.]*

defines the reduction in the slope of the capacity curve with a lower fundamental frequency. In Figure 7, a reduction in the fundamental frequency of the structure (the slope of the line) is represented.

A simplified approach that allows taking into account the influence of damage on the building stiffness involves taking the secant stiffness to the maximum displacement that the structure underwent during the earthquake. However, structures recover stiffness at lower amplitude vibrations after earthquakes. Thus, the secant stiffness to the maximum displacement results in a conservative estimate (lower limit) to the real damaged stiffness. Michel *et al*. (2011) quantified the frequency drop between ambient vibrations and large-cycle vibrations to be approximately 33% for unreinforced masonry structures. This value can be used as a first approximation to derive the stiffness that is measured under ambient-vibration measurements from the secant stiffness, as shown in Equation 1:

$$k_{AVM} = \frac{1}{0.66^2} k_{sec} \tag{1}$$

In Equation 1, k_{AVM} is the stiffness that is measured under AVM after a seismic event and k_{sec} is the stiffness that is secant to the maximum displacement encountered by the building during the seismic event. In the framework of this paper, especially regarding the case study shown in section 3, the secant stiffness has been considered as the large-amplitude-vibration stiffness for damaged structures after the first seismic event (Figure 7).

When the methodology is up-scaled from building- to city-scale level, simulations using detailed three-dimensional models cannot be performed for all buildings. Detailed simulations should be limited to buildings with high importance to the community resilience, such as hospitals and community centers. In addition, dynamic nonlinear simulations may prove to be computationally prohibitive and thus, static nonlinear predictions are preferred. Consequently, as a starting point, predefined capacity curves (Section 2.1), corresponding to building classes, are used as structural model. Compared to models that are used for single buildings, such capacity curves are simplified representations. However, to perform analyses at urban scale, such reductions in the degree of precision are

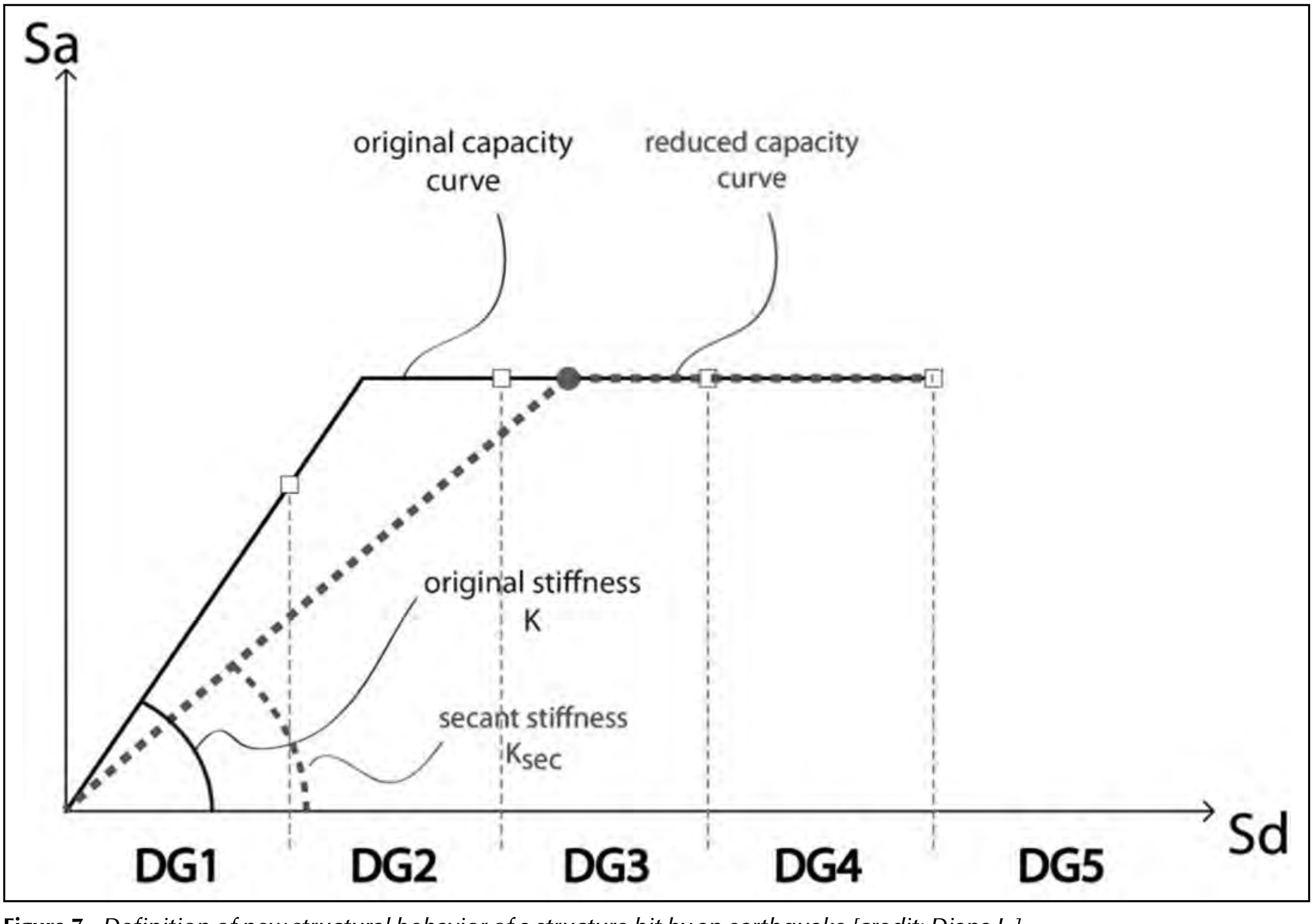

Figure 7 - *Definition of new structural behavior of a structure hit by an earthquake [credit: Diana L.]*

necessary. As described before, capacity curves are available for a large range of building types and are extensively used in pre-seismic assessment at urban scale.

By applying the same methodology (visual inspection + AVM) on buildings belonging to the same class and sharing similar soil conditions, identification results can be widespread at urban scale. The goal is to obtain reliable maps at urban scale showing the real damage suffered by buildings and the damage they may suffer in the case of an aftershock. Providing trustworthy urban disaster risk maps in the case of an aftershock can save lives, can help decision makers in managing the post-earthquake circumstances and can increase the likelihood of stakeholders to preserve their assets. In addition, time is an essential factor in post-earthquake situations. Therefore, a reliable tool to widespread vulnerability and prediction assessment from several sample buildings to entire cities is primordial.

By simulating on every class, with the new reduced (damaged) structural properties, a possible second event with the same characteristics of the previous main shock, the future damage reached by buildings may be determined. The whole post-earthquake procedure that is performed to validate the DG observed from visual inspection and to update the capacity curve to take into account reduce stiffness (resulting from damage) in order to assess the residual capacity is described in Figure 8.

Several properties influence the damage reached by a building being part of a class hit by an earthquake. Some of the main properties influencing the results are the number of floors of the building, the local soil conditions and the epi-central distance. The location of the building presents a central issue: due to local amplification as well as to the epi-central distance, two buildings being part of a same class may attend a different DG. By wide spreading the damage obtained for a building to all buildings of the same class under the same conditions (geo-coordinates, epi-central distance, number of floor, etc.), the distribution of possible future damage at urban scale can be mapped (Figure 9). The accuracy of the "possible damages" may significantly vary after several days as the number of surveyed buildings increases. The reiteration of the surveys (visual inspection + AVM) can refine the data collected and the general accuracy of the distribution.

In the post-earthquake circumstances, time is one of the most important factors, especially for the determination of aftershock damage maps at urban scale. Therefore, it is very useful to reduce the time needed for the elaboration of post-earthquake maps that can provide administrators a handy tool for decision-making (realization of safety interventions, relocation of citizen, closure of road, etc.). At urban scale, a small reduction in the accuracy of assessment (in the order of the 10% of the general error) can be acceptable if results are provided in a short time interval. The post-earthquake maps can be considered as an "open" evaluation: surveys completed in following days can iteratively refine the first distribution and continuously reduce the error.

In the next section, we will show on a real case study the various strategies for the selection of sample buildings to be surveyed based on different factors (building class, number of stories, local soil conditions, and epi-central distance). In detail, we will focus on how to cluster buildings being part of the urban system for choosing those that should be surveyed to reach a trustworthy rate of accuracy and reduce the time needed to reach acceptable evaluations.

3. CASE STUDY

The principles of the proposed methodology are shown through an application to the Swiss city of Martigny. Martigny is located in the canton of Valais, which is the zone with highest seismic hazard in Switzerland. The city of Martigny is characterized by bad local soil conditions. Thus, a specific microzonation study, supported by Crealp[3], is available (Résonance Ingenieurs-Conseils SA, 2015) that takes into account the local soil amplification. Three microzones are defined: MM1; MM2; and MM3. The micro-zone MM1 features the worst soil conditions, due to bad soil conditions, and therefore, attains the highest seismic demand.

In a similar way to the city of Sion (section 2.1 and Figure 3), the standard building taxonomy introduced by Risk-UE does not provide a good fit with the existing building stock of the city of Martigny. As a consequence, the same building classes introduced for Sion have been considered for the case-study of Martigny. The introduced building classes are (Figure 3): (i) type A1 for unreinforced masonry (URM) buildings with a base floor in reinforced concrete (RC); (ii) type A2 for mixed URM-RC buildings; (iii) type B2 for buildings with RC pillars at the base floor; (iv) type C for buildings with RC shear walls; (v) type D2 for buildings with URM shear walls (Diana *et al.*, 2018a and 2018b).

The methodology is applied to 351 buildings of Martigny having 3 to 8 floors. The distribution of the buildings with respect to the 5 building classes described before and the three micro-zones is given in Figure 10 and in Table 2. The geographic distribution of the 351 analyzed buildings is shown in Figure 11. On the total of 351 buildings analyzed, no buildings being part of A2-class have been considered.

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[3] Centre de Recherche sur l'Environnement Alpin - www.crealp.ch.

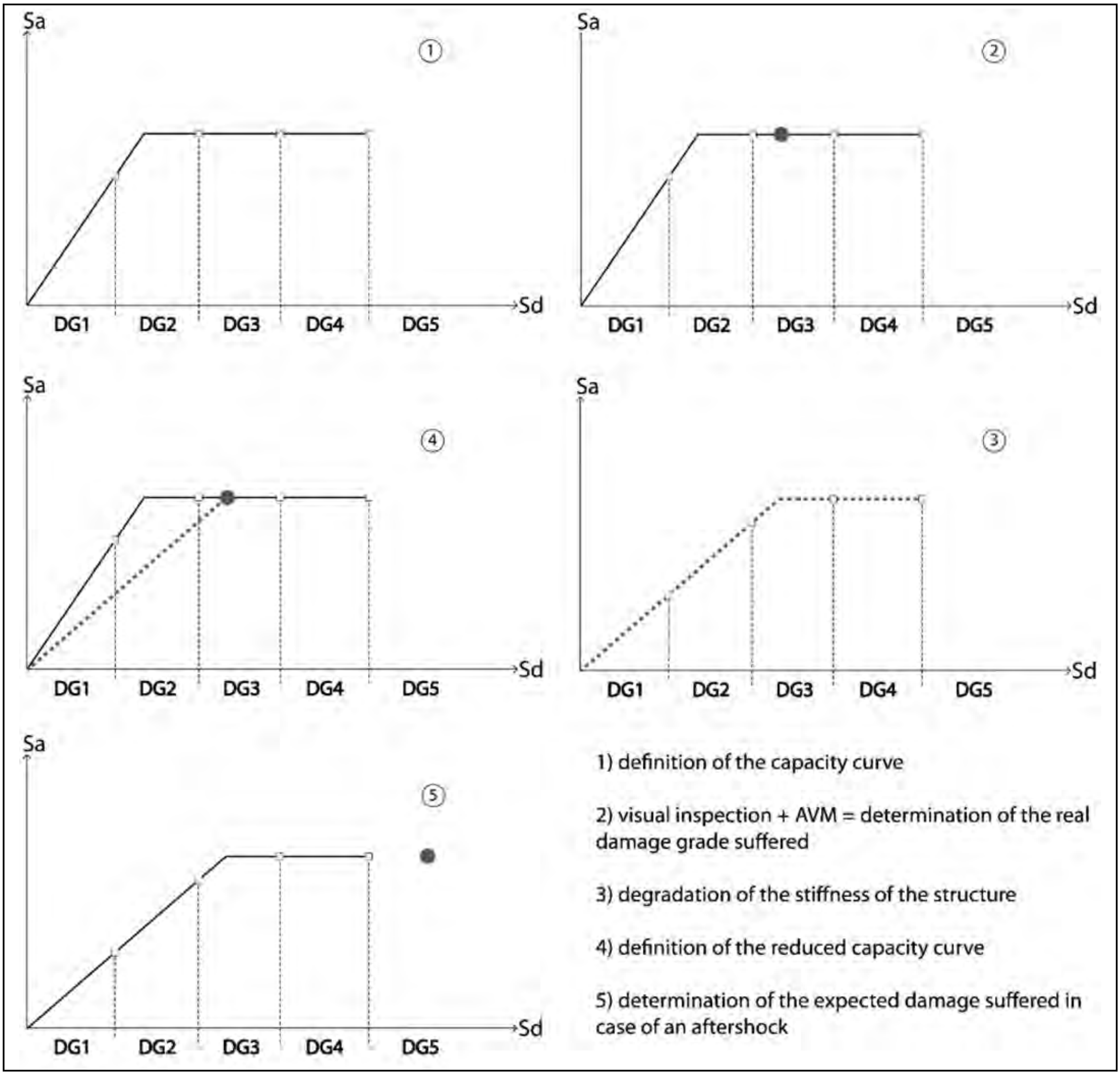

Figure 8 - *The procedure in the post-earthquake phase for the determination of the real damage suffered and of the residual capacity [credit: Diana L.]*

3.1 The pre-earthquake vulnerability predictions in Martigny

In the pre-earthquake phase, the vulnerability of the 351 buildings is assessed using the LM2[4] methodology of the Risk-UE project (Lagomarsino and Giovinazzi, 2006). Considering the analyzed structures, it must be underlined that within the same class, different capacity curves have been considered according to the number of floors. For instance, the capacity curve of a 3-story-building being part of the D2-class is similar but different from the capacity curve of a 4-storey D2-class building. Regarding the seismic demand, the three response spectra describing the soil conditions of the three micro-

[4] Level Method 2.

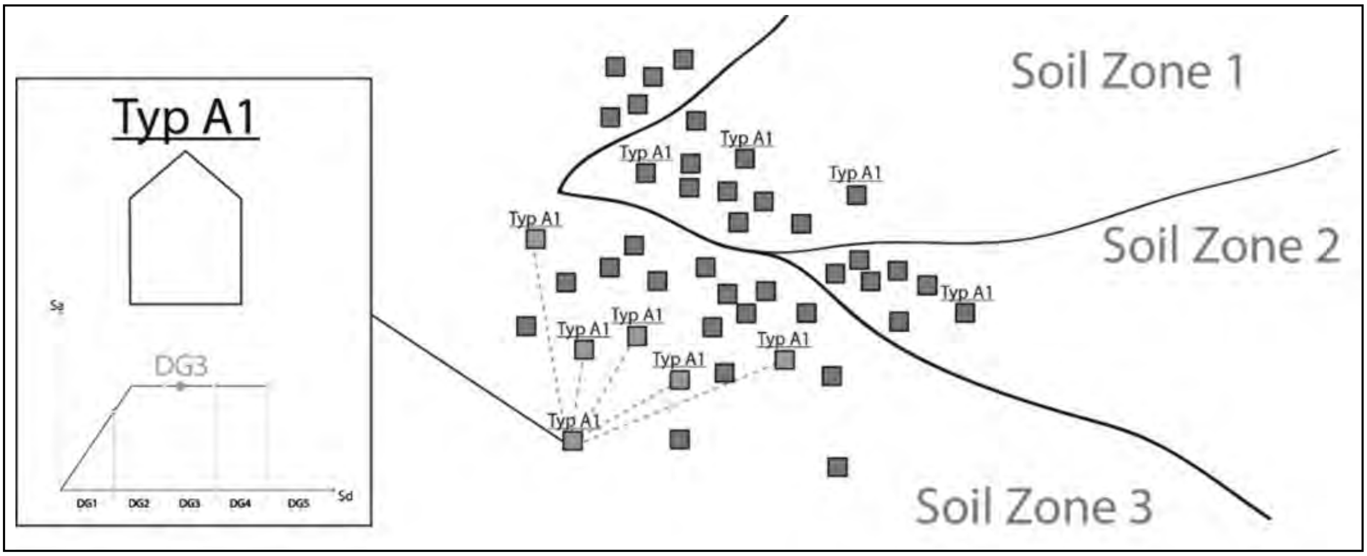

Figure 9 - *The procedure for the wide spreading of the results for one class [credit: Diana L.]*

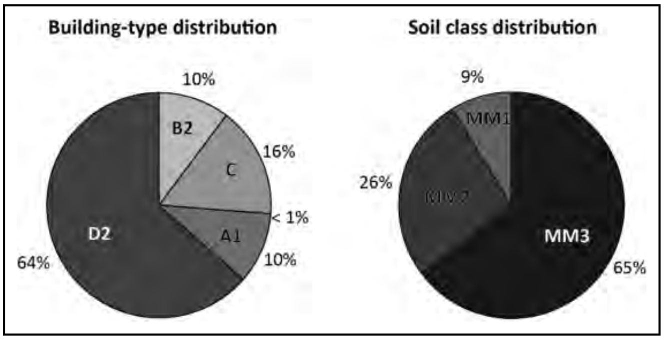

Figure 10 - *Distribution of the 351 analyzed buildings with respect to the building classes and the micro-zones [credit: Reuland Y.]*

zones have been considered. As stated before, for the pre-earthquake vulnerability evaluation, a seismic event of 5.5 magnitude and an epi-central distance of 7.5 km for every building has been considered (return period of 475 year).

As it can be seen in Figure 12, the majority of the analyzed buildings are predicted to undergo serious damage. The 63% of the building stock attain a DG4 while for 9% a complete collapse is expected (DG5). No building attains slight damages (i.e. no DG1). Nearby 30% of the building stock attain medium and serious damages. It can be seen that the micro-zones (that define the seismic demand) have an important influence on the predicted DGs. Indeed, for micro-zone MM1 – the micro-zone with the highest seismic demand – almost all buildings are predicted to collapse.

3.2 The real earthquake scenarios

Two realistic scenarios have been considered: two simulations have been run in order to provide two real

Table 2 - *Distribution of analyzed buildings in Martigny according to type, microzones and number of floors. The distribution of buildings is not homogeneous*

Number of floors	Type D2			Type A1			Type C			TType B2		
	Zone MM1	Zone MM2	Zone MM3	Zone MM1	Zone MM2	Zone MM3	Zone MM1	Zone MM2	Zone MM3	Zone MM1	Zone MM2	Zone MM3
3	8	5	31	5	1	4	0	0	0	0	1	2
4	4	22	52	4	1	4	0	3	8	0	2	3
5	3	20	15	0	1	5	1	0	8	0	1	1
6	4	6	30	0	1	2	1	0	8	0	3	15
7	1	3	14	0	6	2	0	11	12	0	4	2
8	0	1	4	0	0	0	0	1	3	0	0	2

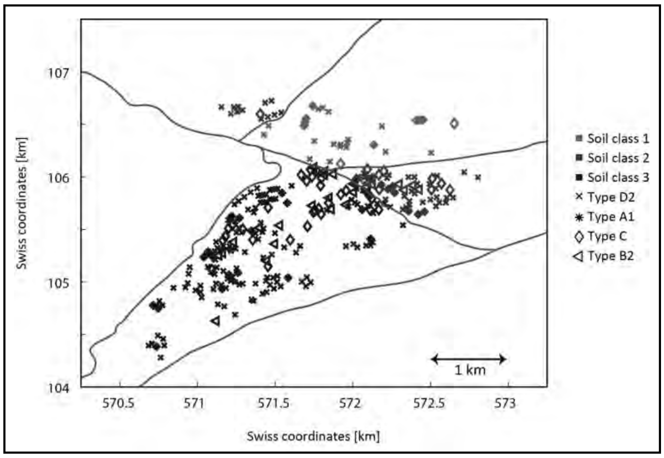

Figure 11 - *The geographical distribution of the 351 analyzed buildings [credit: Reuland Y.]*

damage distributions. In the case of a real scenario, a different seismic demand is applied to every building resulting from the influence of epi-central distance and soil conditions of each building. The two simulated scenarios are: Scenario 1 with an earthquake characterized by an epi-central distance (from the center of Martigny) of 8.7 km in North-West direction and a magnitude of 4.5; Scenario 2 with an epi-central distance of 7.9 km in South-East direction and a magnitude of 5.5 (Figure 13). By taking into account the epi-central distance, buildings may attain different real DGs for the same class and number of floors, potentially even inside the same micro-zone. In addition, the maximum displacement at the top of the building may change (Figures 7 and 8) and thus, different DGs are to be expected following an aftershock.

3.3 The post-earthquake evaluations (real damage and residual capacity) in Martigny

The complete evaluation of the damage really suffered by the building stock, taking into account all the buildings individually, is shown in Figures 14 (distribution) and 15 (map). These results are based on exact knowledge of the performance of every building during the simulated earthquakes. Figures 14 and 15 show that the real damage distribution obtained with Scenario 1 is largely less pessimistic than the pre-earthquake evaluation (Figure 12). This is due to the fact that for pre-earthquake evaluations a seismic event of Magnitude 5.5 with an epi-central distance of 7.5 km is considered. Scenario 1 involves a weaker event. Consequently, the totality of buildings reaches DG1 or DG2. In the case of Scenario 2, the seismic demand is comparable to the one of the pre-earthquake assessment. The only difference lies in the epi-central distance: for the pre-earthquake assessment, the epicenter is slightly closer than for Scenario 2. Therefore, the general damage distribution of Scenario 2 provides less pessimistic results than pre-earthquake predictions.

The complete evaluation of the possible damage that buildings may suffer in the case of an aftershock is shown in Figures 16 and 17. In a similar way to the DG assessment performed in Figures 14 and 15, the real post-earthquake predictions shown in Figures 16 and 17 are obtained using exact knowledge of each building considered

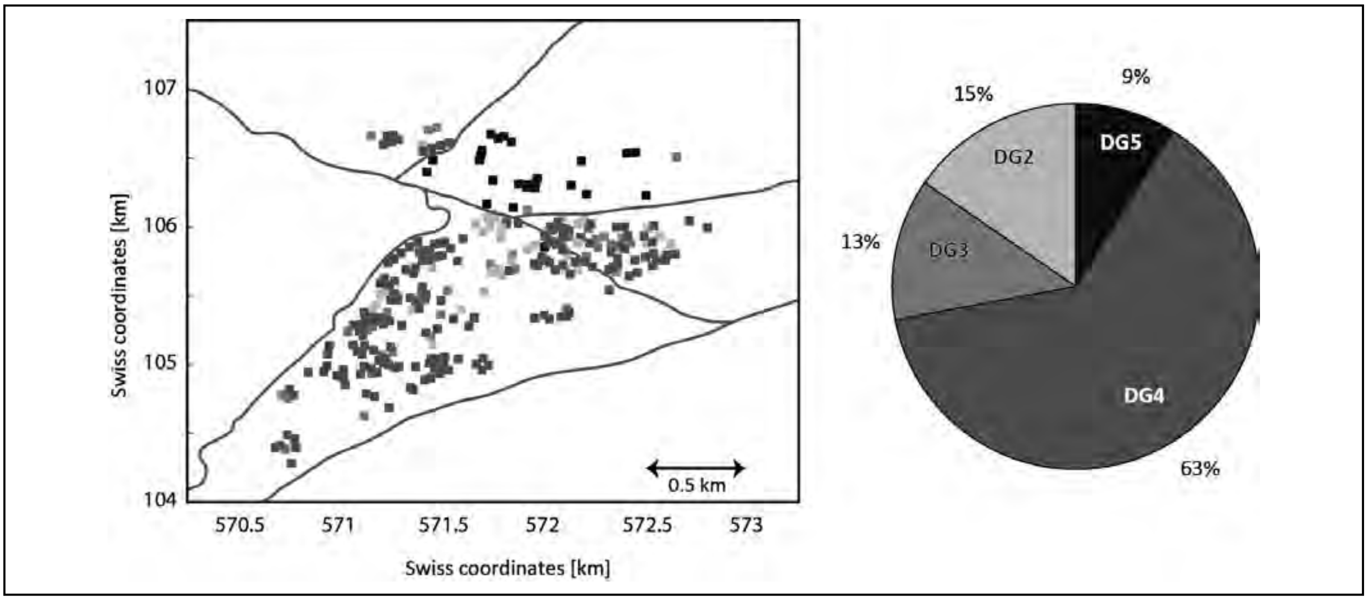

Figure 12 - *Expected (pre-seismic) damage distribution (vulnerability distribution) for the 351 analyzed buildings. Micro-zones have an important influence on the predicted DGs [credit: Reuland Y.]*

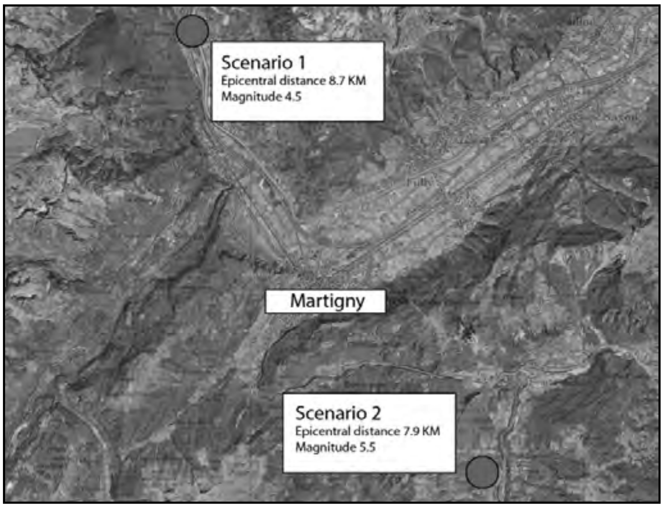

Figure 13 - *The two considered scenarios: SCENARIO 1, epi-central distance of 8.7 km from the center of Martigny, magnitude 4.5; SCENARIO 2, epi-central distance from the center of Martigny 7.9 km magnitude 5.5 [credit Diana L.]*

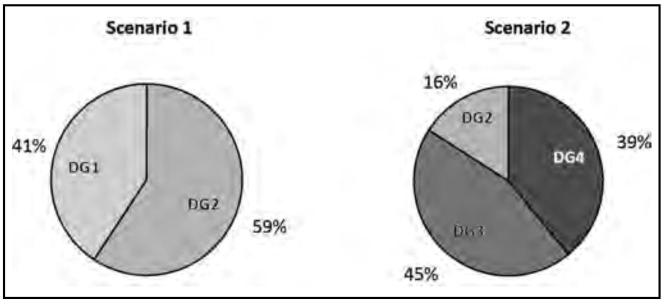

Figure 14 - *Distribution of damage grade resulting from the two analyzed earthquake scenarios. Scenario 1 is a 4.5M earthquake in the North-West of Martigny and Scenario 2 is a 5.5M earthquake in the South-East of Martigny [credit Reuland Y.]*

individually. The post-seismic vulnerability predictions are obtained using the same seismic demand than the pre-earthquake predictions and the updated building state (Figures 7 and 8).

In the case of Scenario 1, a second seismic event may cause DGs that do not significantly differ from the pre-earthquake predictions (Figure 12). This small differences can be explained by the low seismic demand related to Scenario 1. Indeed, DG1 and part of DG2 involve elastic building behavior and therefore, no change in stiffness. For Scenario 2, the building states deteriorate due to the earthquake and thus, the predicted damages under aftershocks show significantly more pessimistic building behavior than for the initial (undamaged) building states. Indeed, Figure 16 shows that under an aftershock with similar properties than the main shock, 81% of the analyzed buildings are predicted to collapse. Such buildings cannot be considered safe for occupancy and would need to be repaired or replaced in order to reach similar resistance than in the pre-earthquake state.

As the damage distributions shown in Figures 16 and 17 are obtained using precise information regarding all buildings, these (geographic) distributions are considered to be the ground truth in the following. However, as stated before, post-earthquake situations are characterized by a need for rapid decision-making. Therefore, it is considered that a first assessment of the response of an entire town to a seismic event needs to be obtained in a quick manner in order to organize emergency actions. Thus, the accuracy of post-earthquake maps that can be obtained by analyzing only a part of the building stock is assessed.

First, the accuracy of assessing the DG suffered by each building is derived and then, the predicted DG under subsequent earthquakes is predicted. Therefore, the

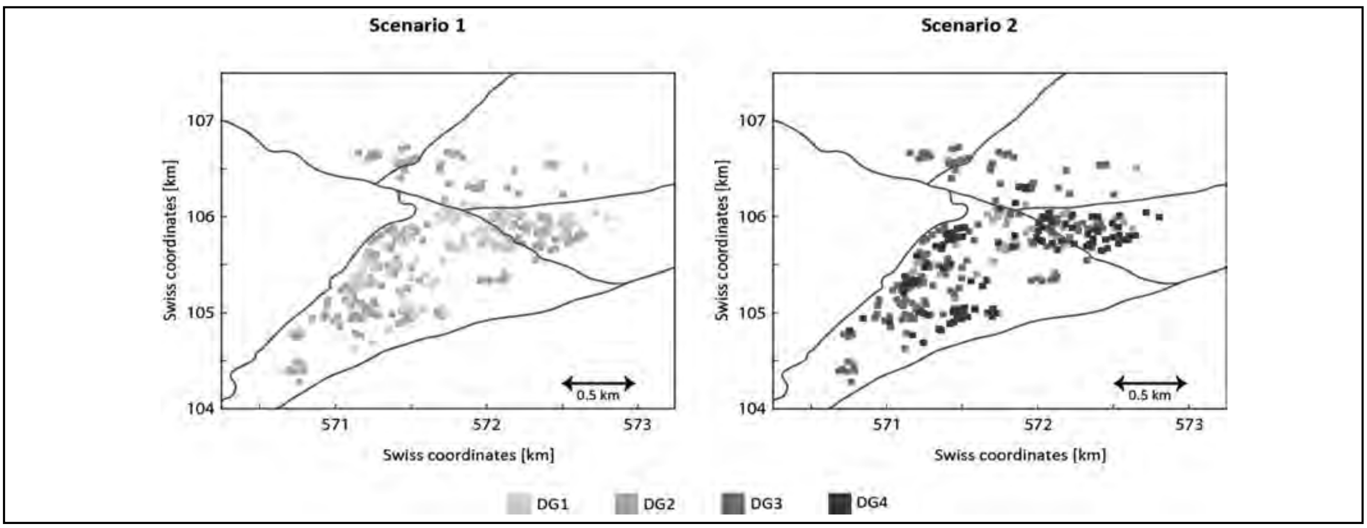

Figure 15 - *Geographical distribution of the damage grades suffered by each building in the city of Martigny related to the simulated earthquake of Scenario 1 and 2 [credit Reuland Y.]*

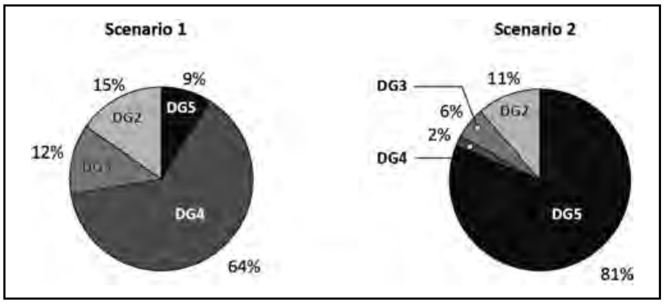

Figure 16 - *Post-earthquake predictions using the LM2 method for the earthquake-damaged buildings after seismic scenarios 1 (on the left) and 2 (on the right) [credit Reuland Y.]*

error committed by wide-spreading the DG suffered by one building is calculated for 4 clustering approaches: (i) selecting only one building per building typology, which in case of Martigny involves wide-spreading the assessment of 4 buildings to 351 buildings; (ii) selecting one building per typology and per micro-zone and thus, 12 buildings out of 351 need to be assessed; (iii) selecting one building per typology and number of floors (it is recalled that the analyzed buildings have 3 to 8 floors), resulting in assessing 24 buildings out of 351; and (iv) selecting one building per typology and per epi-central distance (4 ranges are introduced for epi-central distances), resulting in 16 buildings to assess. It has to be noted that in order to be able to perform such wide-spreading of results, the taxonomy of the entire town needs to be known. However, knowledge of the taxonomy of a town can be obtained prior to an earthquake and should form part of strategic measures to enhance urban resilience.

It is clear that the four clustering approaches have different time demands since the quantity of buildings to be inspected and measured changes from one cluster to another. With the hypothesis of only one team of engineers performing surveys, 120 minutes are considered the minimum amount of time for visual inspection, installation of sensors and registrations of vibration data, elaboration of vibration data and expression of the final judgment regarding the real damage suffered and the future damage in the case of an aftershock. A summary of the time demands for the 4 clustering approaches is shown in Table 3.

Figure 18 shows the accuracy that can be obtained if DGs suffered during an earthquake are wide-spread to the entire town (351 buildings). As the results are influenced by the precise building that is assessed and whose DG is wide-spread to the entire town, 100 random selections of this building are performed. Figure 18 shows the mean, maximum and minimum accuracy that is obtained for the two simulated scenarios. It can be seen that the overall accuracy is better for scenario 1, which can be explained by the fact that only 2 DGs result from this earthquake (DG1 and DG2). Scenario 2 involves 3 DGs (DG2, DG3 and DG4) as can be seen in Figure 14.

As far as identifying the DG suffered during an earthquake is concerned, the highest accuracy is obtained when typology and number of floors are combined to wide-spread results. This result is due to the fact that this combination involves most buildings that are assessed prior to wide-spreading. Along the same line, typology and epi-central distance (16

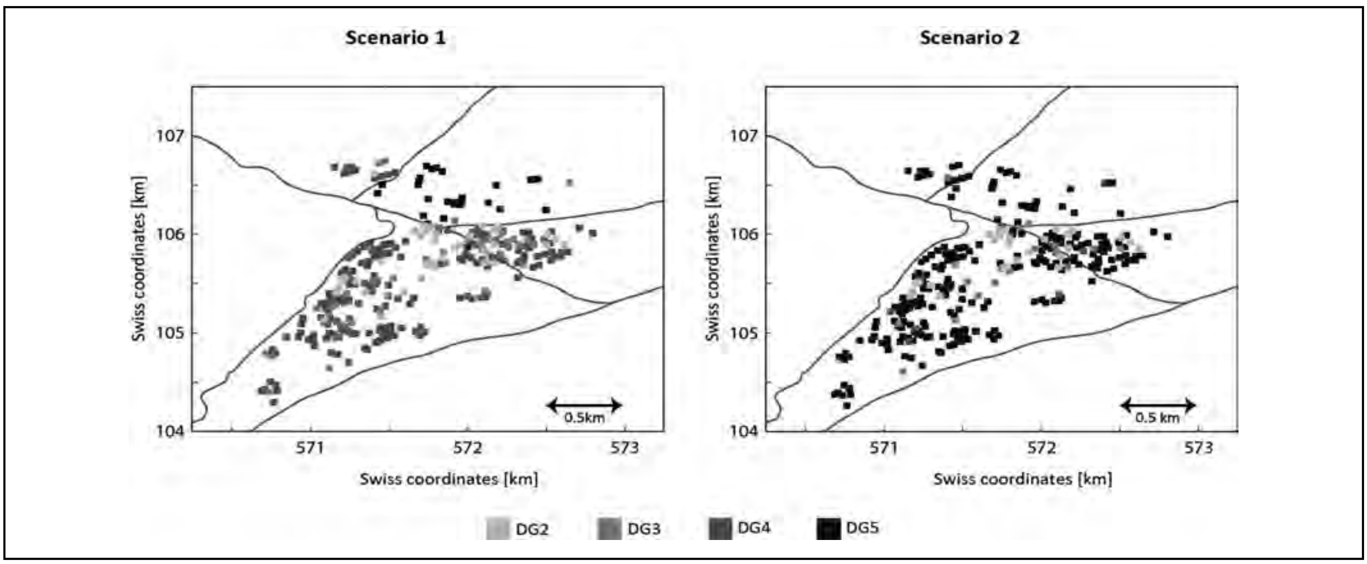

Figure 17 - *Geographical distribution of the predicted damage grades for each building using the seimic demand spectra of the city of Martigny and the damaged building states. The figure represents the vulnerability prediction of deteriorated buildings after the simulated earthquake of scenario 1 (on the left) and scenario 2 (on the right). For vulnerability predictions, the seismic demand given by micro-zones has an important impact [credit Reuland Y.]*

Table 3 - *The four clustering approaches and the related time demand*

Cluster	Selection	Buildings analyzed	Time demand
1	Type	4 buildings	8h
2	Type + micro-zones	12 buildings	24h
3	Type + n. of floors	24 buildings	48h
4	Type + epi-central distance	16 buildings	32h

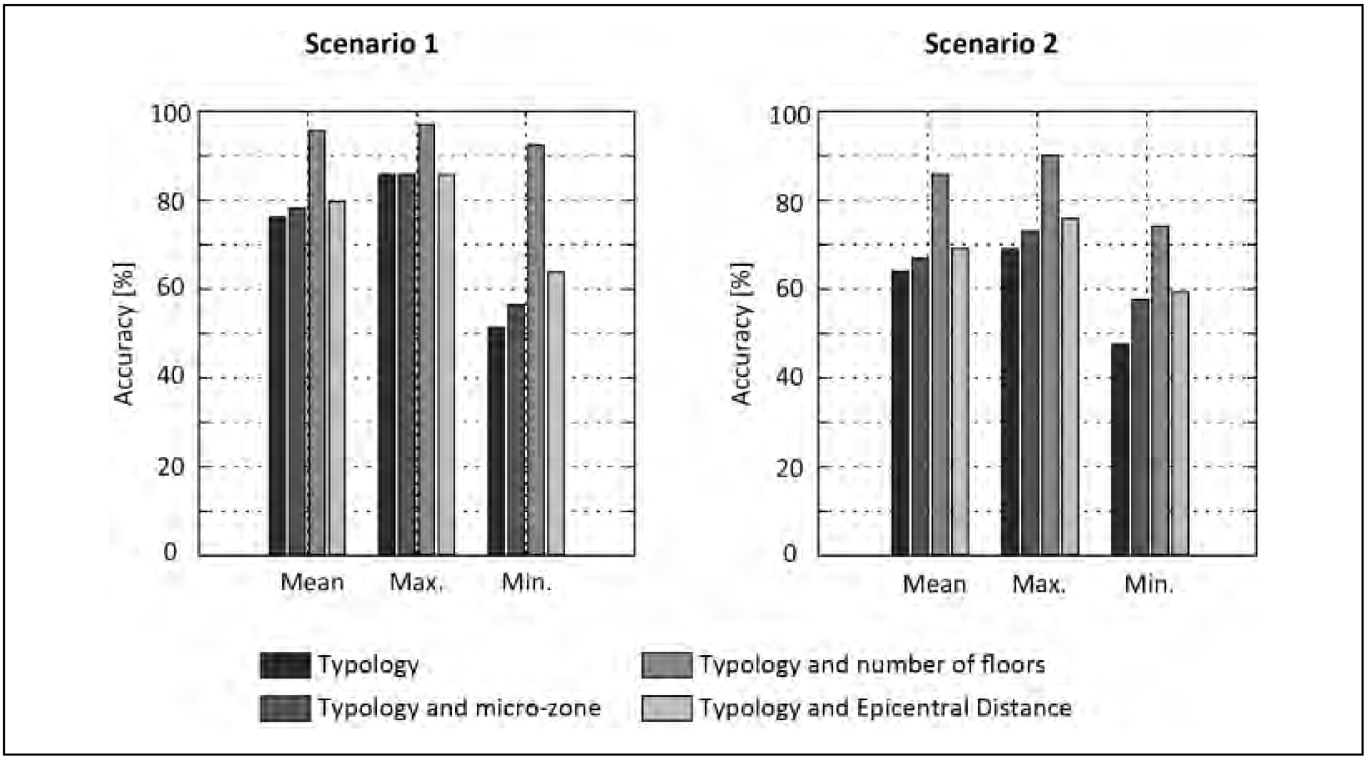

Figure 18 - *Accuracy obtained in the DG evaluation of all 351 buildings using random subsets of buildings based on typology alone or typology combined with either micro-zones, number of floors or epi-central distances [credit Reuland Y.]*

assessed buildings) provide slightly better results than typologies combined with microzones (12 assessed buildings).

When comparing the results for predicted DGs caused by aftershocks (Figure 19), the results change. Indeed, the importance of microzones for the predicted damage, which have been described before, is also reflected by the results of Scenario 1, which is only marginally influenced by damage suffered during the earthquake. When damage has a more prominent role, as it is the case for Scenario 2, the best results are again obtained for the combination of typology and number of floors, which includes most assessed buildings (24).

Finally, the accuracy that can be obtained by assessing buildings that are selected based on typology, microzone and number of floors is evaluated. This approach involves assessing 72 buildings: 4 (typologies) times 3 (microzones) times 6 (amount of floors). 72 buildings represent approximately 20% of the building stock and would imply 6 days of continuous work (144 hours) of inspection. The accuracy obtained for the DG suffered during the earthquake as well as the DGs predicted under future earthquakes are shown in Figure 20. It can be seen that the performance of assessing the DG suffered is inferior to the performance of predicting future DGs. This observation might be caused by the fact that the information left out, epi-central distance, has a more prominent role for the suffered DG than in the predicted DG.

When buildings are clustered according to their typology, microzones and height, the minimal accuracy obtained for the DG assessment exceeds 80%, while for DG prediction accuracy exceeds 95% in all cases. Such figures are deemed sufficient for rapid post-earthquake assessment needs and development of emergency measures. As described before, the buildings analyzed after the first 6 days (of continuous inspection) can be used to continuously increase the accuracy of the damage maps.

However, it is recalled that unless non-structural elements are evaluated, such predictions should not be used to take final decisions regarding safety for occupancy, but rather to prioritize inspection schemes between and inside cities.

4. ECONOMIC IMPACT OF LARGE SCALE ASSESSMENT USING AVM

Although this paper focusses mainly on technical aspects, the use of AVM in large-scale pre- and post-earthquake assessment also has important implications on economic resource management and investments.

It has to be noted that in order to take economic aspects fully into account, a more comprehensive framework is needed, for instance along the lines of "performance-based earthquake engineering" (Krawinkler and Miranda, 2004; Moehle and Deierlein, 2004). In such an approach, cost-benefit ratio of retro-fitting interventions can be estimated and actual economic benefits of increased knowledge in the post-earthquake phase can be assessed.

However, the implementation of such a framework involves large amounts of knowledge of past earthquakes regarding structural analysis and damage analysis, both at component level, as well as loss analysis. Also, large simulation time is necessary to combine all sources of uncertainties, which is not compatible with post-earthquake assessment needs. In addition, little information is available regarding building types that are common in Europe, such as unreinforced masonry structures (Giordano *et al.*, 2018). Thus, in regions with low-to-medium seismic hazard, such knowledge-intensive approaches are not realistic in the short-to-medium term. Finally, for a comprehensive economic assessment it is paramount to take into account indirect costs, such as downtime, business interruption and community functions, which go beyond traditional engineering metrics and for which future work is needed (Krawinkler and Deierlein, 2014). Nonetheless, in the following of this section, even in this frame work of uncertainties, some preliminary numbers and quantification of economic impacts related to the case study are provided.

The clustering of buildings – described in this paper –

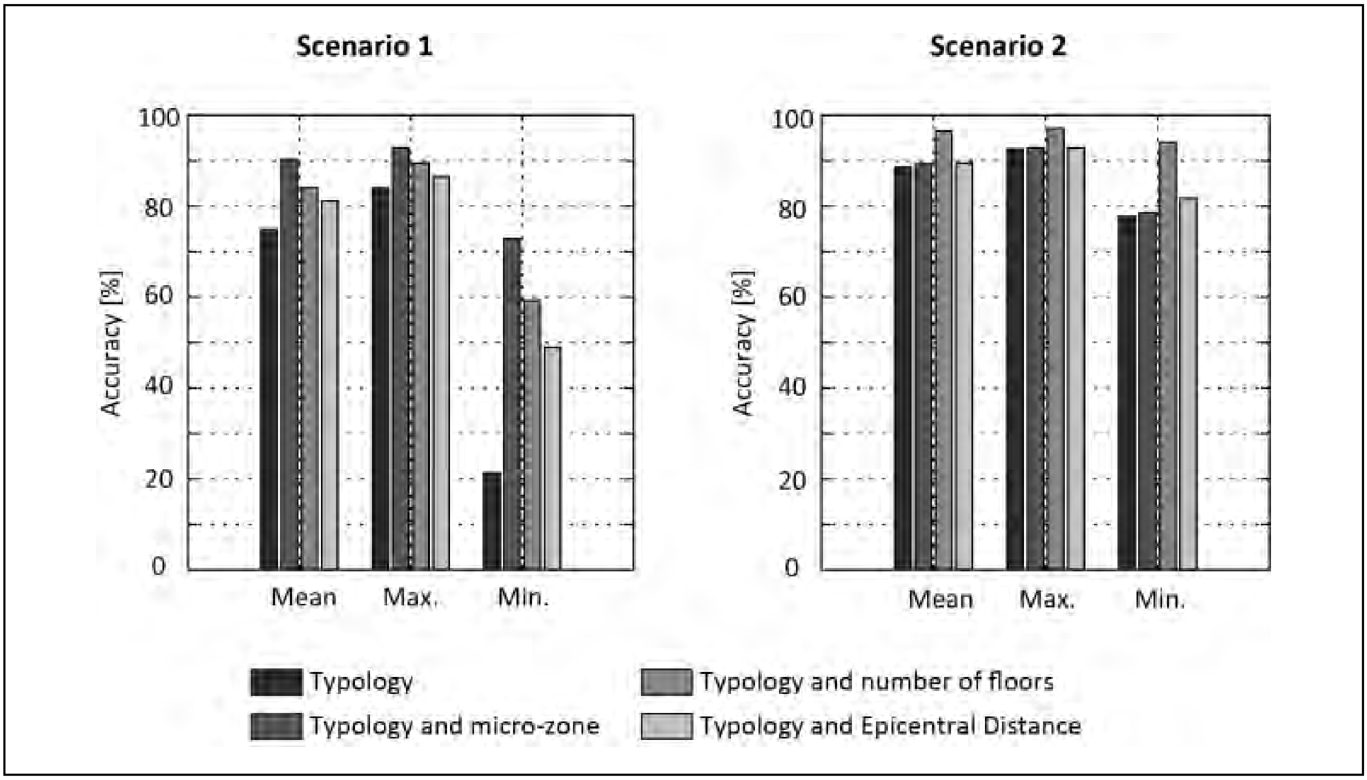

Figure 19 - *Accuracy obtained in the post-seismic vulnerability prediction of all 351 buildings using random subsets of buildings based on typology alone or typology combined with either micro-zones, number of floors or epi-central distances [credit Reuland Y.]*

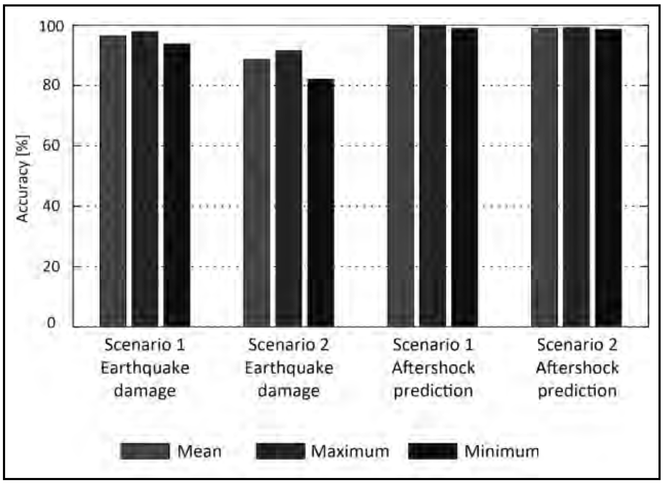

Figure 20 - *Accuracy obtained when combining three sources of building classification: typology, micro-zones and number of floors. The accuracy values obtained using only 20% of the whole building stock are sufficient for post-seismic assessment needs [credit Reuland Y.]*

combined with AVM in the post-earthquake phase, provides opportunities to perform assessment on relatively small subsets of building types. The consequent evaluation of few indicator buildings rather than one-by-one evaluations considerably reduces the time that is needed to provide decision-makers with raw yet trustworthy general damage scenarios. In the prototype town of Martigny (in total 351 buildings are considered), the clustered approach allows a significant reduction of evaluations: only 72 buildings need to be evaluated without losing accuracy. This corresponds to a reduction of time spent for evaluation of 80%. When considering the on-site evaluation and the following data analysis in remote, a minimum time of 120 minutes is needed by a team to express judgments regarding a single building. If a team is composed by four experts, with a general cost between 50 and 75 €/h[5], for the small sample of 351, the total cost of the evaluation is 28,000 - 43,000 € instead of 140,000 - 210,000 €. If a similar calculation is widespread to all the 2,500 buildings of Martigny, the reduction in cost for the real post-earthquake evaluation is even more evident. The AVM clustered approach brings to a total cost of 200,000 – 300,000 € rather than 1,000,000 – 1,500,000 € of the standard building-by-building approach. In addition to these direct costs of assessment, the reduced time of assessment also reduces indirect costs arising from lost business and production time of buildings that are not cleared for occupancy.

[5] DECREE 17 June 2016 Approval of the tables of fees commensurate with the qualitative level of the design services adopted pursuant to Article 24, paragraph 8, of Legislative Decree n. 50 of 2016.

The use of AVM in large-scale assessments yields another important outcome related to direct economic losses and downtime. The direct economic losses consist in costs to repair damage sustained by buildings during the earthquake. Such direct costs are related to the structural damage, the nonstructural damage, and the content damage. Structural damages, that are mainly linked to the concepts exposed in this contribution, range from 10% to 25% of the construction costs, while the non-structural components may result in costs of up to 33%. After an earthquake, the larger proportion of building renovation investments may therefore be related to non-structural components (Mayes 1995). In this paper, nonstructural damage and damage to contents have not been taken into account.

In order to determine the costs resulting from damage in a pre-earthquake phase, a probability prediction related to the expected seismic performance (performance point) can be considered. With respect to the expected performance point, the probability of exceeding each of the defined damage grade *(PDk, $k = 0,\dots,5$)* is evaluated by the mean of specific fragility functions based on lognormal distributions (Lagomarsino and Giovinazzi, 2006) (Figure 21). According to EMS-98 (Grünthal, 1998), to each damage grade can be assigned a specific damage ratio (Table 4). Other damage ratios have been proposed in literature (Kappos, 2006).

Once the probabilities of exceedance of each damage grade and damage ratios are defined on the basis of the performance point obtained, the cost of repair can be calculated. The Mean Damage Ratio (MDR) is defined as:

$$MDR = \sum_{k=0}^{5} P_{Dk} \bullet CDF_k \quad (2)$$

where CDF_k is the central damage ratio (Table 4) that can be defined for every damage grade.

Once the Mean Damage Ratios is defined, the damage cost DC can be calculated as:

$$DC = DR \bullet RPV \quad (3),$$

where RPV is the replacement cost, determined on the basis of public cost manuals for the investigated area. In the case of post-earthquake evaluations, the calculation of DC is directly related to the damage observed. In order to quantify in this case the MDR, no probability calculation should be performed and the MDR directly correspond to the Damage Factor observed on place.

When considering seismic events, the term downtime is referred to the time during which the function of buildings is suspended due to the damage suffered and when making repair works, in other terms the time required to achieve a recovery state after an earthquake. It is therefore more generally connected to the concept of resilience of communities and urban systems. Different recovery states can be defined (Bonowitz, 2011):

re-occupancy of buildings, pre-earthquake functionality, full recovery. Molina Hutt *et al.* (2016) defined the overall downtime calculation by subdividing delays in several categories (utility disruption, impeding factors and repair works):

$$\text{Downtime} = \text{Max}\begin{Bmatrix} \textit{utility disruption} \\ \textit{impeding actors} \end{Bmatrix} + \text{repair work} \quad (4),$$

where utility disruption is considered to be the time for fully or partially recovery of urban systems (water, gas, electricity), impeding factors are the time during which external factors (engineering mobilization, contractor mobilization, lack of financing) prevent the start of repair works.

Such kind of calculation of downtime is undermined by several uncertainties that are difficult to quantify explicitly. A comprehensive calculation of downtime may be object of future works. In the framework of this paper, the calculation of downtime is related exclusively to the re-occupancy of buildings.

Use of AVM at urban scale mainly results in enhanced assessment of the actual damage that buildings sustained during an earthquake. Determining the real damage to buildings has obvious effects on the judgment related to safety for occupancy. Even if, as stated in section 1, safety-for-occupancy judgments cannot be automatized and directly related to AVM results, some positive outcomes can be reported: in simulations presented in section 3, all buildings that are predicted to sustain a DG3, DG4 or DG5 during an aftershock can be considered as unsafe for occupancy. On the other hand buildings in DG1 can be considered as safe for occupancy. Judgement related to DG2 is biased by the visual inspection and the appearance of local mechanism. For simplicity, the hypothesis is to consider DG2 buildings as safe. With the use of AVM, 85% of buildings are predicted to have a DG3 – 4 – 5 in the case of Scenario 1 and equal to 89% of buildings in the case of Scenario 2. Simplified and conservative approaches that involve only visual inspection provide the same result for Scenario 1 (where little to no damage is sustained during the main shock) while 100% of the buildings are considered unsafe for occupancy in the case of Scenario 2.

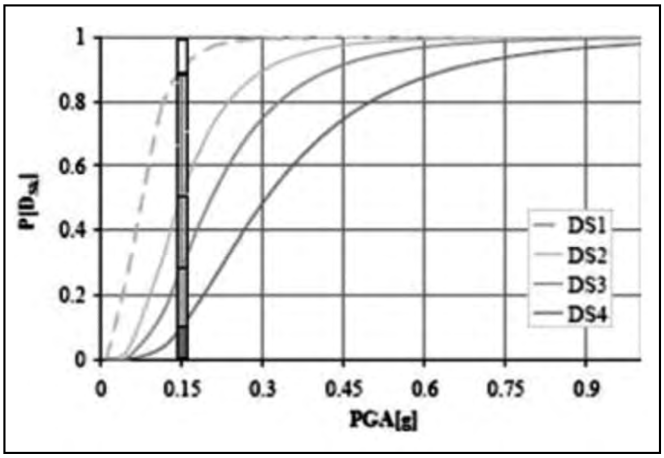

Figure 21 - *Example of a fragility function taken from Lagomarsino and Giovinazzi 2006*

With the use of AVM the total number of buildings considered not safe for occupancy is thus reduced in the case of a severe earthquake scenario while not important differences are shown in the case of a weak event. The use of AVM reduces the uncertainties related to post-earthquake evaluations with a consequent reduction of expected downtime.

5. CONCLUSIONS

Seismic assessment of entire towns requires rapid evaluation tools and engineering judgement. Subjectivity and uncertainties related to standard visual inspections undermine the accuracy of post-earthquake assessment and slow down the entire process. An approach that combines visual inspection and ambient-vibration measurements is proposed. The process of visual inspection cannot be automatized or directly replaced by such ambient-vibration measurements because sources of danger may arrive also from non-structural elements that are hardly detectable by sensors. Application of structural identification technique together with visual inspection reduces the subjectivity as well as the time to

Table 4 - *Damage grades and damage ratio according to EMS-98*

Damage		Damage ratio [%]	Central damage factor (CFD) [%]
0	No damage	0	0
1	Negligible to slight damage	0 – 1	0.5
2	Moderate damage	1 – 20	10
3	Substantial damage	20 – 60	40
4	Very heavy damage	60 – 100	80
5	Destruction	100	100

express the final judgment concerning the real damage suffered by buildings hit by an earthquake and the future damage due to aftershocks. This approach provides decision-makers with more reliable information. A reduction in the time demand for expert judgment is also obtained since the subjectivity of the assessment is reduced drastically with the help of data provided by ambient-vibration measurements. The methodology that was developed for a single building analysis is up-scaled to the entire city and the potential for clustering of buildings is assessed. The following conclusions are drawn:

- Clustering buildings according to their typologies, microzones and height (number of floors) provides decision makers with reliable damage and vulnerability maps after assessing only 20% of the building stock. If less time is available, the analyzed case study suggests relying on typology and height as preliminary clusters.
- The performance of wide-spreading results of a subset of buildings to entire towns in the case of high intensity events is better for predictions under future earthquakes than assessing the DG suffered during the recent seismic event. In the case of the low intensity events, no clear tendency is shown. In addition, especially for the determination of the real damage suffered the performance of wide-spreading decreases with the heterogeneity of the suffered DGs.
- The selection of buildings to be tested has a clear influence on the final distribution. Especially in the case of low intensity event and for the determination of the future damage, the minimal accuracy may drop down to 20% as it is influenced by the precise building that is assessed.
- Various economic aspects are related to post-earthquake assessment. The proposed approach mainly has the potential to provide a reduction in the time that is needed to provide trustworthy judgments as well as the overall time of inactivity of buildings within a city. The reduction of the time for the expression of judgments in the post-earthquake phase has a direct impact on the costs of the engineers needed in the survey phase, for which, thanks to the use of AVM and the clustering of buildings, a reduction of up to 80% may be achieved. In the case of major seismic events, the use of AVM implies also a reduction in the number of buildings (-11% in the case-study presented in this work) that are declared unsafe for occupancy when compared with traditional assessment methods that are based on visual inspections and conservative considerations. No difference between the two approaches is denoted in the case of minor events.

However, it has to be noted that the work presented in this paper does not include several sources of uncertainty (by taking a conservative approach) that will be included in future studies:

- In the case study, all buildings are considered to behave according to the minimum resistance curve. However, this is not realistic and indeed overly pessimistic. An important step towards accurate city-scale assessment relies on identifying which buildings perform according to minimal, maximal or intermediate behavior. The error committed by ignoring reserve capacity (taking into account only minimum curves) should be assessed.
- Uncertainties regarding the damaged stiffness are ignored in the present paper. In other words, the results shown in the case study are based upon the hypothesis that the residual stiffness under large-amplitude shaking is exactly the secant stiffness to the maximum displacement (conservative assumption) and that the measured natural frequency is linked to low-amplitude stiffness that exactly follows equation 1. In reality, this assumption is not realistic and these uncertainties need to be taken into account.
- The proposed methodology should be applied to cities with more typologies and buildings to assess how general the conclusions are.

ACKNOWLEDGMENTS

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