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ORIGINAL RESEARCH PAPER

Validation and improvement of Risk-UE LM2 capacity curves for URM buildings with stiff floors and RC shear walls buildings

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Abstract This paper addresses seismic vulnerability assessment at an urban scale and more specifically the capacity curves involved for building damage prediction. Standard capacity curves are a function of predefined building typology and are proposed in the Risk-UE LM2 method for computation of the corresponding damage grades. However, these capacity curves have been mainly developed for building stock of southern European cities and the accuracy of their application with different building features, such as the ones of cities of northern Europe should be assessed. A recent research project of seismic scenarios for the cities of Sion and Martigny in Switzerland provided the opportunity to check the capacity curves of Risk-UE LM2 method. Within the framework of this project, a detailed analysis was achieved for more than 500 buildings. These buildings were typical Swiss buildings and were composed of both unreinforced masonry buildings with stiff floors and reinforced concrete buildings. The construction drawings of each building were collected in order to have the most accurate information about their main structural characteristics. The typological classification that has been adopted was developed in a recent research project. Based on the individual features of the buildings, individual capacity curves were defined. Results of the seismic assessment applied to the 500 buildings compare very well with those obtained by using Risk-UE LM2 method for unreinforced masonry buildings with stiff floors. A slight improvement may be proposed for buildings with three stories through their introduction to the category of low-rise instead of mid-rise buildings. By contrast, accuracy for reinforced concrete buildings with shear walls is very poor. Damage prediction using related capacity curves of Risk-UE LM2 method does not correspond to reality. Prediction is too pessimistic and moreover damage grades increase with the height category (low-rise, mid-rise and high-rise) of these

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buildings which is in contradiction with the observed damages for this type of buildings. Improvements are proposed to increase the accuracy of the seismic vulnerability assessment for northern European building stock. For unreinforced masonry buildings, a slight modification of the limits of the height category of buildings using the ones defined for RC buildings improves the damage prediction. For reinforced concrete buildings with shear walls improved capacity curves derived from the typological curves of the specific typology C are proposed.

Keywords Risk-UE method · Seismic vulnerability assessment · Existing buildings · Capacity curves · Damage grades · RC shear walls · URM

1 Introduction

Seismic risk analyses at a territorial level are important for both the development of prevention strategies and post-earthquake emergency management. Indeed these analyses, on the basis of exposure and vulnerability data of the built environment, result in an assessment of damage scenarios on a territorial level representative of a possible estimation of damage on the investigated area, as a result of a well-defined seismic event.

In specific reference to vulnerability assessment of the built environment, models, in order to be applicable on a territorial scale, have to necessarily be based on a few easily available data. In a territorial scale vulnerability analysis, the object is not generally represented by a single building, but by classes of buildings characterized by a homogeneous behavior.

Different methods of analysis for the seismic risk at large scale have been developed during the last decades, mainly in regions affected by damages from recent earthquakes, taking advantage of direct evidence offered by post-seismic effects on structures. The first methods have been developed in USA (FEMA 1997; HAZUS 1999), in Japan (Otani 2000), in Canada (Ventura et al. 2005; Onur et al. 2005), in Turkey (Ergunay and Gulkan 1991), in Italy (Benedetti and Petrini 1984; GNDT 1993; Seismocare 1998; Dolce et al. 2003), in Portugal (Oliveira 2003), in Spain (Roca et al. 2006), in France (Guéguen et al. 2007) or in Switzerland (Lang and Bachmann 2003). Generally, these methods are based on the definition of a damage scale and the determination of a building typology classification of the studied environment.

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 categories:

- Typological-observational or empirical methods, which provide damage probability matrices or vulnerability curves, which are defined starting from statistical post-earthquake observed damage data for different classes of buildings.
- Mechanical methods, which allow to use the results of sophisticated hazard analysis and to take into account the various parameters that define the structural dynamic response.

Displacement-based methods that are included in the mechanical method category describe the response of the structures with the increase of seismic input intensity through definition of capacity curves that represent the response evolution in non-linear field. Each point on the capacity curve is associated with a given level of damage. It is possible to obtain an assessment of the seismic response identifying the displacement required (performance point) from a comparison between the capacity curve and the seismic demand using appropriate non-linear static procedures. Finally the distribution of damage levels can be evaluated by defining proper damage states on the capacity curve, corresponding to predefined displacement values.

The findings described in this paper were obtained within the framework of a more comprehensive research project dealing with the seismic vulnerability of the cities of Sion and Martigny in Switzerland. The objective of this project was to assess the seismic vulnerability at urban scale of the two main cities of the canton of Valais by taking into account the specific features of the Swiss building stock. Buildings of both cities were firstly surveyed through rapid visual screening. An additional detailed survey was performed for approximately 500 buildings using construction drawings of each building in the city archives. The detailed survey led to the development of a specific typology valid for typical Swiss buildings with stiff floors. The related capacity curves, called typological curves, were also developed. This paper focuses on the comparison between typological curves and standard capacity curves in terms of damage prediction accuracy.

2 Swiss data

The largest historical earthquake in Europe for the North of the Alps occurred in 1356 in the city of Basel at the French and German borders. However, the earthquake hazard in Switzerland may be qualified as moderate in comparison with the one for southern Europe. The largest peak ground acceleration is 1.6 m/s^2. The most seismically exposed region is situated in the South part of the country, essentially corresponding to the canton of Valais (Fig. 1).

However, seismic prescriptions were totally ignored for a long time in the Swiss codes. First adequate requirements were proposed in 1989. As a consequence, the large majority of the building stock in Switzerland was build without any seismic considerations.

Swiss building stock is mainly composed of low-rise and mid-rise buildings constructed from masonry and reinforced concrete. The masonry buildings are unreinforced masonry, which are subdivided into stone masonry buildings with flexible floors and brick masonry buildings with stiff floors (Fig. 2). Reinforced concrete (RC) buildings are mostly shear walls buildings with low reinforcement ratios (Greifenhagen and Lestuzzi 2005). A specific characteristic in Switzerland is the wide spread construction of basement required for shelter against atomic bombs.

3 Risk-UE methodology

The Risk-UE project (An advanced approach to earthquake risk scenarios with application to different European towns) was a European project focused on the evaluation of the seismic risk at wide scale, accepted within the 5th Framework Research and Developed Program of the European Union (Risk-UE 2003). It was carried out in the years 2001–2004 and represented the first collaborative and comprehensive research program on the study of regional seismic risk focused on the European built environment. As a benchmark, the programme included the application of the developed methodology to the case of seven South-European cities. The general objective of the Risk-UE project was the development

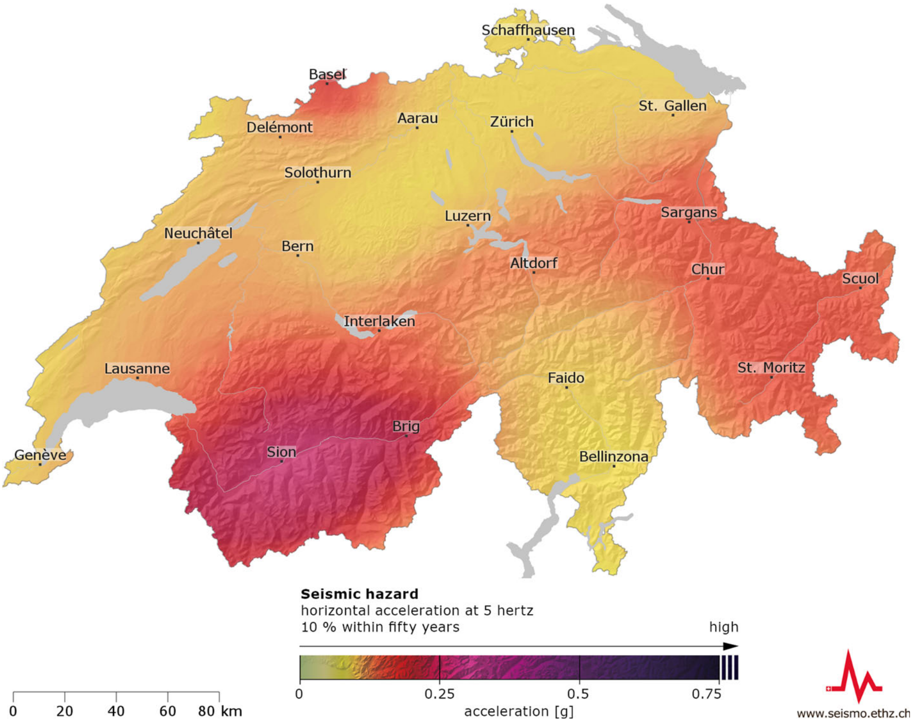


Fig. 1 Earthquake hazard in Switzerland (Swiss Seismological Service (SED) at ETH Zurich 2015)

Fig. 2 Typical unreinforced masonry buildings in Switzerland

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 (Mouroux and Le Brun 2006; Mouroux et al. 2004).

Typological classification (Building Typology Matrix (BTM)) introduced within the project reflects differences between types of structures that are expected to have similar seismic behavior (Table 1). Basically, the typologies defined within the RISK-UE project

Table 1 Building classification in Risk-UE (Lagomarsino and Giovinazzi 2006)

Typologies	Building types
Unreinforced masonry	
M1	Rubble stone
M2	Adobe (earth bricks)
M3	Simple stone
M4	Massive stone
M5	U masonry (old bricks)
M6	U masonry—r.c. floors
Reinforced/confined masonry	
M7	Reinforced/confined masonry
Reinforced concrete	
RC1	Concrete moment frame
RC2	Concrete shear walls
RC3	Dual systems

are related to the building classes provided by EMS-98 (Grünthal et al. 2001), with the addition of a typology related to the reinforced concrete dual system (RC3), and taking into account, through the introduction of sub-typologies (Milutinovic and Trendafiloski 2003; Lagomarsino and Giovinazzi 2006), of particular aspects for a more detailed characterization of buildings.

The Risk-UE methodology proposed two methods, the empirical method LM1 and the mechanical method LM2. The empirical method LM1 deals with macroseismic intensity according to EMS98 and vulnerability indexes (Lagomarsino and Giovinazzi 2006). The mechanical method LM2 deals with standard capacity curves and capacity spectrum method to determine damage grades through determination of the performance point.

The mechanical method adopted within the Risk-UE project is essentially similar to the method adopted by HAZUS (1999). Few modifications are made regarding capacity curves of seismically non-designed European masonry typologies and seismically designed buildings according to European codes.

For each building class, a capacity curve is provided which corresponds to an equivalent single-degree-of-freedom (SDOF) system. Such a curve is defined by four parameters. Yielding displacement, d_y, and ultimate displacement, d_u, have been derived as a function of yielding acceleration, a_y; fundamental period, T is also provided for each building class (Lagomarsino and Giovinazzi 2006). Table 2 shows the capacity curve parameters for

Table 2 Definition of the capacity curves for M6 (unreinforced masonry buildings with stiff floors) and RC2 (shear walls reinforced concrete buildings) types in Risk-UE LM2 mechanical method (M6_L for low-rise, M6_M for mid-rise and M6_H for high-rise; PC for pre-code) (Lagomarsino and Giovinazzi 2006)

Type	n_storey	T [s]	a_y [g]	d_y [m]	d_u [m]
M6_L-PC	1–2	0.211	0.324	0.0036	0.0171
M6_M-PC	3–5	0.355	0.256	0.0080	0.0260
M6_H-PC	6+	0.481	0.168	0.0097	0.0290
RC2_L	1–3	0.539	0.278	0.0201	0.0606
RC2_M	4–7	0.854	0.166	0.0300	0.0904
RC2_H	8+	1.304	0.097	0.0407	0.1227

unreinforced masonry buildings with stiff floors (type M6) and for shear walls reinforced concrete buildings (type RC2). The capacity spectrum method is employed to assess the building's performance within the LM2 method. Therefore, 5 % damping elastic response spectrum can be considered for the seismic demand, most often in the Acceleration-Displacement Response Spectrum (ADRS) format. Seismic performance of the building is defined through identification of the "performance point" (Freeman 1998).

4 Seismic vulnerability assessment for Sion and Martigny

The seismic vulnerability assessment of the cities of Sion and Martigny using Risk-UE methodology is described in details elsewhere (Lestuzzi et al. 2016). Only the main issues are summarized in the following sections.

The city of Sion is the main city of the canton of Valais and has a population of over 30,000 inhabitants for a total of 3600 buildings. The city of Martigny is located southwest of Sion at a distance of around 30 km (Fig. 3). Martigny is the second main city of the canton of Valais and has a population of over 20,000 inhabitants for a total of 2500 buildings. Both cities are located in the highest seismic zone of Switzerland, namely the zone Z3b with a design peak ground acceleration of 1.6 m/s^2 (Fig. 3).

4.1 Building surveys

Within the framework of a research project performed in collaboration with the Canton of Valais, the EPFL and the University of Genoa, the building stocks of the cities of Sion and Martigny were surveyed through rapid visual screening. The rapid survey of the city of Sion concerns around 3200 buildings and the survey of the city of Martigny concerns about

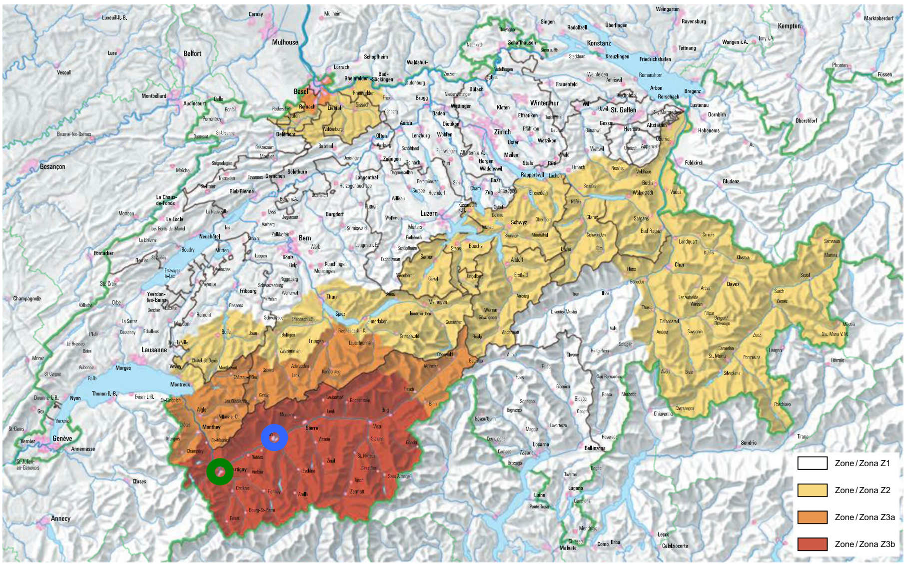


Fig. 3 The four seismic zones in Swiss building code (SIA 2003) and the location of the investigated cities, Sion (*blue circle*) and Martigny (*green circle*)

1600 buildings. Figure 4 shows the global building material distribution for the cities of Sion and Martigny, respectively. Figure 5 shows the related global building height distribution (Lestuzzi et al. 2016).

Distributions of building materials are similar for both cities. Unreinforced masonry buildings represent more than the half of the building stock. The dominating presence of the unreinforced masonry buildings is even more pronounced for Martigny, reaching three quarters of the whole stock. The remaining building stock is composed of reinforced concrete buildings. In Switzerland, the majority of reinforced concrete buildings are shear walls buildings. The distributions regarding number of stories are similar for both cities and correspond to the usual distribution of typical Swiss cities. Low-rise buildings up to three stories height represent 70 % of the building stock. Taller buildings, seven stories and over, are more rare and correspond to less than 6 % of building stock.

An additional detailed survey was also performed for a limited number of buildings in both cities. Within the detailed survey the construction drawings of each building were collected in the city archives (Fig. 6). The detailed survey of Sion concerns 206 buildings and the one of Martigny 306 buildings. The main parameters of the building stock (material, number of stories, irregularities, etc.) collected during the rapid survey are stored in a database.

4.2 Building typology

During the rapid survey the typologies according to the RISK-UE LM1 and LM2 methodology were assigned to each building. Furthermore, the detailed survey led to the development of a specific typology valid for typical Swiss buildings with stiff floors (Fig. 7). The typology A1 is for unreinforced masonry (URM) buildings with a basement floor in reinforced concrete (RC). The typology A2 is for buildings with mixed URM-RC along the height. The typology B2 is for buildings with RC pillars in the base floor. The typology C is for buildings with RC shear walls. The typology D2 is for buildings with URM shear walls. Shear walls extend from base floor to top because ground floor is built of reinforced concrete and thus is generally much stronger than the upper floors.

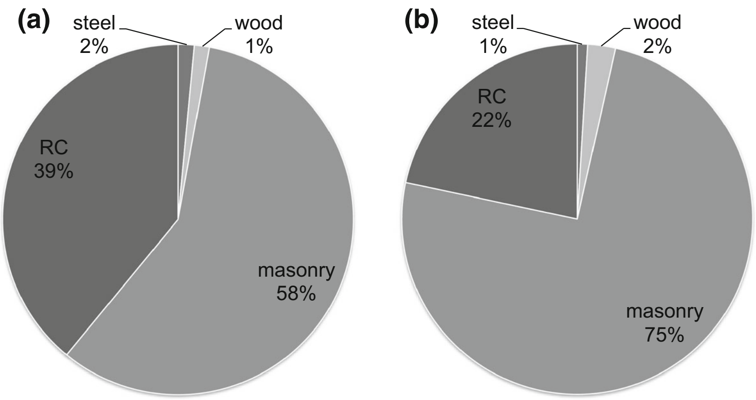


Fig. 4 Building material global distribution **a** 3200 buildings of Sion and **b** 1600 buildings of Martigny (Lestuzzi et al. 2016)

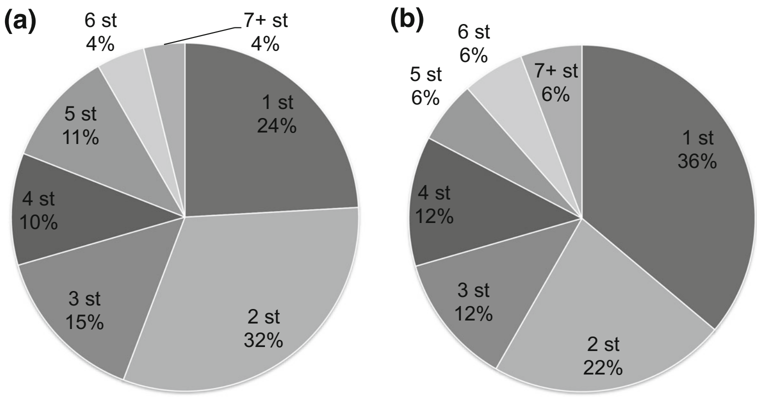


Fig. 5 Building height global distribution **a** 3200 buildings of Sion and **b** 1600 buildings of Martigny (Lestuzzi et al. 2016)

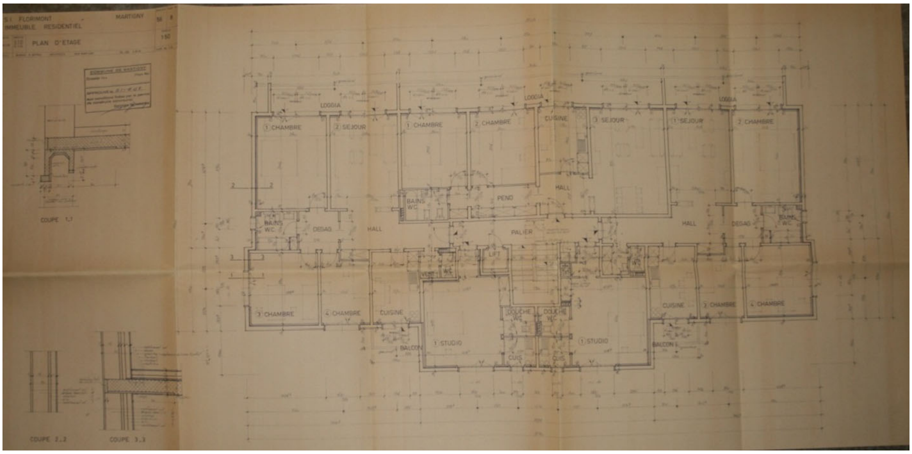


Fig. 6 Building drawing including construction detailing (Kazantzidou-Firtinidou et al. 2015)

4.3 Building typological distribution

The global distribution of the more than 500 detailed survey buildings into the specific typology (Fig. 7) is different for the cities of Sion and Martigny (Fig. 8). The distribution is nearly uniform for the city of Sion but typology D2 is clearly dominant in the city of Martigny.

The major part of the detailed survey buildings is composed of low-rise and mid-rise buildings up to six stories (Fig. 9). Buildings taller than six stories are less present. It should be noted that compared to those of Figs. 4 and 5, the distributions of Fig. 9 are biased somewhere since buildings of less than three stories were not considered for the detailed survey. Nevertheless, low-rise and mid-rise buildings represent the largest part of the detailed survey buildings (70 % for Sion and 75 % for Martigny).

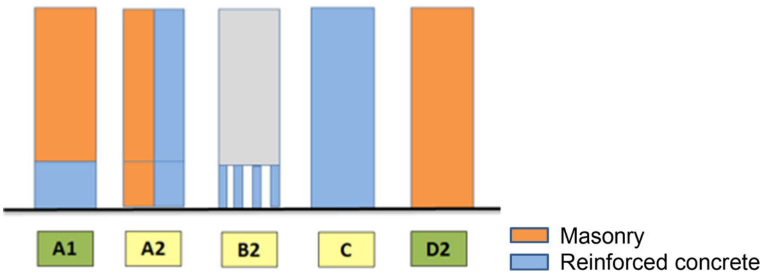


Fig. 7 Specific typology for typical Swiss buildings (Luchini 2016)

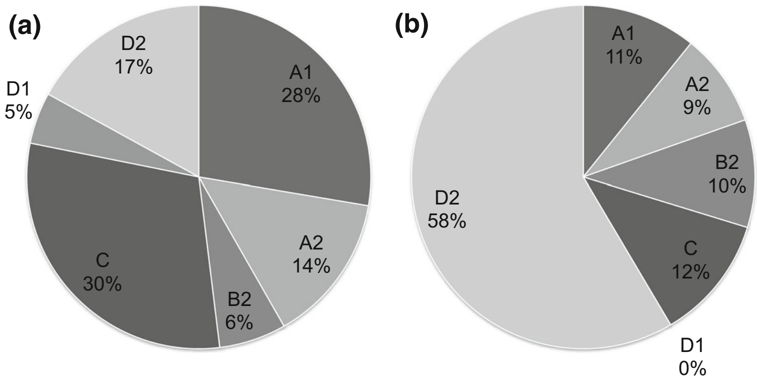


Fig. 8 Building specific typological global repartition **a** 206 buildings of Sion and **b** 306 buildings of Martigny

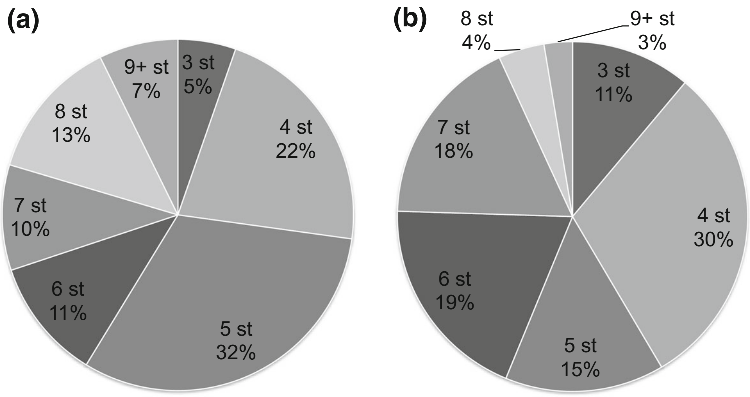


Fig. 9 Building height global distribution **a** 206 buildings of Sion and **b** 306 buildings of Martigny

5 Typological curves

Different approaches are available in literature to obtain capacity curves in a simplified form for territorial scale assessment. In particular the mechanical model known as Displacement Based Vulnerability (DBV) method (Lagomarsino and Cattari 2013), defined for both masonry and reinforced concrete frame structures, has been chosen, as starting point, for the seismic vulnerability assessment of Swiss built environment (Fig. 10). 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 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 et al. 2001) 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.

A fundamental aspect for the application of a mechanical model on a territorial scale is the classification of buildings into groups, characterized by a homogeneous behavior, to which associate a suitable analysis model. Therefore a specific displacement based model has been defined for every Swiss constructive type previously described (Fig. 7) and typological capacity curves were developed using statistical assessment of the individual capacity curves of the 500 buildings surveyed in detail.

For the identified structural classes, since there was no direct comparison with real damage observed [last earthquake in Valais was in 1946 and is not well documented (Fritsche and Fäh 2009)], detailed structural analyses have been carried out on a selection of buildings to calibrate the corrective factors of the DBV method and validate the

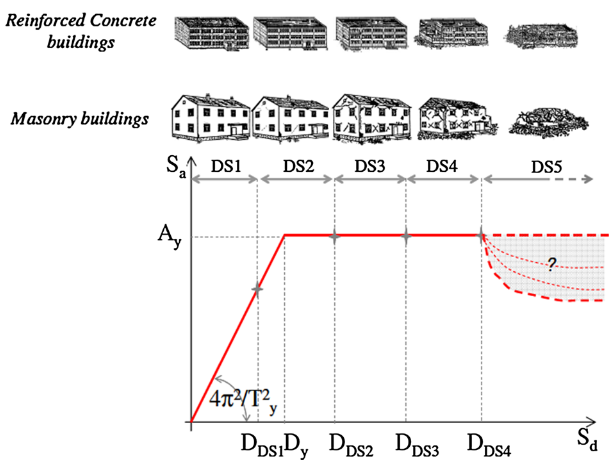


Fig. 10 Capacity curve according to displacement based vulnerability method and definition of damage limit state (Lagomarsino and Cattari 2013)

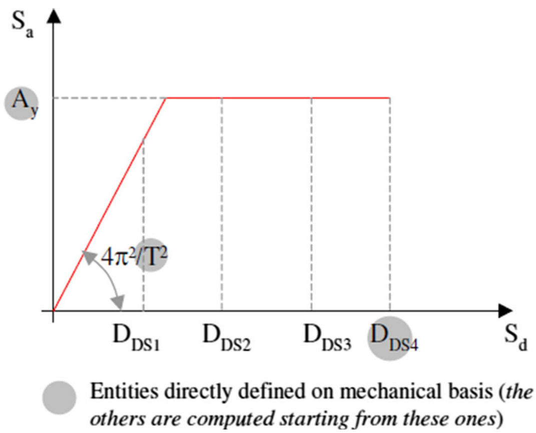
vulnerability model developed for mixed structure and for reinforced concrete shear walls structures.

5.1 Capacity curves for masonry buildings with stiff floors

The DBV method for masonry structure, originally proposed by Cattari et al. (2004), defines a capacity curve, through few geometrical and mechanical parameters. This is representative of the structure response in non-linear field and to obtain a simplified assessment of the structure overall strength. The assessment considers only in-plane behavior of walls and takes into account two different collapse modes: uniform and soft-storey. The capacity curve is schematized by a bilinear behavior, in particular a curve with elastic perfectly-plastic behavior is assumed (Fig. 11). It is completely defined by three parameters: the yield acceleration A_y, the fundamental period T and the ultimate displacement capacity D_u. However, the calculation of these parameters depends on the definition of specific corrective factors: ξ, ζ_{res} and ζ_{rig}. These give the model a possibility to take into account, although in a simplified way, some of the effects that more properly characterize the real behavior of existing masonry buildings. In particular, ξ is a coefficient which takes into account the different prevailing failure modes which may occur in masonry piers; ζ_{res} is a corrective factor that allows to take into account the effects which affect the strength related to the non homogeneous size of masonry piers (ζ_1), the geometric and shape irregularities in the plan configuration (ζ_2) and the spandrels stiffness (ζ_3) and ζ_{rig} a corrective factor that allows to take into account the effects which affect the stiffness related to the bending component (ζ_4) and the spandrels stiffness (ζ_5). These parameters were defined on a sample of buildings damaged by the 2009 L'Aquila earthquake (Luchini 2016), so they are representative of the most widespread masonry structures in Italy that are very different from Swiss masonry constructive types. This determines the need of a new parameters calibration in order to ensure the model reliability.

The corrective factors calibration was carried out through detailed structural analyses on a selection of concrete blocks masonry structures surveyed in Sion and Martigny. After having fixed these coefficients, different changes were introduced in the DBV method in order to define a reliable model also for A1 and A2 building type. Detailed information

Fig. 11 Capacity curve definition for unreinforced masonry buildings (Lagomarsino and Cattari 2013)



about the new models definition and the structural analyses results can be found in Luchini and Podestà (2015).

5.2 Capacity curves for reinforced concrete buildings

In the model defined for reinforced concrete frame structure the displacement capacity of the equivalent SDOF system is compared with the displacement capacity assessed on the spectrum at defined vibration period (Fig. 12). This approach is therefore based on the evaluation of the vibration period (T_{DSi}) and the displacement capacity related to different damage limit states (D_{DSi}), according to DBELA method (Crowley et al. 2004).

The evaluation of these parameters is carried out on the basis of the building typology, the construction period (parameter that is necessary to identify the code used in the design phase), the number of stories and the definition of different geometrical parameters (H_T total height; h1 inter-story height at ground floor; $h_{s(T)}$ height section of the main structural element that governs the global collapse mechanism; d_b longitudinal bar diameter) and the mechanical parameters (ε_{cu} ultimate concrete strain; ε_y steel strain at yielding; ε_{su} ultimate steel strain; f_y strength of steel, f_c concrete strength; L_V shear span).

New displacement-based models have been defined for B2 (RC columns at ground floor and concrete blocks masonry at higher levels) and C (RC walls) constructive types. The DBV method defined for RC frame structures has been chosen as reference for the typology B2 considering only the possibility to have a soft-storey collapse mechanism and making some changes in order to take into account the presence of concrete blocks masonry walls at higher levels. Whereas in the model defined for the building type C it has been proposed to take into account only the uniform failure mode. The values chosen to characterize the steel and concrete strength have been deducted from the tables attached to SIA (2018) as a function of the construction period. Additional information about the definition of new models and the detailed structural analyses results can be found in Luchini (2016).

5.3 Determination of typological curves

A capacity curve is representative of the structure response in non-linear field with the increase of seismic input and it is defined in terms of stiffness, overall strength and ultimate

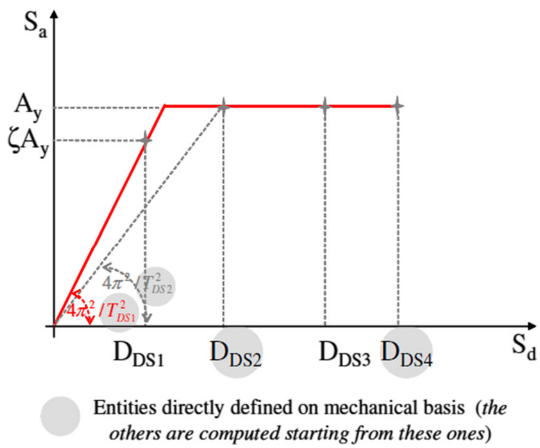


Fig. 12 Capacity curve definition for reinforced concrete buildings (Lagomarsino and Cattari 2013)

displacement capacity. For every typology of the Swiss taxonomy (Fig. 7), capacity curves have been calculated for different number of storeys. The main parameters that influence the curves should carefully be defined for each typology and collected from the geometric data of the sample: the first floor height (h_1), the inter-storey height (h), the thickness of the slab (s), the ratio of bearing walls in both directions (a) for the masonry model, the length of the shear walls (L) or the column's section (b) in both directions, for RC model.

Dispersion on the capacity curve of a building is related to random variables, such as the material parameters, the geometry and the drift capacity of the bearing elements. 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 should be defined for all these parameters, however, only those whose variability significantly affects the response have to be assumed as random variables, with a proper probability distribution and related parameters (mean value and confidence levels at 16 and 84 %) (Luchini and Podestà 2015).

Every typological capacity curve has a variability range which is related to two borderline cases. This confidence interval has been evaluated by using the response surface method (Liel et al. 2009; Pagnini et al. 2011). A probabilistic study of the variable geometric parameters, on which is based the displacement-based model, has been carried out, for each structural type, thanks to the collected geometrical data. A lognormal distribution has been assumed for all these parameters, then the 16 and 84 % are obtained (Fig. 13).

Referring to the different Swiss building typologies, the 16 and 84 % confidence levels of the geometrical parameters that were considered as independent variables in the displacement-based models have been highlighted in Table 3.

It was possible to obtain the typological capacity curve using displacement-based methods for all the structural types. These curves were calibrated using building class, number of stories, global collapse mechanism, and construction period (Fig. 14). Typological curves for the structural classes A1, A2 and D2 have been evaluated considering a hybrid failure mode between soft story and uniform collapse mechanism. The ultimate displacement capacity has been defined as the mean of ultimate displacement capacity calculated with the uniform and soft story formulas. This step has been carried out to associate a single typological capacity curve to each structural class.

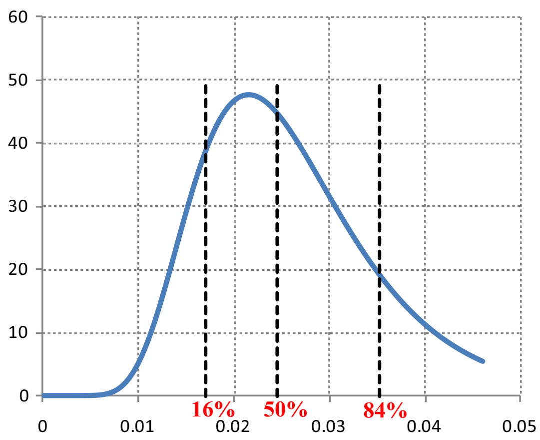


Fig. 13 Lognormal distribution, mean value and confidence interval (Luchini 2016)

Table 3 16 and 84 % confidence levels of the parameter assumed as random variables

Geometrical parameters	A1		A2		D2		B2		C	
	16 %	84 %	16 %	84 %	16 %	84 %	16 %	84 %	16 %	84 %
h_1 inter-story height at ground floor	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
h inter-story height	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
s floor thickness	✔	✔	✔	✔	✔	✔	✔	✔	✔	
$\alpha_{m,dir}$ resistant wall area parameters	✔	✔	✔	✔	✔	✔				
$\alpha_{r.c.,dir}$ resistant wall area parameters			✔	✔						
h_s section dimension							✔	✔		
L_w average walls length									✔	✔

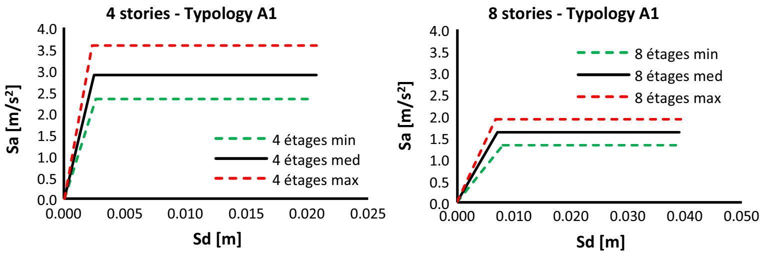


Fig. 14 Typology A1, minimal, mean and maximal typological curves for buildings of 4 and 8 stories. (Luchini 2016)

The typological curves defined in Table 4 show the most unfavorable typological capacity curves (minimal typological capacity curves with the lowest strength) for each confidence level (see Fig. 14). The typological capacity curve with the lowest strength has been selected because the comparison between the damage scenarios obtained using the median typological capacity curves and capacity curves calculated using real geometrical data has showed that the real damage scenario is more pessimistic than the one obtained using the median capacity curves. This is also a conservative assessment in the event of a single damage scenario is evaluated using typological capacity curves.

The performance points are determined according to EC8 procedure for seismic zone Z3b (peak ground acceleration of 1.6 m/s^2) and soil class C. The EC8 procedure for the determination of the displacement demand (performance point) is derived from the N2 method (Fajfar 1999). The N2 method is essentially based on the empirical equal displacement rule valid for the large to medium period range. Additionally, it is adjusted by increasing that approximate prediction for the short period range (plateau of the response spectrum; Michel et al. 2014). Note that by contrast to the competing procedures dealing with equivalent period and increased damping ratio, the performance point is not located at intersection between capacity curves and response spectrum in ADRS format.

Figure 15 shows the typological curves for the specific typology A1 (from 3 storey up to 8 storey buildings) and the related performance points (red star).

Table 4 Definition of the typological curves for A1, A2, C and D2 types of the specific Swiss typology (see Fig. 7; Luchini 2016)

Type	n_storey	T [s]	a_y [m/s^2]	d_y [m]	d_u [m]
A1	3	0.150	3.03	0.0017	0.0160
	4	0.213	2.32	0.0027	0.0204
	5	0.278	1.92	0.0037	0.0248
	6	0.344	1.66	0.0050	0.0293
	7	0.412	1.48	0.0064	0.0339
	8	0.481	1.34	0.0079	0.0385
A2	3	0.195	3.19	0.0031	0.0206
	4	0.254	2.63	0.0043	0.0250
	5	0.312	2.28	0.0056	0.0296
	6	0.371	2.03	0.0071	0.0342
	7	0.424	1.89	0.0086	0.0387
	8	0.478	1.77	0.0102	0.0433
C	4	0.400	2.28	0.0092	0.0999
	5	0.470	2.07	0.0116	0.1364
	6	0.540	1.92	0.0140	0.1761
	7	0.600	1.80	0.0164	0.2184
	8	0.660	1.69	0.0188	0.2627
D2	3	0.234	2.15	0.0030	0.0205
	4	0.304	1.80	0.0042	0.0249
	5	0.375	1.58	0.0056	0.0294
	6	0.445	1.43	0.0072	0.0340
	7	0.515	1.31	0.0088	0.0386
	8	0.535	1.33	0.0097	0.0401

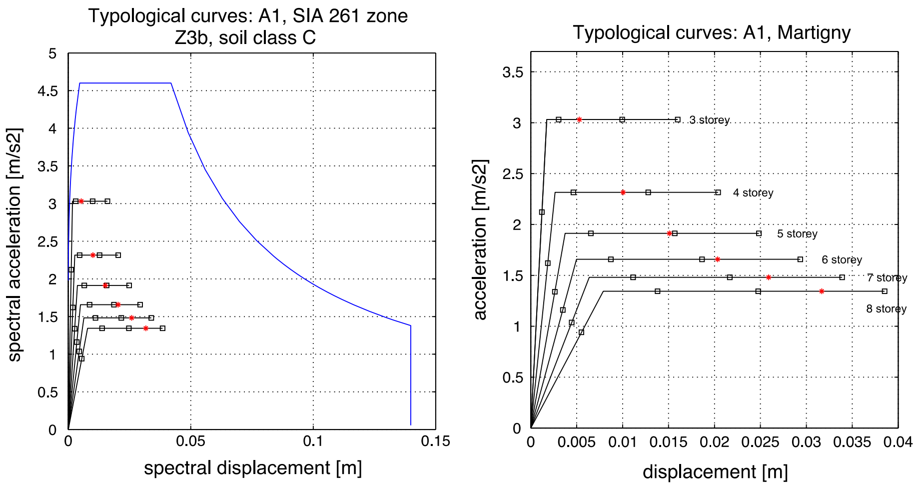


Fig. 15 Typological curves for the specific typology A1 and the performance point related to response spectrum of soil class C and seismic zone Z3b (SIA 2003)

Figure 16 shows the typological curves for the specific typology A2 (from 3 storey up to 8 storey buildings) and the related performance points (red star).

Figure 17 shows the typological curves for the specific typology C (from 4 storey up to 8 storey buildings) and the related performance points (red star).

Figure 18 shows the typological curves for the specific typology D2 (from 3 storey to 8 storey buildings) and the related performance points (red star).

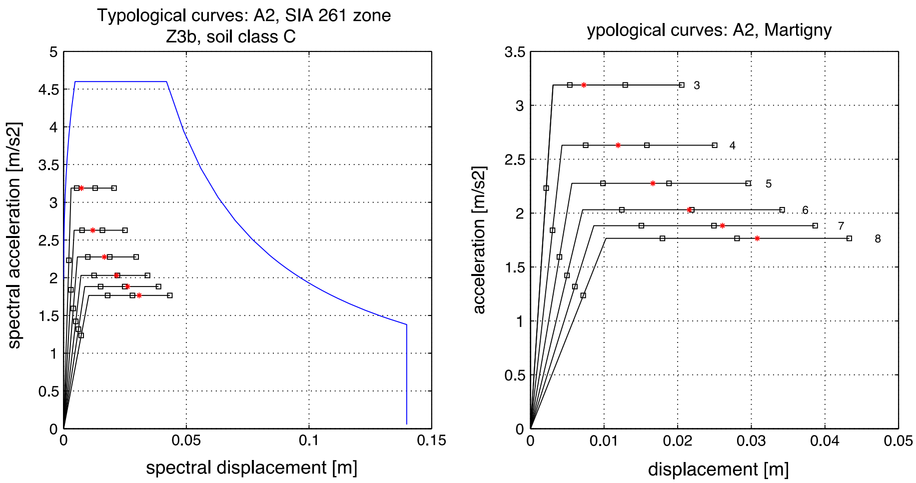


Fig. 16 Typological curves for the specific typology A2 and the performance point related to response spectrum of soil class C and seismic zone Z3b (SIA 2003)

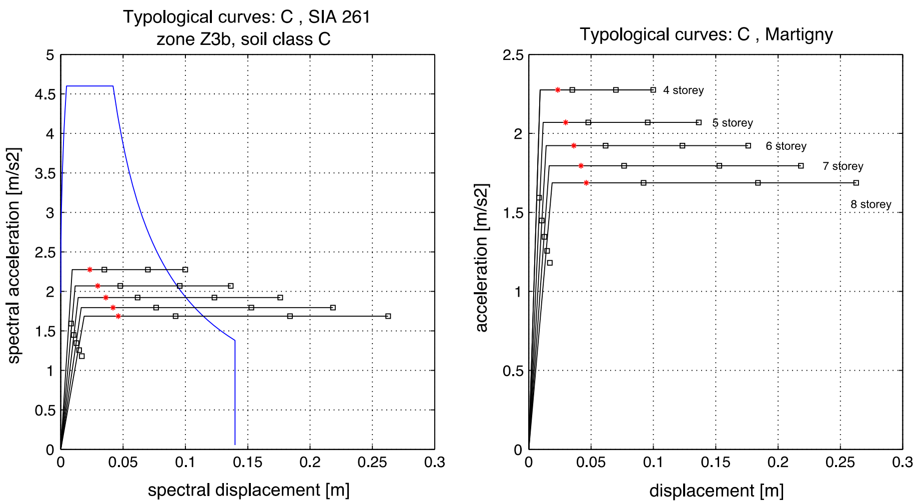


Fig. 17 Typological curves for the specific typology C and the performance point related to response spectrum of soil class C and seismic zone Z3b (SIA 2003)

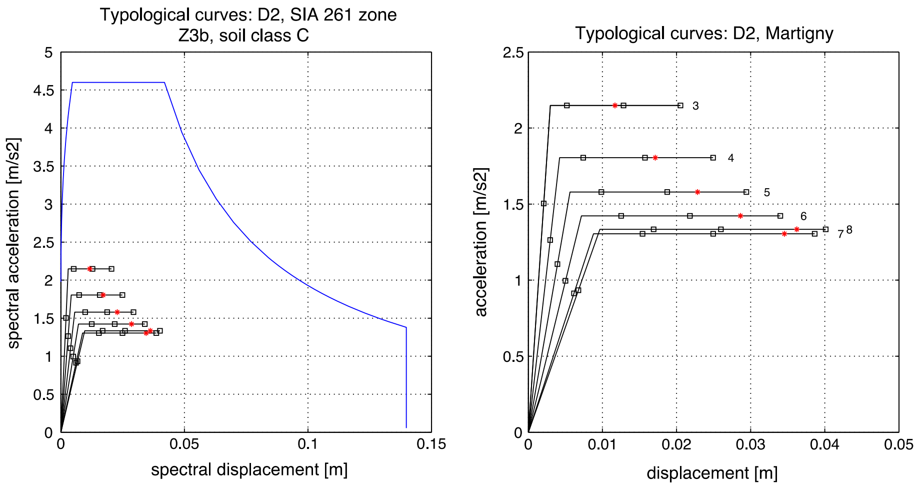


Fig. 18 Typological curves for the specific typology D2 and the performance point related to response spectrum of soil class C and seismic zone Z3b (SIA 2003)

6 Results with LM2

The damage grade predictions may also be computed using the capacity curves of Risk-UE LM2 method. The typology RC2 is considered for RC buildings with shear walls and the typology M6-PC is considered for URM buildings with stiff floors (see Table 1). The capacity curves are defined for three different categories of building height (Table 2): low-rise (_L), mid-rise (_M) and high-rise (_H). Damage grade determinations for RC2 typology and the response spectrum of soil class C for seismic zone Z3b are shown in Fig. 19.

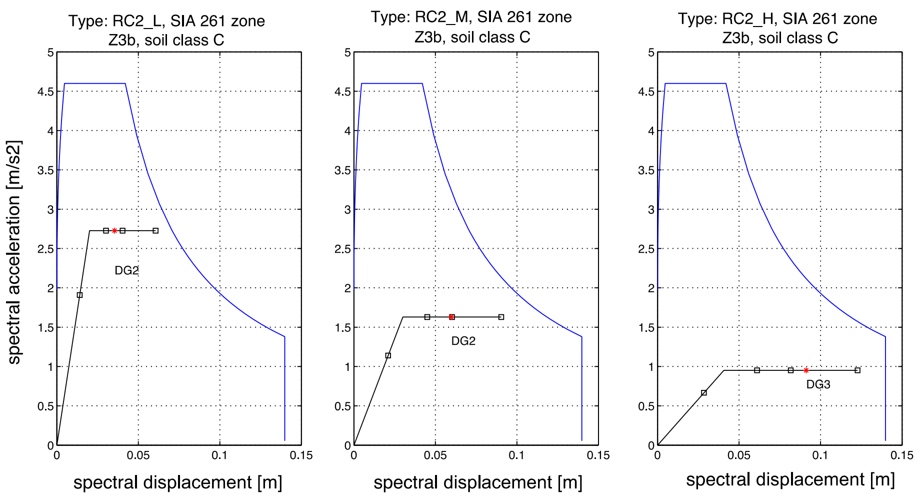


Fig. 19 Method LM2: damage grade of RC2 typology for soil class C and seismic zone Z3b

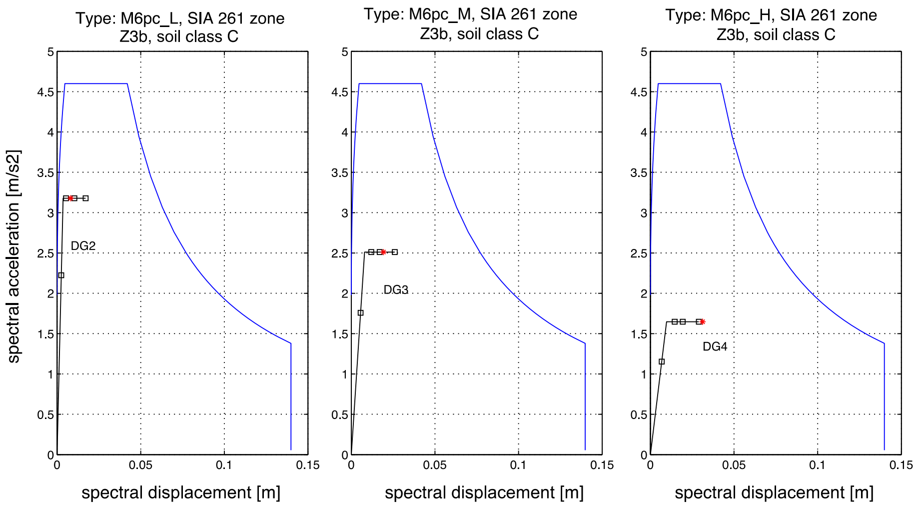


Fig. 20 Method LM2: damage grade of M6-PC typology for soil class C and seismic zone Z3b

The computation of the performance point is performed according to the EC8 procedure which is based on the N2 method. Damage grade determinations for M6-PC typology and the response spectrum of soil class C for seismic zone Z3b are shown in Fig. 20.

According to Risk-UE LM2 capacity curves, the damage grade increases with the increase of building height category (from _L to _H). This trend is fully compatible with field surveys after earthquake events for unreinforced masonry buildings but does not correspond to seismic behavior of reinforced concrete buildings with shear walls. It is well established that high-rise RC shear walls buildings are seismically less vulnerable than mid-rise or low-rise buildings.

7 Comparison between typological curves and 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 is compared with the specific typology C and M6-PC is compared with the specific typology D2. The comparisons are performed for soil class C and seismic zone Z3b which correspond to the conditions of the majority of the city of Martigny.

7.1 Specific typology C versus 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) means buildings from 8 storey and above. The results for 5-storey building of typology C and typology RC2_M are shown in Fig. 21.

The results for 8-storey building of typology C and typology RC2_H are shown in Fig. 22.

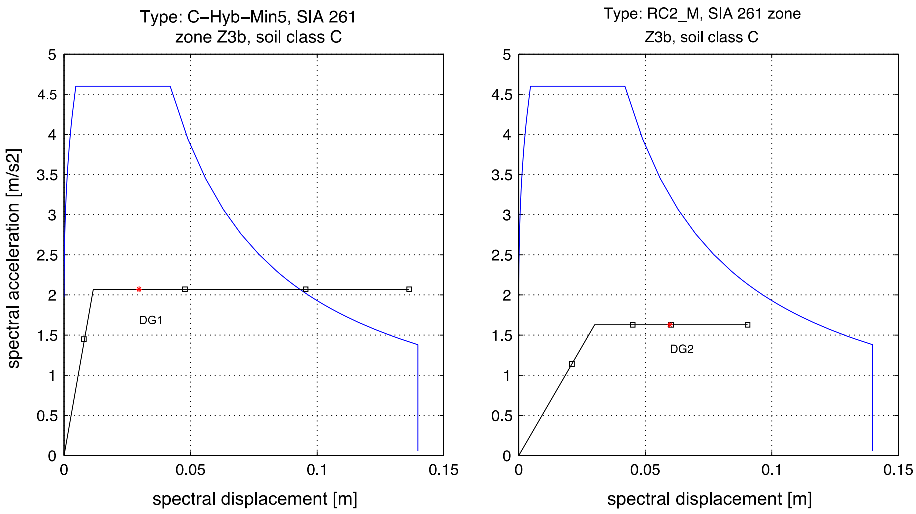


Fig. 21 Comparison: results for 5-storey building of typology C and RC2_M

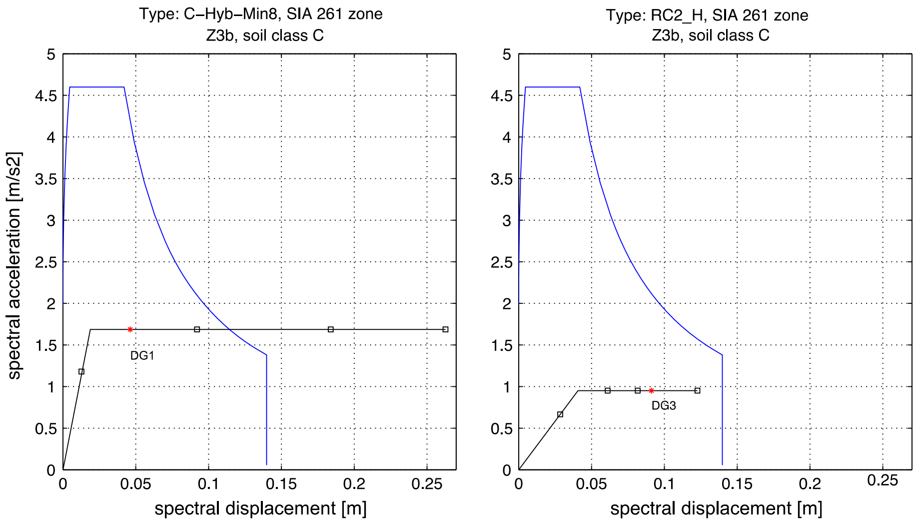


Fig. 22 Comparison: results for 8-storey building of typology C and RC2_H

The capacity curves of specific typology C are quite different from the ones of Risk-UE LM2 method for RC2 typology. They are larger in all characteristics (strength, displacement capacity and stiffness). As a consequence, a marked discrepancy appears between the damage prediction of both capacity curves families. The difference reaches up to two damage grades for high-rise building height category. The results reported above are computed for soil class C. However, this trend holds true for different soil classes. The difference is mainly related to the significant higher stiffness of the curves of the specific typology. Moreover, the trend is more realistic for the specific typology C since the damage grade does not increase with increasing number of stories.

7.2 Specific typology D2 versus typology M6-PC

According to the definition of Risk-UE LM2 method, for unreinforced masonry buildings, low-rise (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) means buildings from 6 storey and above. The results for 3-storey building of typology D2 and typology M6-PC_L are shown in Fig. 23.

The results for 4-storey building of typology D2 and typology M6-PC_M are shown in Fig. 24.

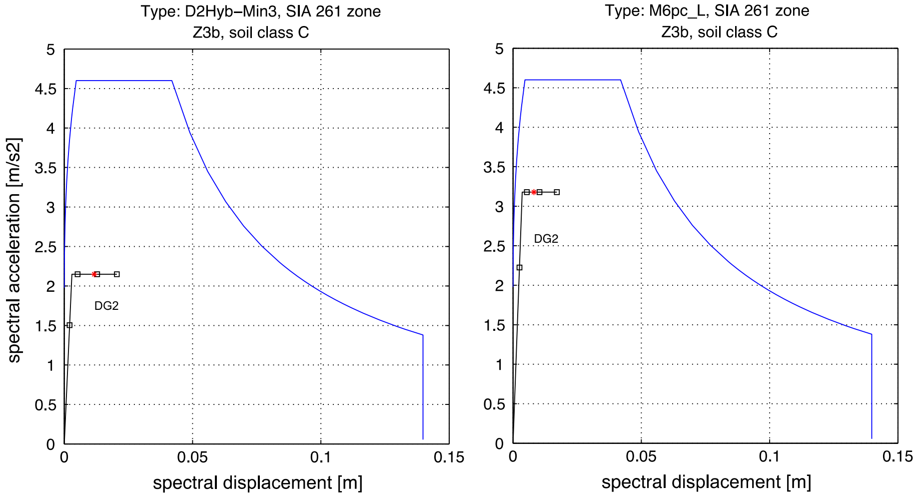


Fig. 23 Comparison: results for 3-storey building of typology D2 and M6-PC_L

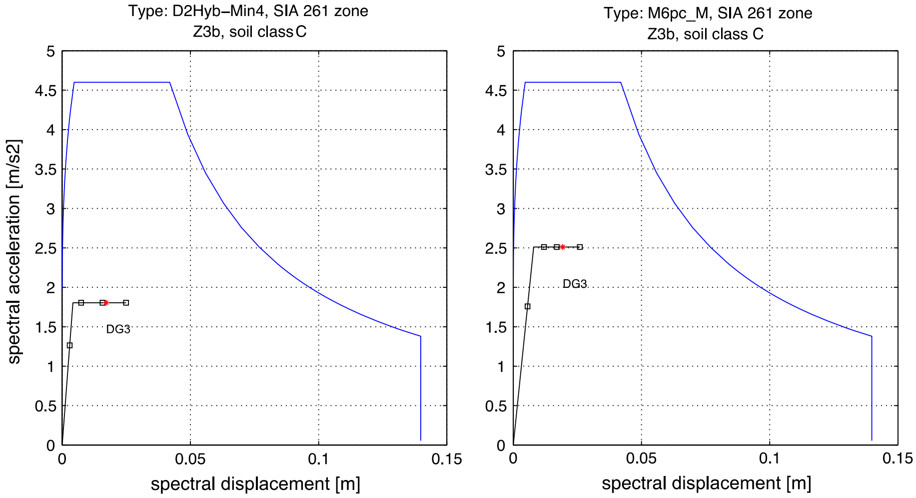


Fig. 24 Comparison: results for 4-storey building of typology D2 and M6-PC_M

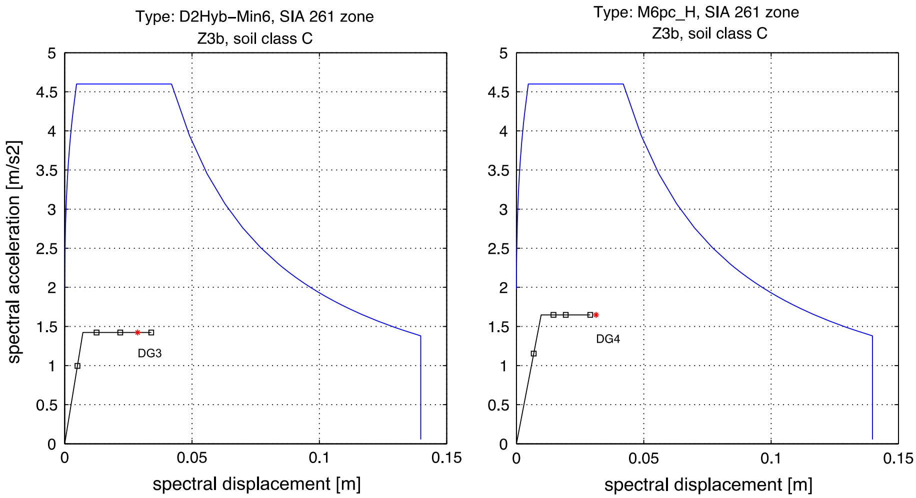


Fig. 25 Comparison: results for 6-storey building of typology D2 and M6-PC_H

The results for 6-storey building of typology D2 and typology M6-PC_H are shown in Fig. 25.

These results show that the typology M6-PC of the Risk-UE LM2 method leads to damage grade predictions very similar to the ones of specific typology D2. The typology M6-PC_H is more pessimistic than the specific typology D2 for buildings of 6 storey height or more. The typology M6-PC_L corresponds also to the specific typology D2 for 3 storey height. The results reported above are computed for soil class C. However, this trend remains for different soil classes.

8 Improvement of Risk-UE 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 Risk-UE LM2 method. The capacity curves of the M6-PC typology are well suited for an accurate damage prediction. However, improvement may be obtained by a slight modification of the limits of the height category of buildings. The categories defined for RC buildings apply better: low-rise (M6-PC_L) should include buildings up to 3 storey height, mid-rise (M6-PC_M) should corresponds to buildings between 4 and 7 storey height and high-rise (RC2_H) should start with buildings from 8 storey height. By contrast, capacity curves of the RC2 typology are not suited for an accurate damage prediction of buildings with shear walls such as ones present in Switzerland. It should be noted that within the Risk-UE project and by contrast to masonry buildings, vulnerability assessment of RC buildings was done roughly, without any validation or consensus among the partners (Risk-UE 2003; Mouroux and Le Brun 2006). This is probably the main reason why the comparison is so bad for RC buildings. As a consequence, different capacity curves should be used for shear walls RC buildings. Based on the developed typological curves for the specific typology C and the definition of the category heights, the following capacity curves may be proposed:

Table 5 Proposed capacity curves for RC shear walls buildings to be used with LM2 method

BTM	T [s]	A_y [-]	d_y [m]	d_u [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

The values proposed in Table 5 correspond to the ones of specific typology C of 3 storey, 6 storey and 8 storey height for RC2_L, RC2_M and RC2_H respectively.

9 Conclusions

Standard capacity curves of the Risk-UE LM2 method were checked to validate the accuracy of their application for the computation of the corresponding damage grades in case of seismic vulnerability assessment of cities of northern Europe.

A recent research project of seismic scenarios for the cities of Sion and Martigny in Switzerland provided the opportunity for checking the defined 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 and typological curves were developed afterwards using statistical considerations.

The comparison of damage grade related to use of Risk-UE LM2 capacity curves or use of typological curves shows that the results are very similar for unreinforced masonry buildings with stiff floors, i.e. the M6-PC typology. By contrast, accuracy for reinforced concrete buildings with shear walls, i.e. the RC2 typology, is very poor.

As a consequence, seismic vulnerability assessment of cities of northern Europe may be performed adequately using capacity curves of M6-PC typology but use of the capacity curves of RC2 typology should be avoided because the related damage prediction is too much pessimistic. Moreover, the trend of damage grades with respect to building height is in contradiction with observed damages for this type of buildings.

Improvements are proposed to increase the accuracy of the seismic vulnerability assessment using Risk-UE LM2 method for northern European building stock. For unreinforced masonry buildings, i.e. M6-PC typology, a slight modification of building height limit using limits defined for RC buildings improves the damage prediction. Low-rise (M6-PC_L) should include buildings up to 3 storey height, mid-rise (M6-PC_M) should corresponds to buildings between 4 and 7 storey height and high-rise (RC2_H) should start with buildings from 8 storey height. For reinforced concrete buildings with shear walls, i.e. RC2 typology, improved capacity curves derived from the typological curves of the specific typology C are proposed.

However, seismic risk and loss assessment of northern European urban territories may be achieved with even more accuracy using the new typological curves presented in this paper instead of the standard Risk-UE LM2 capacity curves.

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