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Improvement of Risk-UE LM2 capacity curves for reliable seismic vulnerability assessment at urban scale in Switzerland

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ABSTRACT

This paper presents the main results concerning mechanical approach for seismic vulnerability assessment obtained during a recent research project, having as objective the creation of risk maps at the urban territory of the cities of Sion and Martigny, highest seismic zone of Switzerland. It focuses on validation and improvement of Risk-UE LM2 capacity curves for unreinforced brick masonry (URM) buildings, with stiff floors and reinforced concrete (RC) shear wall buildings. Given that the standardized Risk-UE capacity curves have been mainly developed for building stock of southern European cities, their reliability for different building features is validated. Within the framework of the development of seismic scenarios for the two cities, a detailed survey was performed for a sample of 500 buildings. Individual capacity curves were determined for all buildings, following the DBV simplified approach. Specific typological classification has been proposed for the Swiss built environment and related characteristic capacity curves have been developed for each typology after appropriate statistics elaboration of the individual response. Risk analysis of the sample lead to the following findings: damage evaluated per Risk-UE LM2 is comparable to the results obtained with application of typological curves for URM buildings, whereas it is overestimated for RC buildings.

Keywords: Risk-UE method, seismic vulnerability assessment, existing buildings, capacity curves, damage grades, typological curves

1. INTRODUCTION

Disaster risk identification of large urban portfolios is highly linked with the following key areas of decision making: preparedness, through emergency measures, early warning systems and contingency planning and risk reduction by raising awareness, improve and enrich building codes as well as prioritize resilient retrofitting and reconstruction. Risk identification for seismic prone areas is quantified through the estimation of seismic damage scenarios at territorial scale. For the latter, the recognition of the exposure data, the attribution of the vulnerability model and their combination with the seismic hazard estimate, are necessary steps.

The assessment of seismic vulnerability initiated in USA in terms of estimation of damage and damage probabilities (NOAA, 1972; ATC-13, 1985) and has been widely adopted by the end of the '90s. An analytical estimation of the structural damage in urban scale has been standardized by HAZUS (1999), which

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constituted the benchmark for several other methodologies developed worldwide. In Europe, the RISK-UE project (Milutinovic and Trendafiloski, 2003) launched after the disastrous earthquakes of Izmit and Athens in 1999. Each approach is characterized by limitations; subsequently, the choice of the most feasible one depends predominantly on the level of information available and on the extent of the area under examination.

Methods available for seismic vulnerability assessment of buildings are various and based on different approaches, depending on the result to be achieved, and they can be substantially divided into two main categories: Empirical or Macroseismic methods, based on statistical observations of recorded damage data by strong past earthquakes; Analytical or Mechanical methods, which allow the use of results of sophisticated hazard and structural analysis. Hybrid and expert elicitation based models use variations of the abovementioned approaches.

The Risk-UE project represents the first collaborative and comprehensive research program focused on the study of regional seismic risk on the European built environment, mainly of south-european cities. The general objective of the Risk-UE project was the development of a modular methodology for the assessment of earthquake scenarios based on the analysis of the global impact of one or more plausible earthquakes at the city scale, within a European context. Typological classification (Building Typology Matrix (BTM)) was introduced within the project, reflecting differences between types of structures that are expected to have similar seismic behaviour, based on EMS-98 (Grünthal, 1998) building classes. 23 main classes are identified on the basis of the lateral resisting system, construction material, height and seismic resistance standards. Two approaches have been proposed, following the abovementioned scheme.

The Level 1 (LM1) method is based on the vulnerability model of EMS-98, for which damage probability matrices (DPM) and mean semi-empirical vulnerability functions (MVF) have been proposed, so as to quantify the building behavior within a vulnerability category. MFV correlates the mean damage grade with the vulnerability index and the macroseismic estimated intensity, while DPM calculates the probability of occurrence of the damage grade.

The Level 2 (LM2) method, which implementation is discussed herein, is a simplified displacement-based method. The seismic response of each structural category is obtained by comparison of the representative capacity curve with the seismic demand, using appropriate non-linear static procedures (definition of "performance point"). Finally the distribution of damage levels can be evaluated by defining proper damage states on the capacity curve, corresponding to predefined displacement values. Following the conceptual framework implemented in HAZUS (1999), standardized capacity curves are proposed, after multi-parametric study, accounting for variations of geometric and material properties within the same BTM classes.

Given that Risk-UE building typologies mainly reflect urban reality of southern European countries, the objective of the discussed project was to recognize constituting typologies of the Swiss building stock and to create representative capacity curves. A simplified non-linear assessment method, developed by Lagomarsino & Cattari (2013), has been applied, with the necessary adaptations, for the establishment of new idealized capacity curves. The results are compared and new standardized curves are proposed for seismic risk assessment at national scale.

2. SWISS DATA

2.1 Seismic hazard in Switzerland

The Alpine Arc, meeting line of the Eurasian and African tectonic plates, saw a tectonic and seismic activity recorded since the fourteenth century. Valais, in particular, is the part of Switzerland with the highest seismic hazard. Yet the related risk has long been underestimated and the seismic loading has been only considered in the Swiss design standards in 1989. As a consequence, the large majority of the building stock in Switzerland was built without any seismic consideration.

The regional distribution of the seismic hazard is given on the map of seismic zones of the Swiss seismic code (SIA 261, 2003) (Figure 1). Switzerland is divided into four areas with a constant design value of horizontal ground acceleration. This value corresponds to the peak ground acceleration for class A foundation soil (rock), with a 475-year return period for the limit state of non-collapse. The cities of Sion and Martigny with their surroundings, correspond to the highest Zone 3b for which α_{gd} = 1.6m/sec^2. Earthquakes expected in Zone 3b for the return period of 475 years are approximately of a magnitude of 6-6.5 on the Richter scale. For the definition of the design spectrum the soil conditions are also taken into account, according to SIA 261. In specific, for the valley of Rhone, at the boarders of which the two cities are located, being prone to site effects, microzonation studies have been performed releasing elastic acceleration spectra per zone (www.crealp.ch; Lestuzzi et al., 2016a).

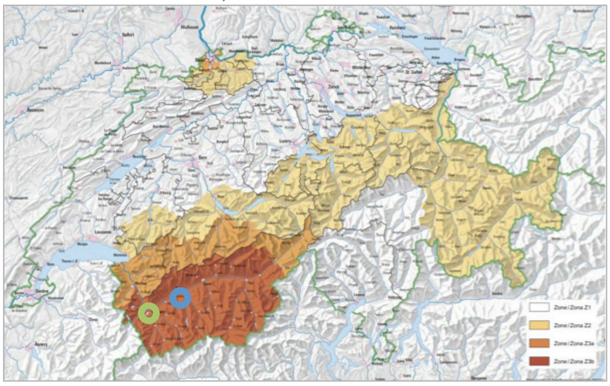

Figure 1. The four seismic zones in Swiss building code (SIA 261, 2003) and the location of the investigated cities, Sion (blue circle) and Martigny (green circle).

2.2 Characteristics of Swiss buildings (Exposure model)

The city of Sion is the capital of the canton of Valais, with great history and professional activity. It contains around 30'000 inhabitants and almost 20'000 commuters for a total of 3'600 buildings. The city of Martigny is located southwest of Sion at a distance of 30 km. Martigny is the second main city of the canton of Valais and contains around 20'000 inhabitants for a total of 2'500 buildings. 196 buildings have been surveyed in detail in Sion and 306 in Martigny. For Martigny the 306 buildings correspond to the 75% of the building stock of interest in this study. This is concentrated to residential blocks with more than 3 floors, raised before 2004 (new design code's implementation). Within the detailed survey the construction drawings of each building were collected from the city archives (Figure 2left) and a 30-min site visit per building took place (Figure 2center, right) (Bozzano et al., 2015). The structural system typology, the construction material, the height, regularity, geometrical data, possible interventions and existing damage, are some of the characteristics inspected.

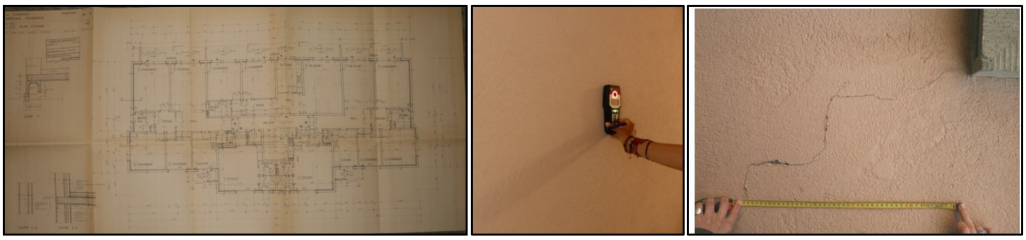

Figure 2. Detailed survey included: (left) collection of drawings with construction details (Kazantzidou et al., 2015), (center) on site detection of construction material, (right) on site dimension measurements

Swiss building stock is mainly composed of low-rise and mid-rise buildings constructed from masonry and reinforced concrete. The masonry buildings are of unreinforced masonry, subdivided into stone masonry buildings with flexible floors and concrete brick masonry buildings with stiff floors. Within the framework of the project, the detailed survey led to the development of a specific taxonomy valid for typical Swiss buildings with stiff floors (Figure 3). The typology A1 corresponds to unreinforced masonry (URM) buildings presenting a special wide-spread Swiss characteristic, this includes heavily reinforced basement, often above ground, required as nuclear shelter (Figure 4right). The typology A2 is for buildings with mixed URM-RC walls along the height (Figure 4center). The typology B2 is for buildings with RC pillars in the ground floor, creating a clear soft-storey. The typology C is for buildings with RC shear walls with low reinforcement ratio (Greifenhagen & Lestuzzi, 2005). The typology D2 is for buildings with URM shear walls (Figure 4left). Furthermore, a rapid visual survey of the total building stock of both cities was performed, in order to attribute a building category (per LM1, LM2 and specific Swiss typology) to all existing structures and collect all important characteristics (number of stories, irregularities, use, etc.).

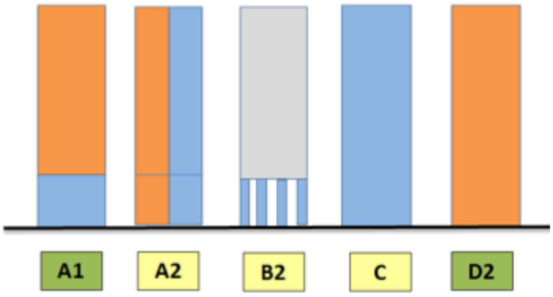

Figure 3. Building taxonomy for Swiss urban areas, for structures with stiff floors (Kazantzidou et al., 2015).

Figure 4. Illustration of typical Swiss typologies; (left) D2; (center)A2; (right) A1

The global distribution of the detailed survey buildings into the specific typology is different for the cities of Sion and Martigny (Figure 6left, center). The distribution is nearly uniform for the city of Sion but typology D2 is clearly dominant in the city of Martigny. The distribution with respect to the height has been also illustrated for both cities (Figure 5right). The majority of the building stock surveyed is composed of mid-rise buildings up to 6 stories. Taller buildings of seven stories or more have an important presence as well. It should be noted that the distribution is strongly biased, being based on the selected structures and do not represent the total cities building inventory. Further information upon the entire building stock of both cities are given in Lestuzzi et al. (2016a).

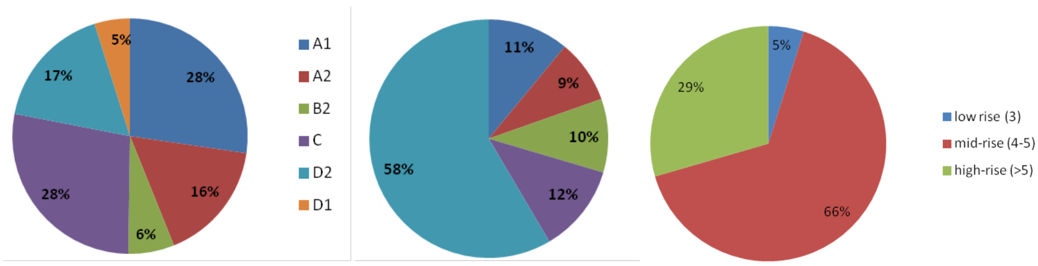

Figure 5. Distribution per structural typology for (left) Sion and (center) Martigny sample; (right) per height for both cities sample

The knowledge of the evolution of the seismic codes in Switzerland is of primer importance, especially for RC buildings, which performance clearly differs according to the application of Earthquake Resistant Design (ERD). Three wide periods are recognized: (1) no ERD prior to 1989, (2) moderate-ERD for first seismic provisions 1989-2003, (3) high-ERD with modern ERD standards SIA 261(2003) and compulsory application after 2004.

3. TYPOLOGICAL CAPACITY CURVES

Different approaches are available in literature for obtaining capacity curves in a simplified form for territorial scale assessment. In particular, the mechanical model known as Displacement Based Vulnerability (DBV) method (Lagomarsino & Cattari, 2013), defined for both masonry and reinforced concrete frame structures, has been selected, as benchmark, for the seismic vulnerability assessment of Swiss built environment. The response of a building asset is idealized in terms of a capacity (force-displacement) curve, which describes the structural response in terms of stiffness, overall strength and ultimate displacement (Figure 6) of an equivalent SDOF system. Four Damage States are defined on the capacity curve as displacement capacity thresholds. Based on the principles of performance-based earthquake engineering, it is assumed that the Damage States of a structure are associated with a specific performance (deformation) level.

Four Damage States (D_{DSi}) are adopted for five Damage Levels (D_{Si}) or Damage grades (DG), according to EMS-98 (Grünthal, 1998) definition: *No/Slight* Damage (D_{S1}), *Moderate* (D_{S2}) for slight structural and moderate non-structural damage, *Substantial to Heavy* (D_{S3}) for moderate structural and heavy non-structural damage, *Very heavy* (D_{S4}) for heavy structural and very heavy non-structural damage and (D_{S5}) *Destruction*, for total or near collapse.

As building assets, groups of structures having a homogeneous behavior are defined, to which a suitable performance model is associated. Therefore a specific displacement-based model has been defined for every Swiss constructive type previously described (Figure 3) and representative capacity curves were developed after statistical elaboration of the individual simplified capacity curves of the 500 buildings surveyed in detail. For the identified structural classes, since no direct comparison with real damage observed was possible (last earthquake in Valais was in 1946 and is not well documented (Fäh et al., 2012), detailed structural analyses have been carried out on a selection of buildings (Luchini, 2016) so as to calibrate the DBV method and validate the vulnerability model developed for the new typologies.

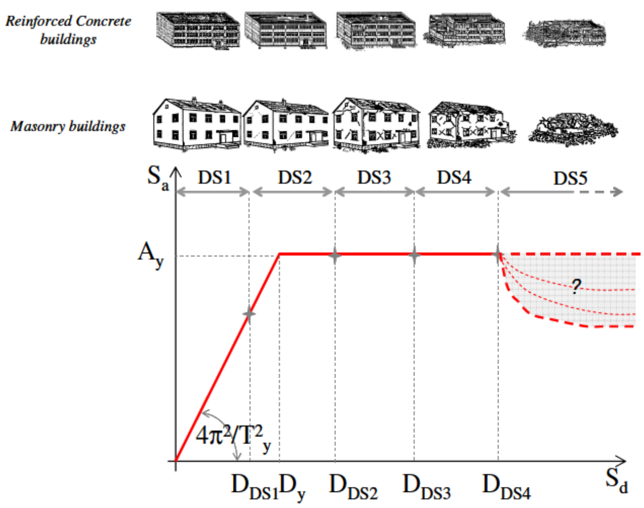

Figure 6. Capacity curve according to Displacement Based Vulnerability method and definition of damage limit states (Lagomarsino & Cattari, 2013)

3.1. Simplified Capacity curves

The DBV method for masonry structures, originally proposed by Cattari et al (2005), defines a capacity curve, through few geometrical and mechanical parameters, representative of the structural response in the non-linear field. The assessment considers only in-plane behavior of walls and hypothesizes two different collapse modes: uniform and soft-storey. The capacity curve is schematized by a bilinear behavior, with elastic perfectly-plastic behavior. It is completely defined by three parameters: the yield acceleration A_y, the fundamental period T and the ultimate displacement capacity D_{DS4}.

The definition of the capacity curve of RC buildings is based on the period of vibration (T_{DSi}) and the displacement capacity (D_{DSi}) of the different limit states (i), according to DBELA (Crowley et al., 2004) method. Two different mechanisms are again considered; the uniform or "beam-sway" mechanism and the "soft-storey" or "column-sway' mechanism of RC frames.

The calibration of the abovementioned models was carried out through detailed structural analyses on a selection of representative structures surveyed in Sion and Martigny. Special modifications took place for the development of reliable models, different from existing ones, for A1 and A2 building types. A *hybrid approach* has been proposed (Kazantzidou et al. 2015) for the development of a unique curve per typology, according to which both mechanisms have equal weight contribution. Detailed information about the new models definition and the structural analyses results can be found in Kazantzidou et al. (2015), Luchini & Podestà (2015), Luchini (2016), and Lestuzzi et al. (2016b).

3.2 Determination of typological curves

In a seismic vulnerability analysis at territorial scale, a typological capacity curve has to be representative of a wide class of buildings, so the above parameters have to be considered as random variables, with a dispersion that is compatible with the variability of the characteristics of buildings in the class. Proper ranges of values are defined for all important parameters (interstorey height, structural elements dimensions) with a proper probability distribution (lognormal distribution has been selected) and related parameters (mean value and confidence levels at 16% and 84%) (Luchini & Podestà, 2015; Lestuzzi et al, 2016b). The confidence interval has been evaluated by using the response surface method.

All typological capacity curves developed have a variability range directly related to the mean value of each parameter and the two borderline cases. The combination of the maximum and minimum parameters, which lead to the creation of the extreme-case curves, is an iterative procedure (Luchini & Podestà, 2015; Kazantzidou et al., 2015). The tendency of the structure with respect to its resistance and ductility is analyzed with an exhaustive parametric analysis. Hence a bracket of typological curves is given, per building height and construction period (Figure 7), with its range depending on the variability of the important parameters within the sample. In order to be consistent with the rapid character of the data collection, for which the typological curves are designed, further discretization of the sample and the resulting curves, has been avoided.

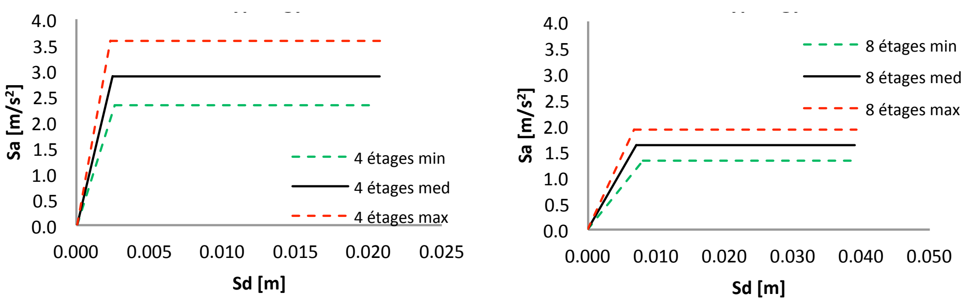

Figure 7. Typology A1, minimum, mean and maximum typological curves for buildings of (left) 4 and (right) 8 stories. (Kazantzidou et al., 2015)

4. TYPOLOGICAL CURVES vs RISK-UE LM2 CAPACITY CURVES

The typological curves and the Risk-UE LM2 capacity curves are compared in the following sections in terms of related damage prediction. In order to avoid additional uncertainties, only the nearest typologies are considered for the comparisons. Consequently, RC2 (Lagomarsino & Giovinazi, 2006) for no-ERD buildings, is compared with the specific typology C of the corresponding design era, and M6-PC (pre-code) is compared with the typology D2. It is assumed that during the construction period of 1989-2003, although first seismic provisions have been included in swiss seismic codes, given that they were not of compulsory application, they have rarely been implemented. The performance points are also computed for soil class C and seismic zone Z3b, according to the N2 method (Fajfar, 2000) as described in Eurocode 8 (CEN, 2005), and the resulting damage grade has been marked.

4.1. Specific typology C vs typology RC2

According to the definition of Risk-UE LM2 method for reinforced concrete buildings, low-rise (RC2_L) includes buildings up to 3 storey height, mid-rise (RC2_M) corresponds to buildings between 4 and 7 storey height and high-rise (RC2_H) describes buildings from 8 storey and above. The results for 5-storey building of typology C and typology RC2_M are shown in Figure 8. The results for 8-storey building of typology C and typology RC2_H are shown in Figure 9. More comparisons can be found in Lestuzzi et al. (2016b).

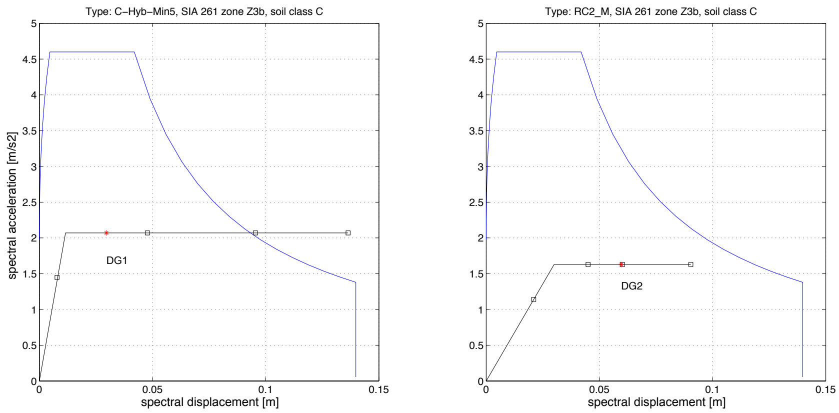

Figure 8. Capacity curve and damage grade for 5-storey building of typology C (left) and RC2_M (right).

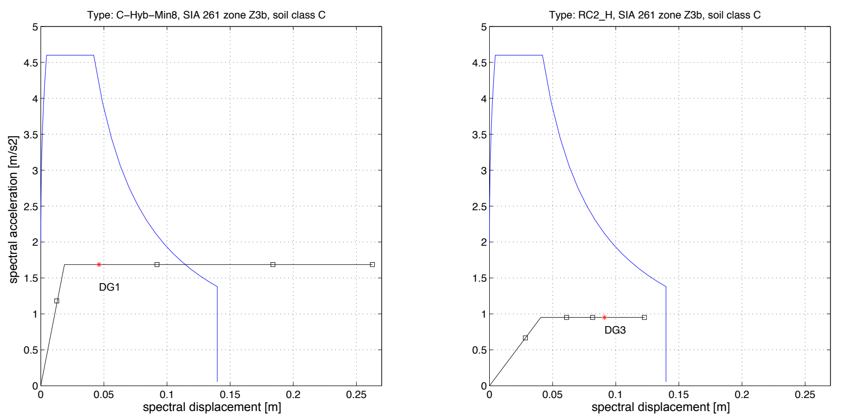

Figure 9. Capacity curve and damage grade for 8-storey building of typology C (left) and RC2_H (right).

The capacity curves of specific typology C are quite different from the ones of Risk-UE LM2 method for RC2 typology. They exhibit enhanced performance in all characteristics (strength, displacement capacity and stiffness). As a consequence, a marked discrepancy appears between the damage predictions of both capacity curves families. The difference reaches up to two damage grades for high-rise building category. The results reported above are computed for soil class C. However, this trend holds true for different soil classes. Material strength characteristics, regularity of walls configuration in plan and in elevation, construction detailing and elements dimensions, as well as solid slabs imposing high axial loads, are some of the Swiss characteristics different from south European shear wall buildings'. These lead to stiffer, but also more ductile response, as well as higher global strength.

4.2. Specific typology D2 vs typology M6-PC

According to the definition of Risk-UE LM2 method, for unreinforced masonry buildings, low-rise with no seismic provision (M6-PC_L) includes buildings up to 2 storey height, mid-rise (M6-PC_M) corresponds to buildings between 3 and 5 storey height and high-rise (RC2_H) describes buildings from 6 storey and above. The results for 3-storey building of typology D2 and typology M6-PC_L are shown in Figure 10, being the 3-storey building the lowest height category analyzed. The results for 4-storey building of typology D2 and typology M6-PC_M are shown in Figure 11. The results for 6-storey building of typology D2 and typology M6-PC_H are shown in Figure 12.

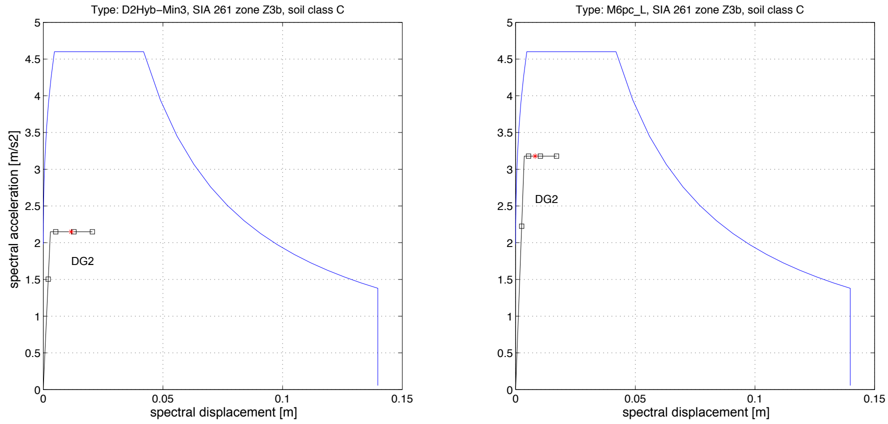

Figure 10. Comparison of capacity curve and damage grade for 3-storey building of typology D2 and M6-PC_L.

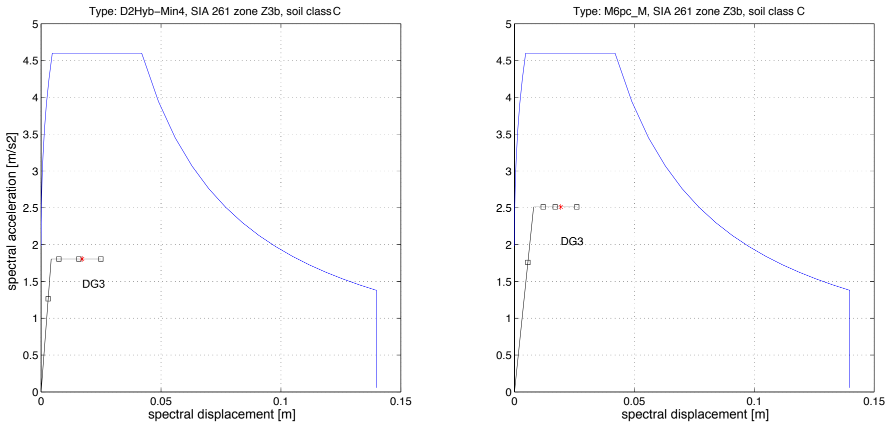

Figure 11. Comparison of capacity curve damage grade for 4-storey building of typology D2 and M6-PC_M.

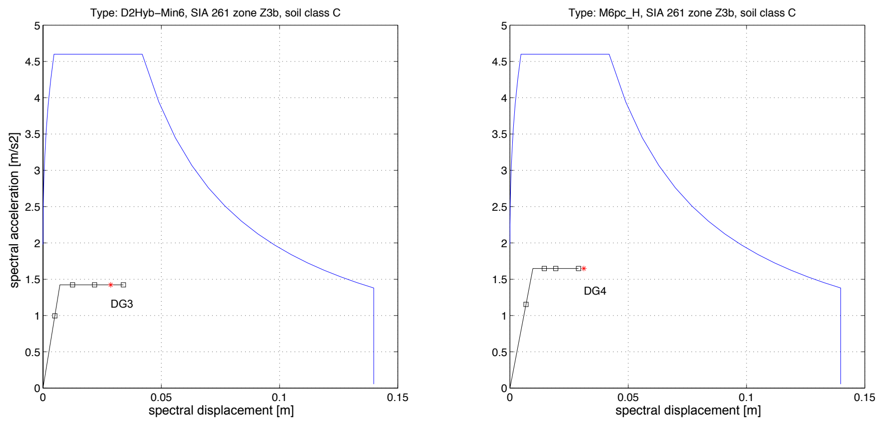

Figure 12. Comparison of capacity curve, performance point and damage grade for 6-storey building of typology D2 and M6-PC_H.

Although Swiss buildings exhibit lower global strength, in overall, it is concluded that damage grade predictions resulting following the two approaches are comparable, being the displacement capacity the critical parameter. More specifically, for low and mid-height buildings the capacity curve according to RiskUE-LM2 studies, exhibits higher strength but very similar ductility. Difference in material's strength, geometric irregularities and piers configuration may significantly influence the base shear capacity, whereas the deformation is for both cases directly dependent on Eurocode 8 (CEN,2005) drift thresholds. If the 3-storey D2 typology is compared with the M6-PC_M, which is also developed for 3-storey structures, more conservative results are expected per LM2, although for higher strength. However, it is generally observed that the discrepancies of the two methods curves are reduced as the height of the structure increases. The same trend is expected for different soil classes. More comparisons are performed for buildings of different heights (Lestuzzi et al., 2016a).

4.3. Improvement of Risk-EU LM2 typologies RC2 and M6-PC

Based on the results described above, improvements may be proposed for the typologies M6-PC and RC2 of the RiskUE LM2 method for the Swiss building stock. The capacity curves of the M6-PC typology are quite well suited for damage prediction at territorial level. However, improvement may be obtained by a slight modification of the limits of the height category of buildings: low-rise (M6-PC_L) should include buildings up to 3 storey height, mid-rise (M6-PC_M) category should correspond to buildings between 4 and 7 storey height and high-rise (RC2_H) may better include buildings from 8 storey height. On the other hand, for accurate risk and loss assessment, for which fragility curves will be developed in a next step, the actual typological curves computed for the Swiss typologies will be of use (Lestuzzi et al., 2016b).

Contrary, capacity curves of the RC2 typology are not suited for a safe damage prediction of buildings with shear walls such as the ones present in Switzerland. The implementation of the new typological curves, for the no-ERD shear wall buildings, is strongly recommended. The capacity curves for buildings of the three height categories are proposed, by means of the following defining parameters (Table 2). The curves proposed in Table 2 correspond to the ones of specific typology C of 3, 6 and 8 storey height for RC2_L, RC2_M and RC2_H respectively.

Table 2. Proposed capacity curves for RC shear walls buildings to be used with LM2 method

BTM	T [s]	Ay [-]	dy [m]	du [m]
RC2_L	0.34	0.209	0.006	0.065
RC2_M	0.54	0.193	0.014	0.176
RC2_H	0.66	0.176	0.019	0.263

5. CONCLUSIONS

A recent research project of seismic scenarios for the cities of Sion and Martigny in Switzerland provided the opportunity for checking the standardized capacity curves of Risk-UE LM2 typologies RC2 and M6-PC. Within the framework of this project, a detailed analysis was achieved for more than 500 typical Swiss buildings composed of both unreinforced masonry buildings with stiff floors and reinforced concrete shear walls buildings. Based on individual features of the buildings, individual capacity curves were first determined by a simplified method and typological curves were developed by appropriate statistical elaboration.

The comparison of the capacity curves of RiskUE-LM2 with the specific ones of the swiss building stock, and the corresponding damage grade yields to similar results for unreinforced masonry buildings with stiff floors, i.e. the M6-PC EMS-98 typology. By contrast, accuracy for reinforced concrete buildings with shear walls, i.e. the RC2 EMS-98 typology, is very poor.

As a consequence, seismic vulnerability assessment of cities of northern Europe is accepted to be performed using capacity curves of M6-PC typology, but implementation of the capacity curves of RC2 typology should be avoided, leading to too conservative damage prediction. Defining parameters for new standardized curves are suggested for the RC2 typology of the three height categories. Meanwhile, improvements are proposed for the M6-PC typology, slightly modifying the height limits of the height categories. At all means, the new capacity curves of the URM typology is strongly recommended to be used for risk and loss assessment of northern European urban territories with higher accuracy.

The risk assessment and the related seismic scenarios for the cities of Sion and Martigny have been performed using the individual capacity curves for the studied buildings and the elaborated typological curves for the entire building stock.

Acknowledgments

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6. REFERENCES

ATC (1985). Earthquake damage evaluation data for California (ATC-13). Appl. Technology Council, Redwood City, California.

Bozzano, C., Kazantzidou-Firtinidou, D., Belo, A., Glassey, J. (2015). Relevé de vulnérabilité sismique des bâtiments existants, Guide pratique, Centre de Recherche de l'Environnement Alpin, Sion, Suisse.

Cattari, S., Curti, E., Giovinazzi, S., Lagomarsino, S., Parodi, S., Penna, A. (2005). Un modello meccanico per l'analisi di vulnerabilità del costruito in muratura a scala urbana, Proceedings of XI Convegno Nazionale "L'ingegneria sismica in Italia", Gênes, Italie.

Crowley, H., Pinho, R., Bommer, J. J. (2004). A probabilistic displacement-based vulnerability assessment procedure for earthquake loss estimation, Bulletin of Earthquake Engineering, vol. 2, no. 2, pp. 173-219

Fäh D. et al. (2012). Coupled seismogenic geohazards in Alpine regions. Bolettino di Geofisica Teorica ed Applicata. Vol. 53, n. 4, pp. 485-508.

Fajfar, P. (2000). A non-linear analysis method for performanced-based seismic design, Earthquake Spectra, 16, 3 : pp.573-591

Greifenhagen C. and Lestuzzi P. (2005). Static-cyclic tests on low reinforced concrete shear walls. Engineering Structures. Vol 27/11, pp. 1703-1712.

Grünthal, G. (1998). European Macroseismic Scale 1998, Cahier du Centre Européenne de Géodynamique et de Séismologie, Vol. 15, Luxembourg.

HAZUS. (1999). Earthquake loss estimation methodology – Technical and user manuals, vol. 1–3. Federal Emergency Management Agency (FEMA), National Institute of Building Sciences, Washington, DC.

Kazantzidou-Firtinidou, D., Bozzano, C., Rouiller, J.-D., Lestuzzi, P., Podestà, S., Luchini, C. (2015). Evaluation expéditive de la vulnérabilité sismique du bâti des agglomérations de Sion et Martigny. Projet SEISMOVAL-Risk-UE-UniGEN. Rapport final. CREALP. (in French)

Lagomarsino S., Cattari S. (2013). Seismic vulnerability of existing buildings: Observational and mechanical approaches for application in urban areas – Chapter 1. In: Seismic vulnerability of structures. P. Guéguen (ed.), 1-62. ISTE Ltd and John Wiley and Sons, 2013.

Lagomarsino, S., Giovinazzi, S. (2006). Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. Bulletin of Earthquake Engineering, Vol. 4, pp. 415-443.

Lestuzzi, P., Podestà, S., Luchini, C., Garofano, A., Kazantzidou-Firtinidou, D., Bozzano, C., Bischof, P., Haffter, A. (2016a). Seismic vulnerability assessment at urban scale for two typical Swiss cities using Risk-UE methodology. Natural Hazards. Vol. 84, Issue 1, pp. 249-269. DOI 10.1007/s11069-016-2420-z

Lestuzzi, P., Podestà, S., Luchini, C., Garofano, A., Kazantzidou-Firtinidou, D., Bozzano, C. (2016b). Validation and improvement of Risk-UE LM2 capacity curves for URM buildings with stiff floors and RC shear walls buildings. Bulletin of Earthquake Engineering. DOI 10.1007/s10518-016-9981-9

Luchini C. (2016). Development of displacement-based methods for seismic risk assessment of the existing built environment. PhD thesis, University of Genova, Italy, 2016.

Luchini C., Podestà S. (2015). Sviluppo di modelli meccanici con approccio agli spostamenti per la valutazione della vulnerabilità sismica delle tipologie strutturali svizzere. In: Proc. of 16th Italian Conference on Earthquake Engineering, L'Aquila, Italy. (in Italian)

Milutinovic, Z.M., Trendafiloski, G.S. (2003). An advanced approach for earthquake risk scenarios with applications to different European towns. WP-4: Vulnerability of current buildings. Risk-UE Project, European Commission.

NOAA, 1972. A study of earthquake losses in the San Francisco Bay Area - Data and Analysis, A report prepared for the Office of Emergency Preparedness: U.S. Department of Commerce, 220 p.

SIA 261 (2003, Swiss standard). Actions on structures, Swiss Society of Engineers and Architects (SIA), Zurich 2003.