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ORIGINAL PAPER

Seismic vulnerability assessment at urban scale for two typical Swiss cities using Risk-UE methodology

P. Lestuzzi[1] · S. Podestà[2] · C. Luchini[2] · A. Garofano[1] · D. Kazantzidou-Firtinidou[3] · C. Bozzano[3] · P. Bischof[1] · A. Haffter[1] · J.-D. Rouiller[3]

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Abstract This paper contains a seismic assessment at urban scale of the cities of Sion and Martigny in Switzerland. These two cities have been identified for the present research based on their importance regarding size and the characteristics of the building stock for which information was available. Moreover, microzonation investigations are available for both cities. This results in a more accurate characterization of local expected ground shaking, which is expressed through specific response spectra. Sion and Martigny represent, respectively, the capital and second largest city of the canton of Valais. This region is characterized by the highest seismicity within Switzerland. The paper focuses on the assessment using Risk-UE methodology, namely the empirical method LM1 and the mechanical method LM2. The obtained results are compared in order to assess the related accuracy. Firstly, buildings of the two cities were surveyed in order to collect main structural characteristics in a database. Building stock is typical of that region and can be found similar to many other medium-sized Swiss cities. Around half of the buildings are unreinforced masonry buildings, while several others are reinforced concrete buildings with shear walls. Results show the most vulnerable part of the cities regarding earthquake. There are significant differences in global results between LM1 and LM2 methods. The mechanical LM2 method is more pessimistic since it predicts damage grades of about one degree higher than LM1 method. However, the main drawback of the empirical LM1 method is that an a priori determination of an adequate value of the macroseismic intensity is required. Nevertheless, LM2 method may lead to a global overestimation of damage prediction.

Keywords Risk-UE method · Seismic vulnerability assessment · Existing structures · Damage grade · Urban seismic risk · Microzonation

✉ P. Lestuzzi
pierino.lestuzzi@epfl.ch

[1] Ecole Polytechnique Fédérale de Lausanne, EPFL-ENAC-IIC-IMAC, Bâtiment GC, Station 18, 1015 Lausanne, Switzerland

[2] DICCA, University of Genoa, Genoa, Italy

[3] CREALP, Sion, Switzerland

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1 Introduction

An important step for the reduction in the seismic risk requires the evaluation of physical vulnerability of buildings. The methods which are employed for this purpose must be adapted and properly calibrated. As in the case of Switzerland, they must be suitable for the application to a built environment characterized by a moderate seismicity.

The methods for evaluation of seismic risk should allow estimation of damages expected to occur during a given seismic event, knowledge of the distribution of the urban impacts and preliminary identification of the most vulnerable buildings on which financial resources for seismic retrofitting process should be concentrated.

Difficulties linked to such an evaluation are the large number of structures present in a building stock and lack of information regarding properties of existing buildings. Moreover, a further source of complexity arises from variability of building typologies and construction techniques, as well as non-conventional structural behaviour of old buildings under seismic actions.

Different methods of analysis for seismic risk at a large scale have been developed during the last decades, mainly in regions affected by the damages of recent earthquakes. These regions take advantage of the direct evidence offered by post-seismic effects on the structures. The first methods have been developed in the USA (FEMA 178 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) and in Switzerland (Lang and Bachmann 2003). Generally, these methods are based on the definition of a damage scale and determination of a building typology classification of the studied environment. In addition, they calculate damage probability matrices or vulnerability index to estimate damage distribution for a given level of hazard.

Similarly to recent studies (e.g. Barbat et al. 2010; Veludo et al. 2013), the general framework of the methodology developed within the Risk-UE project can be followed and applied also to the Swiss case (e.g. the cities of Sion and Martigny), considering the specific elements and particularities of the Swiss territory in terms of seismicity and building stock in terms of more diffuse typologies. The Risk-UE classification is derived from the observation of characteristics of Italian and Mediterranean typologies; therefore, it cannot be employed in Switzerland. Particularly, equivalence of Swiss masonry building stock could not be established to Italian masonry, studied in Risk-UE. However, the LM2 mechanical method provides a good and simple approach in order to determine the seismic vulnerability of different typologies taking into account their seismic over capacity.

Seismic vulnerability analysis at urban scale requires collecting information on studied building and assigning a specific typology. Each Risk-UE typology (Milutinovic and Trendafiloski 2003) represents many situations across Europe. The specificity of Europe compared to the USA or Japan lies in the prominence of masonry types, which are not taken into account in the US methods (FEMA 178 1997). In Europe, the EMS-98 typology is an acknowledged reference. The GNDT (GNDT 1993) proposed a typology for Italy. Other typologies at the city level exist such as Albstadt in Germany (Schwarz et al. 2007), Grenoble in France (Guéguen et al. 2007; Michel et al. 2012) or Aigle (Brennet et al. 2001, 2002) and Basel (Lang and Bachmann 2003) in Switzerland. On the contrary to the case of reinforced concrete (RC) buildings, equivalence of Swiss masonry building stock could not be established to the USA or Italian masonry, studied, respectively, in HAZUS (FEMA 178 1997) and Risk-UE (Milutinovic and Trendafiloski 2003).

1.1 Switzerland and earthquakes

Although the largest European historical earthquake north of the Alps has occurred in 1356 in Basel at the French and German borders, the earthquake hazard in Switzerland may be qualified as moderate in comparison with the one in southern Europe. The largest peak ground acceleration specified in the building code is 1.6 m/s^2 for 475-year return period. The most seismically exposed region is situated in the south part of the country, corresponding to the canton of Valais (Fig. 1).

However, seismic prescriptions have been ignored for a long time in the codes. First adequate requirements in the Swiss building code have been proposed in 1989. As a consequence, the large majority of the building stock in Switzerland has been built without any seismic considerations.

1.2 Swiss buildings features

Swiss building stock is mainly composed of low-rise and mid-rise buildings constructed from masonry and reinforced concrete (Badoux 2001). 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 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.

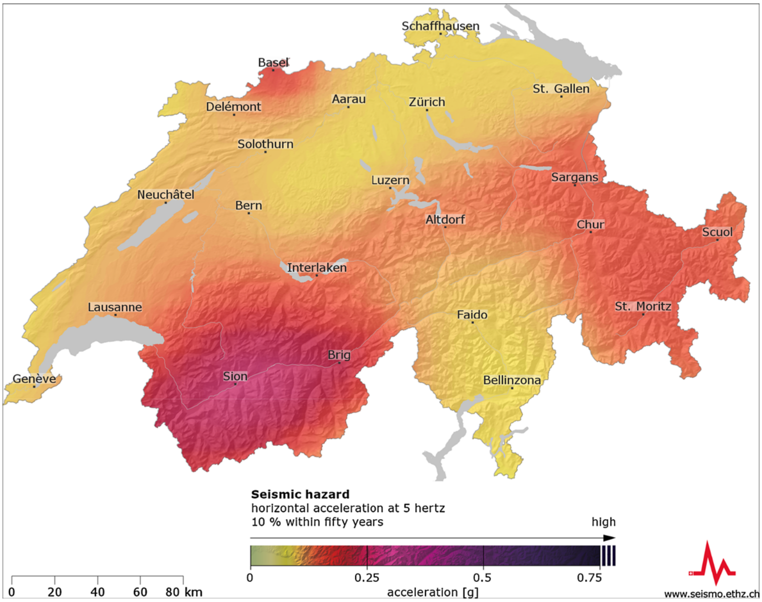

Fig. 1 Earthquake hazard in Switzerland (Swiss Seismological Service (SED) at ETH Zurich 2015)

Fig. 2 Typical unreinforced masonry buildings in Switzerland

1.3 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. It was accepted within the 5th Framework Research and Developed Program of the European Union (Risk-UE 2003). Carried out in the years 2001–2004, it represented the first collaborative and comprehensive research programme that studied territorial seismic risk focused on the European built environment. As a benchmark, the programme included application of the developed methodology to seven south European cities. The overall objective of the Risk-UE project was development of a modular methodology for the assessment of earthquake scenarios based on 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).

Building Typology Matrix (BTM) is a typological classification introduced within the project and reflects the differences between types of structures that are expected to have similar seismic behaviour (Table 1). Typologies defined within the Risk-UE project are inspired by building classes in EMS-98 (Grünthal et al. 2001). The addition of a typology related to the reinforced concrete dual system (RC3) takes into account, through the introduction of sub-typologies (Lagomarsino and Giovinazzi 2006; Giovinazzi and Lagomarsino 2004), particular aspects for a more detailed characterization of buildings.

The empirical LM1 method is a basic first-level method for the assessment of the seismic vulnerability, damage and loss. Its application is suitable for areas where no specific site seismic hazard studies are available and detailed seismic intensity information is available. The LM1 method has been developed from the study of Giovinazzi and Lagomarsino (Mouroux and Le Brun 2006) on the basis of the European macroseismic scale EMS-98 (Grünthal et al. 2001). The definition provided by EMS-98 includes establishing a link between earthquake macroseismic intensity and damage suffered by the building vulnerability classes. This has been translated numerically using classical probability theory and fuzzy set theory. The method was subsequently calibrated through the damages data from different earthquakes. As a result, vulnerability of a building belonging to a given typology is defined by a vulnerability index, V. Values of V are reported in

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 system

Table 2 for the typologies where probable and less probable vulnerability indices are also reported.

The mechanical LM2 method is the second-level approach for evaluation of seismic vulnerability proposed within the Risk-UE project. Application of the mechanical method is suitable for studying existing buildings or built sites in areas where local seismicity studies are available. In particular, it is necessary to know the hazard at site of the building in terms of spectral values (acceleration, velocity or displacement).

Table 2 Vulnerability indexes in the Risk-UE LM1 empirical method (Lagomarsino and Giovinazzi 2006)

Typologies	Building types	$V_{I,min}$	V_I^-	V_I^*	V_I^+	$V_{I,max}$
Vulnerability index						
Masonry						
M1	Rubble stone	0.62	0.810	0.873	0.980	1.02
M2	Adobe (earth bricks)	0.62	0.687	0.840	0.980	1.02
M3	Simple stone	0.46	0.650	0.740	0.830	1.02
M4	Massive stone	0.30	0.490	0.616	0.793	0.86
M5	Unreinforced (old bricks)	0.46	0.650	0.740	0.830	1.02
M6	Unreinforced with RC floors	0.30	0.490	0.616	0.790	0.86
M7	Reinforced or confined	0.14	0.330	0.451	0.633	0.70
Reinforced concrete						
RC1	Frames (without E.R.D)	0.30	0.490	0.644	0.800	1.02
RC2	Frames (moderate E.R.D)	0.14	0.330	0.484	0.640	0.86
RC3	Frames (high E.R.D)	−0.02	0.170	0.324	0.480	0.70
RC4	Shear walls (without E.R.D)	0.30	0.367	0.544	0.670	0.86
RC5	Shear walls (moderate E.R.D)	0.14	0.210	0.384	0.510	0.70
RC6	Shear walls (high E.R.D)	−0.02	0.047	0.224	0.350	0.54
Steel						
S	Steel structures	−0.02	0.170	0.324	0.480	0.70
Timber						
W	Timber structures	0.14	0.207	0.447	0.640	0.86

The mechanical method adopted within the Risk-UE project is essentially similar to the method adopted by HAZUS (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 (Table 3). 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; Giovinazzi and Lagomarsino 2004; Cattari et al. 2004). The tool employed to assess the building's performance within the LM2 method is the capacity spectrum method (Freeman 1998). 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" (Michel et al. 2014).

2 Seismic conditions of the investigated cities

The cities of Sion and Martigny are both situated in the highest seismic zone of Switzerland, zone 3b, with a peak ground acceleration of 1.6 m/s^2 (Fig. 3). Since 1524, six earthquakes of magnitude of 6 or larger were recorded in historical catalogues in this region of Switzerland at regular intervals (Fäh et al. 2012). As a consequence, an earthquake of at least magnitude 6 is expected every 100 years. The last event occurred in 1946 in Sierre, east of Sion. Therefore, in this region, an earthquake of at least magnitude 6 is expected in the next decades.

2.1 Brief outline of the cities

The city of Sion is the main city of the canton of Valais with a population of about 30,000 inhabitants for a total of 3600 buildings. The city of Martigny is located approximately 30 km southwest of Sion (Fig. 3). Martigny is the second largest city of the canton of Valais with a population of about 20,000 inhabitants for a total of 2500 buildings. During the earthquake of 1946, Sion was hit but reported damages were not very extensive (Fritsche and Fäh 2009). However, similar to other regions in Switzerland, both cities are linked with a large expansion of building stocks, principally in the 1970s and 1980s.

Table 3 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

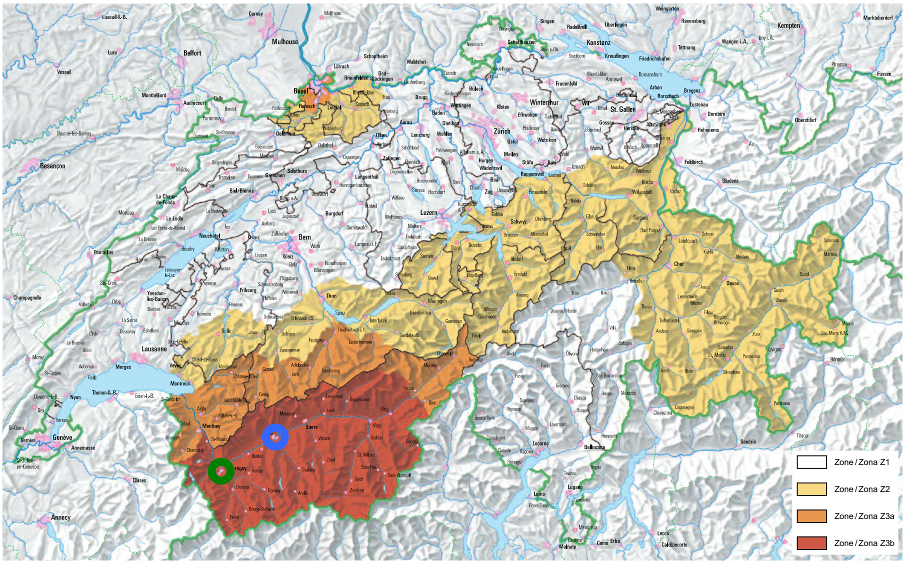

Fig. 3 Four seismic zones in Swiss building code (SIA 261 2003) and the location of the investigated cities, Sion (*blue circle*) and Martigny (*green circle*)

Unfortunately, these sites are in areas associated with significantly worse soil conditions regarding seismic actions.

2.2 Soil conditions and microzonation

Soil conditions are defined according to soil class of Eurocode 8 (EC8, 2004), and seismic actions are given by the related response spectrum. In Switzerland, the type 1 EC8 response spectrum is used. However, for both cities, a microzonation is available (Centre de Recherche sur l'Environnement Alpin (CREALP), www.crealp.ch). This means that a specific study was performed taking into account the potential soil amplification in order to precise the expected ground shaking and three microzones were defined with the associated response spectrum (Fig. 4 for Sion and Fig. 5 for Martigny). The main parameters of the microzone elastic response spectra are listed in Table 4. The plateau is defined by the corner periods T_B and T_C, and the value $S_{e,max}$ indicates its level. Similarly to EC8 response spectrum, the period T_D defines the beginning of the constant spectral displacement range. Figure 6 shows the response spectra plotted in the ADRS format.

Compared to the usual soil classes of EC8, response spectra of the microzones of Sion reach similar peak values. The plateau level of the response spectrum of microzones A1, A2 and A3 corresponds to the one of EC8 soil class A, C and D, respectively. However, plateau corners of the response spectrum of microzones A1 and A2 are shifted towards high period range. These extensions are related to increased seismic demands with respect to the ones of corresponding soil classes of EC8.

Plateau levels of the response spectra of microzones M1 and M3 of Martigny are higher than the ones of those of Sion. The response spectrum of microzone M1 is large and is thus related to large seismic demand. Except for the low period range, the response spectrum of microzone M2 meets the response spectrum of the soil class C.

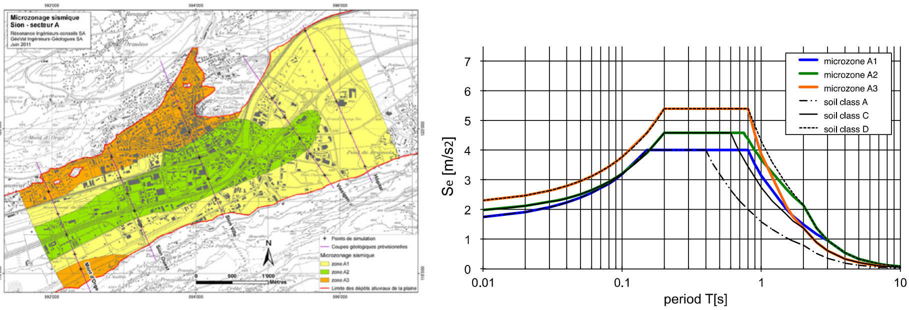

Fig. 4 Microzonation of Sion with the three microzones A1, A2 and A3 (Centre de Recherche sur l'Environnement Alpin (CREALP), www.crealp.ch) and the related elastic response spectra for a return period of 475 years and 5 % damping ratio

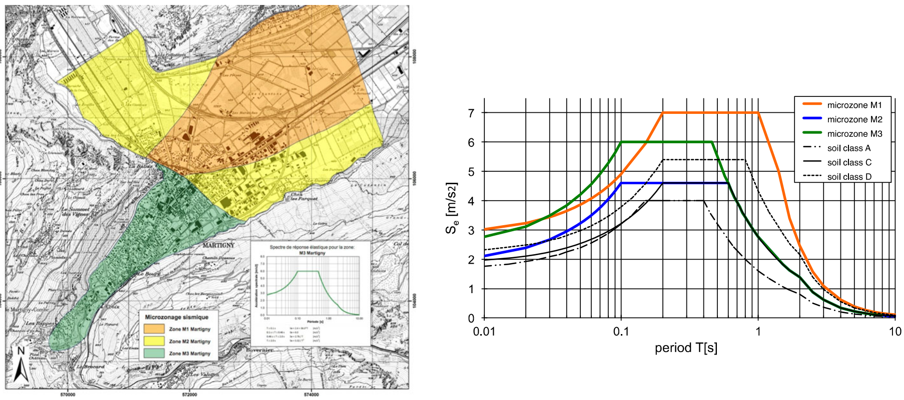

Fig. 5 Microzonation of Martigny with the three microzones M1, M2 and M3 (Centre de Recherche sur l'Environnement Alpin (CREALP), www.crealp.ch) and the related elastic response spectra for a return period of 475 years and 5 % damping ratio

Table 4 Main parameters of the microzone response spectra (Centre de Recherche sur l'Environnement Alpin (CREALP), www.crealp.ch)

City	Microzone	$S_{e,max}$ [m/s^2]	T_B [s]	T_C [s]	T_D [s]
Sion	A1	4.0	0.15	0.80	3.00
	A2	4.6	0.20	0.75	2.00
	A3	5.4	0.20	0.80	2.00
Martigny	M1	7.0	0.20	1.00	1.40
	M2	4.6	0.10	0.60	2.00
	M3	6.0	0.10	0.46	2.00

3 Survey of the cities

Estimation of existing buildings vulnerability needs field surveys in order to have a better overview of building stock that is studied. The performed survey is a rapid visual survey in order to collect the crucial parameters of the building stock. It consists in walking the

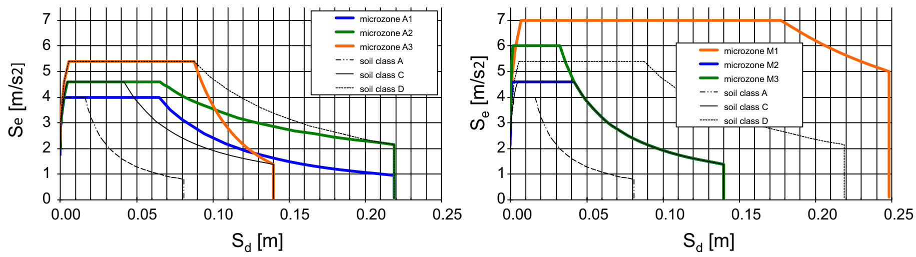

Fig. 6 Response spectra in ADRS format for Sion (*left*) and Martigny (*right*). Response spectra for soil classes A, C and D are type 1 EC8 considering $a_{gd} = 1.6$ m/s^2 (zone 3b)

Table 5 Main parameters collected during rapid visual survey

General data	
Number of stories	Stories under or above the ground level
Position of the building	Isolated or in contact with adjacent buildings
In-plan regularity	Compact floor plan
Elevation regularity	Pilotis, irregular floors height…
Bearing structure	Type, dimension of elements
Construction date	Period of construction
Horizontal elements	Wooden, r.c. or mixed slabs
Roof	Material and shape of the roof structure
Use of the building	Activity carried out in the building
Level of detail of the survey	External, internal survey

streets of study cities and taking notes of the structural properties of buildings. Time required for one building is around 10 min. Surveyed parameters are then stored in a database, and knowledge obtained on the building stock can be displayed on maps using geographical information system (GIS).

3.1 Parameters

The main parameters collected during the quick survey for each building are listed in Table 5.

3.2 Building stock

As a result of the performed surveys, the overall distribution of the building stock can be assessed for both cities. Figure 7 shows the distribution for the city of Sion, and Fig. 8 shows the distribution for the city of Martigny (Kazantzidou-Firtinidou et al. 2015). Based on selected buildings representative of the building stocks of the city of Sion and Martigny, it was possible to identify the most common building typology present in the two cities. The following types of buildings were found: buildings with structural system composed by RC walls and masonry walls, buildings with structural system composed by RC walls and RC columns, buildings with structural system composed by RC walls as well as buildings with structural system composed by masonry walls.

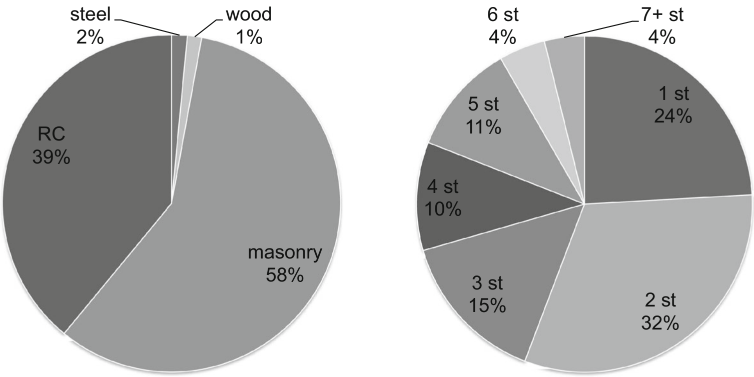

Fig. 7 Overall distribution of building material (*left*) and building height (*right*) for Sion (Kazantzidou-Firtinidou et al. 2015)

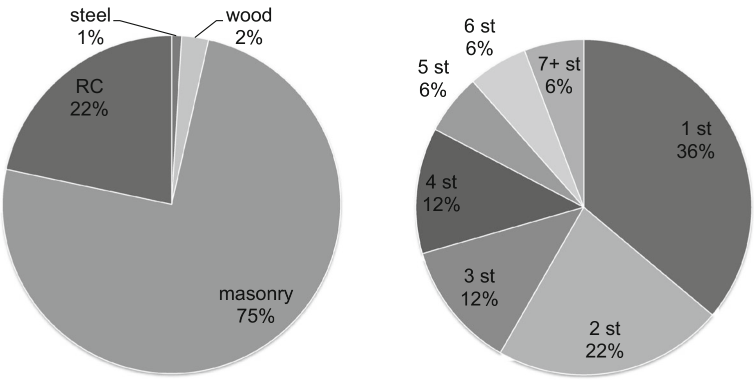

Fig. 8 Overall distribution of building material (*left*) and building height (*right*) for Martigny (Kazantzidou-Firtinidou et al. 2015)

Distributions of building types 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. Low-rise buildings compose the majority of building stock. For both cities, 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.

4 Method LM1

Using vulnerability index (V) of a building, computation of the expected damage is defined as (Lagomarsino and Giovinazzi 2006):

$$\mu_{\mathrm{D}} = 2.5\left[1 + \tanh\left(\frac{I + 6.25V - 13.1}{Q}\right)\right] \tag{1}$$

In the LM1 method, the hazard is described through the macroseismic intensity according to the EMS-98 (Risk-UE 2003). However, for the physical damage to the building, EMS-98 damage grades are considered. In particular, for the application of the method, five damage grades, D_k (with k from 0 to 5), are identified. Therefore, in the previous formula, I is the EMS-98 macroseismic intensity, while Q is a ductility factor also calibrated on the basis of the structural typology.

EMS-98 macroseismic intensity and site effect related to soil conditions should be first determined before using the LM1 method.

4.1 Macroseismic intensity and site effects

A procedure similar to one by Cauzzi et al. (2015) used for ShakeMap in Switzerland is followed to determine the value of macroseismic intensity. Taking into account that both cities are located in Swiss seismic zone 3b, the related peak ground acceleration (PGA) of 1.6 m/s^2 is first adjusted to the Swiss reference rock model. This model considers a higher shear wave velocity ($V_{s30} = 1100$ m/s instead of 800 m/s) by multiplying it with sqrt(800/1100). Using the relationship proposed by Faenza and Michelini (2010), PGA is then converted to intensity at the Swiss reference rock. In the case of Swiss seismic zone 3b, a value of $I = 7.19$ was obtained for the macroseismic intensity.

In order to account for site effects, Giovinazzi and Lagomarsino (2004) proposed soil correction factors to consider the level of shaking related to the response spectrum associated with actual soil classes. However, this way is not followed in this study. In order to remain in a full empirical approach, the amplification map of Fäh et al. (2011) as proposed by Cauzzi et al. (2015) is applied. This map provides intensity increments depending on the surface geology. In Martigny, the investigated buildings are mainly located in the alluvial plain that corresponds to an intensity increment of 1.52, i.e. a total macroseismic intensity of 8.71. Although most of the buildings in Sion are also located in the alluvial plain, others are on harder rock conditions. Those buildings experience therefore macroseismic intensities up to one degree lower (see Fig. 9). Although this simplified approach for site effect is not as accurate as a full microzonation study and is moreover associated with large uncertainties, an empirical approach is advantageous because it remains consistent with the LM1 method considerations.

In order to show the impact of the intensity increment on the damage grade values, the expected damage is calculated (see Table 6) according to Eq. 1 for M6 building type (unreinforced masonry with stiff floors) with different building heights (M6_L for low-rise, M6_M for mid-rise and M6_H for high-rise). The two extreme values of intensity increment (0.16 and 1.52) are considered. For simplification, other modification factors (e.g. irregularity) are not taken into account. The macroseismic intensity of 7.19 corresponds to the level of seismic hazard for zone 3b. Table 7 shows the probable vulnerability index range ($V_{\mathrm{I}}^{-}/V_{\mathrm{I}}^{+}$, see Table 2) that highlights the range of obtained expected damage values (μ_{D}^{-} and μ_{D}^{-}). The influence of the building height (low-rise, mid-rise and high-rise) is taken into account by the related correction factor $\Delta V_{m,storey}$ (Lagomarsino and Giovinazzi 2006). The largest values of the expected damage in Table 6 occur for high-rise M6 buildings (from 6 storeys and above). An average expected damage value of 2 is obtained for M6 buildings located in the alluvial plain (intensity increment of 1.52). For M6

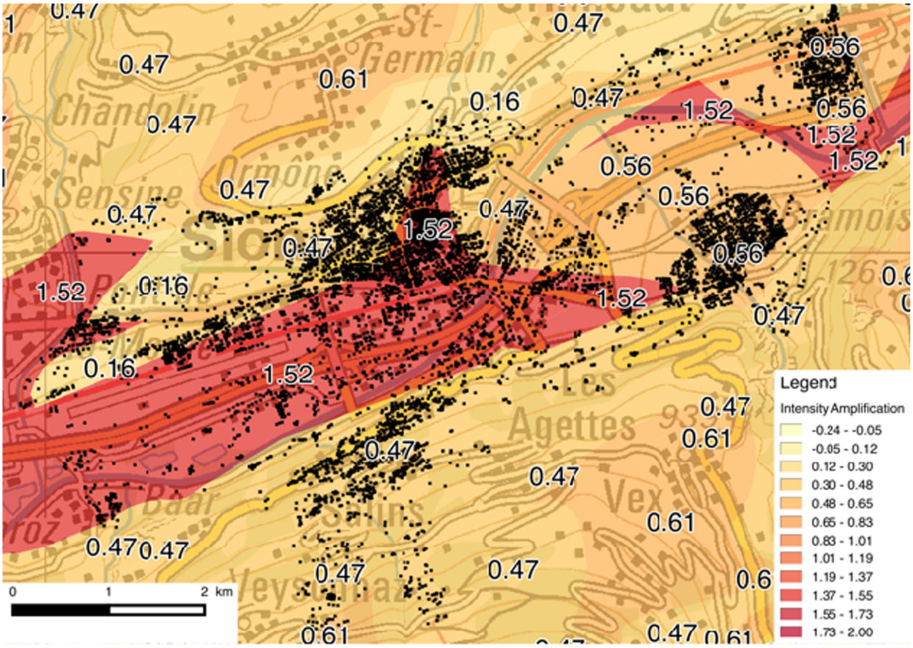

Fig. 9 Method LM1: intensity increment for Sion ranging from 0.16 to 1.52 (Fäh et al. 2011)

Table 6 Method LM1, computed expected damage for unreinforced masonry buildings with stiff floors (M6) with a value of $I = 7.19$ and the two extreme increment values $\Delta I = 0.16$ and $\Delta I = 1.52$ (for simplification other modification factors are not taken into account)

Type	n_storey	ΔI_{EMS}	V_{I}^{-}	V_{I}^{*}	V_{I}^{+}	$\Delta V_{\mathrm{m,storey}}$	μ_{D}^{-}	μ_{D}^{*}	μ_{D}^{+}
M6_L	1–2	0.16	0.49	0.616	0.79	−0.04	0.36	0.67	1.42
M6_M	3–5	0.16	0.49	0.616	0.79	0.00	0.44	0.80	1.65
M6_H	6+	0.16	0.49	0.616	0.79	0.04	0.54	0.96	1.90
M6_L	1–2	1.52	0.49	0.616	0.79	−0.04	1.01	1.67	2.82
M6_M	3–5	1.52	0.49	0.616	0.79	0.00	1.20	1.92	3.08
M6_H	6+	1.52	0.49	0.616	0.79	0.04	1.41	2.19	3.33

Table 7 Correspondence between damage level D_{Sk} (LM2) and damage grades D_{k} (LM1) related to structural and non-structural damage (Lagomarsino and Giovinazzi 2006)

D_{Sk}	D_{K}	Structural (SD) and non-structural (N-SD) damage
Slight (D_{S1})	Slight (D_1)	No SD slight N-SD
Moderate (D_{S2})	Moderate (D_2)	Slight SD moderate N-SD
Extensive (D_{S3})	Heavy (D_3)	Moderate SD heavy N-SD
Complete (D_{S4})	Very heavy (D_4)	Heavy SD very heavy N-SD
	Destruction (D_5)	Very heavy SD

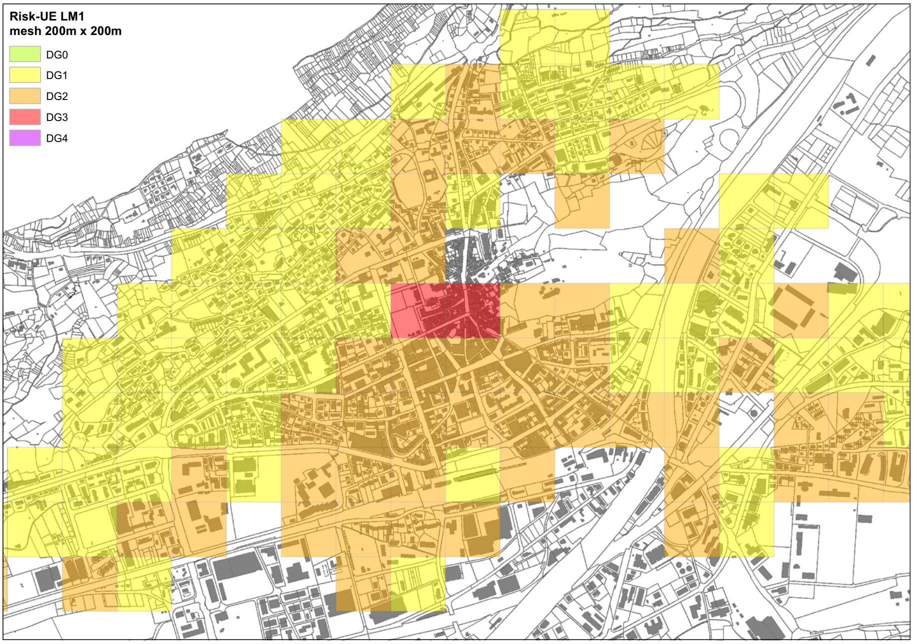

Fig. 10 Method LM1: results for the city of Sion for a macroseismic intensity $I_{\mathrm{EMS}} = 7.19$ and site effect according to Fig. 9

buildings located in firm soil conditions (0.16 intensity increment), the average expected damage value is less than one regardless of the buildings height.

4.2 Results for Sion

The damage grade predicted values according to the LM1 method are computed (Eq. 1) for a value of the macroseismic intensity of 7.19 corresponding to the level of seismic hazard for zone 3b. Site effect is considered according to Fig. 9. Results for the city of Sion are shown in Fig. 10. Note that the white area in the centre of Fig. 10 corresponds to the old town of Sion, which was outside the scope of this research project and was therefore not assessed.

Figure 10 shows the obtained results using a mesh of 200 m $\times$ 200 m and the related average value of the damage grades computed for each surveyed building within the area.

4.3 Results for Martigny

Results for the city of Martigny are shown in Fig. 11.

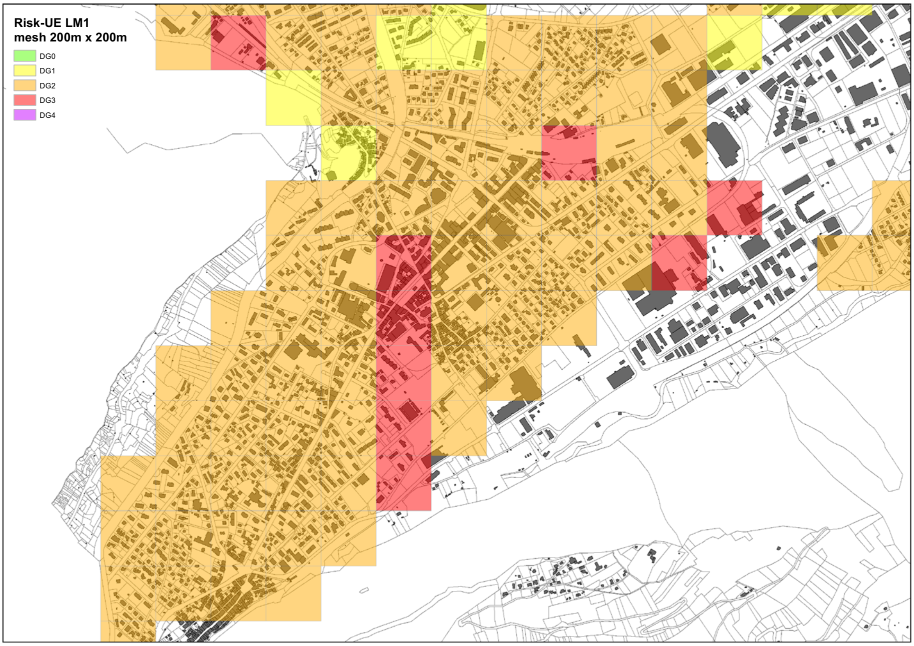

Fig. 11 Method LM1: results for Martigny for a macroseismic intensity $I_{\mathrm{EMS}} = 7.19$ and site effect according to intensity increment (mainly 1.52)

5 Method LM2

The method LM2 is a mechanical method and does not require a macroseismic intensity value. On the capacity curves of the building, several damage limit states are identified in terms of displacement, $S_{\mathrm{d,k}}$ (with $k = 1, 2, 3, 4$):

$$\begin{aligned} S_{\mathrm{d},1} &= 0.7 d_{\mathrm{y}}, \\ S_{\mathrm{d},2} &= 1.5 d_{\mathrm{y}}, \\ S_{\mathrm{d},3} &= 0.5\left(d_{\mathrm{y}} + d_{\mathrm{u}}\right), \\ S_{\mathrm{d},4} &= d_{\mathrm{u}}. \end{aligned} \tag{2}$$

Four damage levels, D_{Sk} (with $k = 1, 2, 3, 4$), are defined and correspond to the four damage limit states. In Table 7, the considered damage levels are listed, and a correspondence is reported with respect to the damage grades, D_{k}, assumed in the LM1 method. It is shown that for the first damage levels considered in the two methods, a direct correspondence can be assumed. Since these two conditions cannot be clearly distinguished within a mechanical-based model, complete damage level DS4 is representative of both very serious damage and of building destruction (collapse).

Within the mechanical method, the performance point, identified by the spectral displacement $S_{\mathrm{d}*}$, can be calculated as (Mouroux and Le Brun 2006):

$$S_{d*} = \begin{cases} \left[1 + \left(\frac{S_{ae}(T)}{a_y} - 1\right)\frac{T_C}{T}\right]d_y, & T < T_C \text{ and } \frac{S_{ae}(T)}{a_y} > 1, \\ \frac{S_{ae}(T)}{a_y}d_y, & T_C \le T < T_D \text{ or } \frac{S_{ae}(T)}{a_y} \le 1 \\ \frac{S_{ae}(T_D)T_D^2}{4\pi^2}, & T \ge T_D \end{cases} \tag{3}$$

where $S_{ae}(T)$, T_C and T_D are parameters defining the seismic demand and T and a_y are parameters related to building capacity.

The damage grade computations for M6 building type (unreinforced masonry with stiff floors) with different building heights (M6pc_L for low-rise, M6pc_M for mid-rise and M6pc_H for high-rise) are shown in Fig. 12 for the response spectra of the microzonation of Sion and in Fig. 13 for microzones M2 and M3 of Martigny. Note that the response spectrum of microzone M1 of Martigny is such that DG4 occurs for all (low-rise to high-rise) M6 buildings.

Damage grades in Figs. 12 and 13 are clearly above the range of corresponding LM1 probable values of expected damage (see Table 6). According to these partial results, LM2 method predicts systematically higher damage grade values than LM1 method and therefore appears to be more pessimistic. As a consequence, damage grade values of LM2 method correspond to average values of expected damage of LM1 method plus about one additional degree. However, the relative difference between low-rise, mid-rise and high-rise buildings is much more pronounced in the LM2 than in the LM1 method. This issue shows that prescribed values of building height correction factors ($\Delta V_{m,storey}$) in LM1 method are too small to reflect the corresponding seismic behaviour differences.

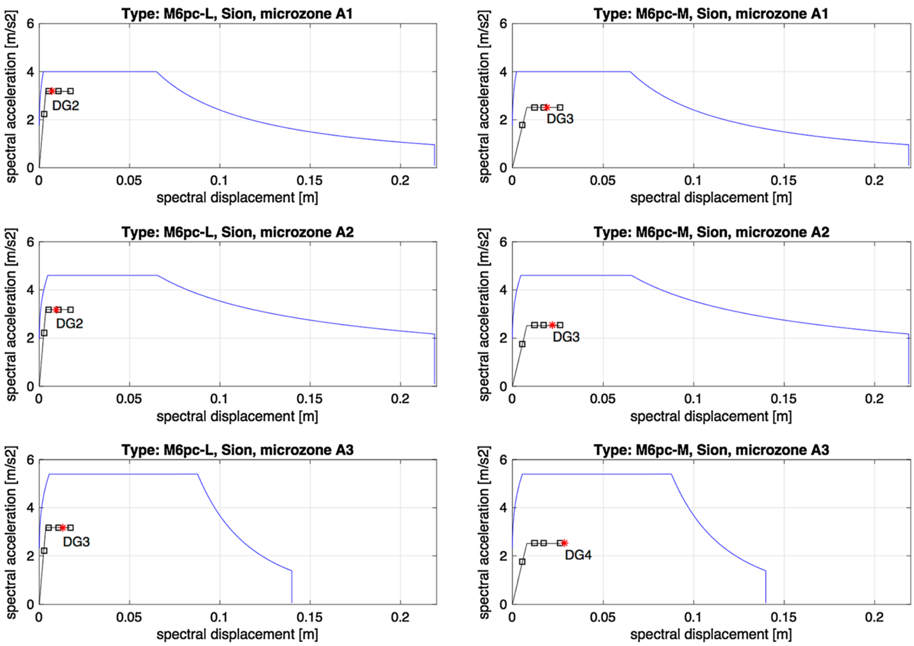

Fig. 12 Method LM2: computed damage grades for unreinforced masonry buildings with stiff floors (*low-rise left* and *mid-rise right*) for the three microzones of Sion

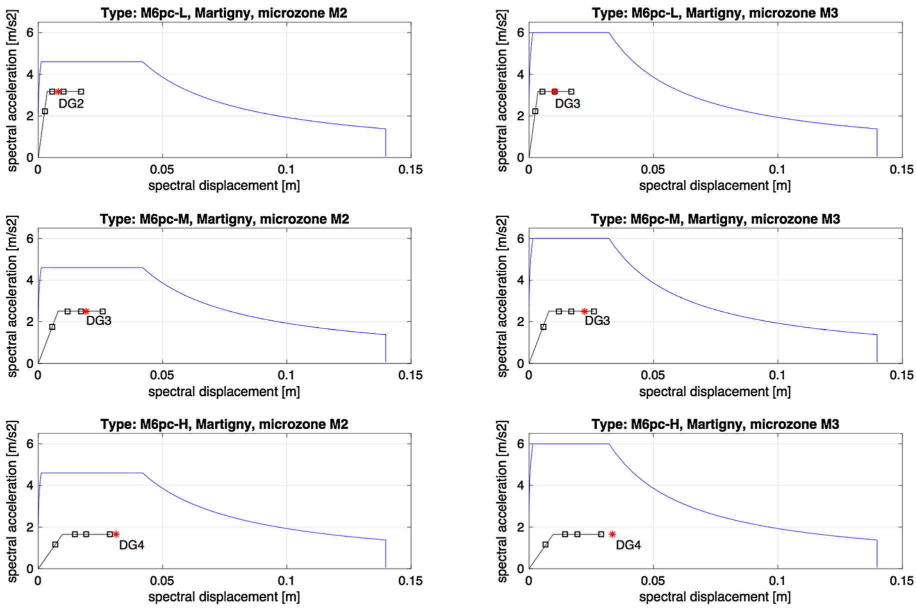

Fig. 13 Method LM2: computed damage grades for unreinforced masonry buildings with stiff floors (low-rise, mid-rise and high-rise from *top* to *bottom*) for the microzones M2 and M3 of Martigny

5.1 Results for Sion

Results for the city of Sion are shown in Fig. 14. Similarly to Fig. 10, Fig. 14 shows the obtained results using a mesh of 200 m × 200 m and the related average value of the damage grades computed for each surveyed building within the area.

Compared to LM1 method (see Fig. 10), results of the LM2 method are globally one degree of damage grade higher than the ones of LM1 method. This confirms the trend also obtained with M6 buildings (see Figs. 12, 13).

5.2 Results for Martigny

Results for the city of Martigny are shown in Fig. 15.

Compared to the LM1 method (see Fig. 11), the results of LM2 method are globally one degree of damage grade higher than the ones of LM1 method. Note that purple squares (collapse) correspond to microzone M1 which is associated with large response spectrum values (see Fig. 5). LM2 results are consequently more pessimistic than LM1 results.

6 Comparison of the results

Obtained results may be used to achieve a comparison between the methods, leading to the following finding: both methods, LM1 and LM2, do not lead to similar global results if a macroseismic intensity value of 7.19 is considered with LM1 method. Nevertheless, this value of macroseismic intensity is compatible with the seismic hazard specified for seismic zone 3b in Switzerland. LM2 method predicts globally damage grades of one degree higher

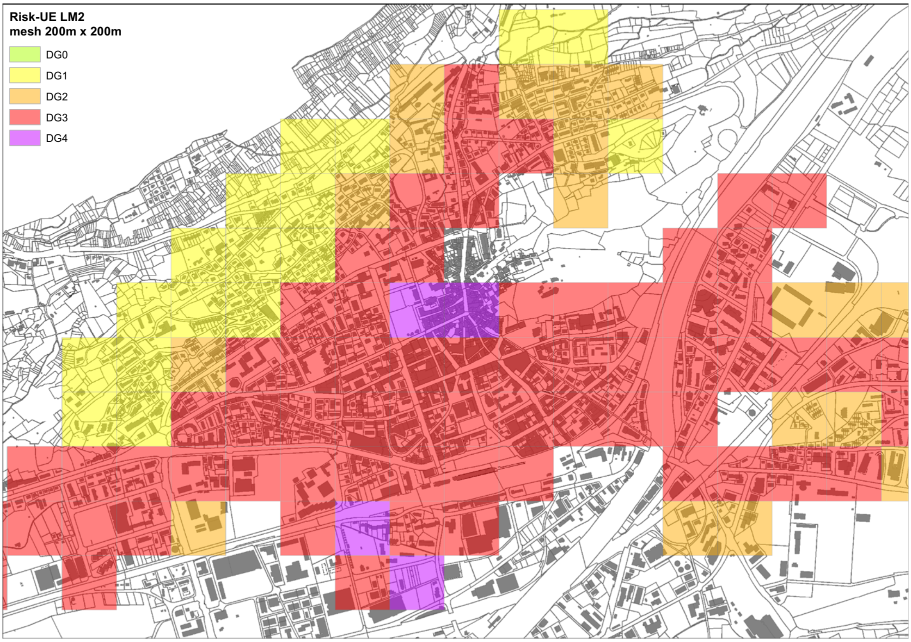

Fig. 14 Method LM2: results for the city of Sion

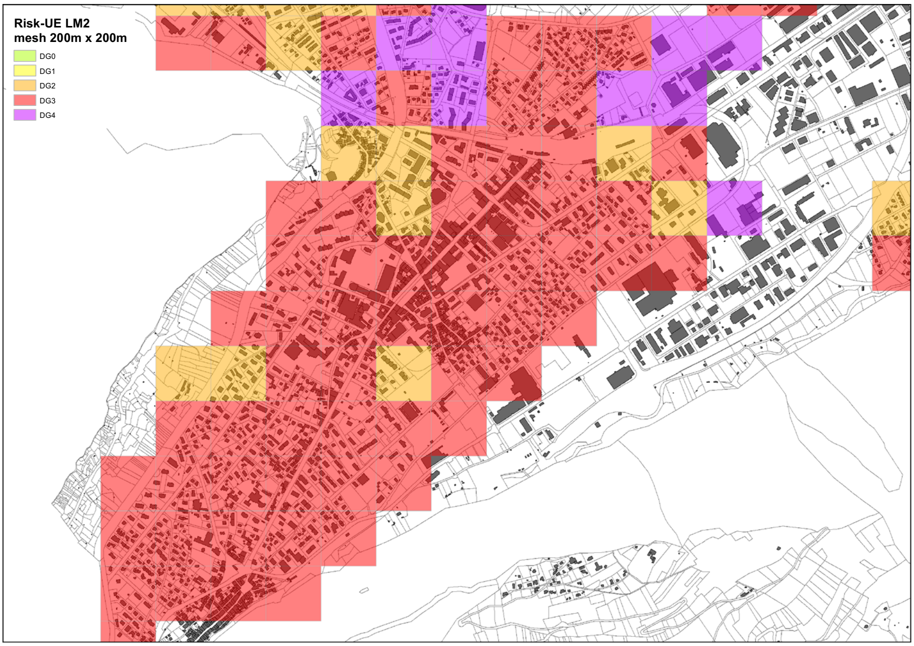

Fig. 15 Method LM2: results for Martigny

Table 8 Synthesis of the global results showing for both cities the distribution of the overall building stock into the damage grades for LM1 method and LM2 method

DG	LM1		LM2	
	Sion (%)	Martigny (%)	Sion (%)	Martigny (%)
DG1	62	15	10	0
DG2	30	53	41	25
DG3	6	31	35	55
DG4 + DG5	2	1	14	20

than LM1 method. However, damage distributions due to historical earthquakes in the examined region are more coherent with the results of LM1 method than of LM2 method. Thus, the macroseismic intensity of the last event in Sierre in 1946 was estimated to be $I =$ VIII (Fritsche and Fäh 2009), value considered in LM1 method by taking into account site amplification.

The obtained results may also be used to perform a comparison between the cities, leading to the following finding: both methods, LM1 and LM2, show similar trend. Damage grades are more severe for Martigny than for Sion regardless of the method used (see Table 8). This issue may not be explained by the distribution of building stock in each city. Although there are more masonry buildings in Martigny (see Figs. 7, 8), this does not fully explain the different damage grades. Soil conditions, however, are probable sources of the different damage grades. Martigny is mainly built on alluvial deposits and is therefore subjected to larger amplification due to site effect.

The results obtained from LM2 method compared to those from LM1 method show a greater difference between low-rise, mid-rise and high-rise buildings. This is realistic since it corresponds to the observations of the field surveys after seismic events.

7 Conclusions

The building stock of two cities, Sion and Martigny, situated in the highest seismic zone of Switzerland has been surveyed to determine their main structural features. The Risk-UE methodology, i.e. both the empirical method LM1 and the mechanical method LM2, is used to achieve seismic damage predictions. Microzonation studies are available for both cities, and specific response spectra could therefore be considered. The performed analyses at the urban scale level show the expected damage distribution related to the scenario of the design earthquake (475-year return period). Even if this scenario does not correspond to a realistic event, it shows the areas where extended damages are expected. Without surprise, these areas are mainly related to the microzones with the largest response spectra, such as the microzone M1 of the city of Martigny.

From a quantitative point of view, the obtained results of empirical method LM1 and mechanical method LM2 do not correlate well when using a macroseismic intensity of 7.19 even if this value corresponds to the seismic hazard specified for seismic zone 3b in Switzerland. LM2 mechanical method is more pessimistic. Similar trend was already obtained in other studies (Hannewald et al. 2016). This discrepancy may not only be related to the reliability of the determination of macroseismic intensity value in LM1 method. By LM2 method, there are also several issues, such as accuracy of the displacement demand determination or reliability of capacity curves, which may lead to significant overestimation of damage grades. More research efforts are needed in order to identify in detail the real causes of the discrepancy in the results of LM1 and LM2 methods, with focus on application in regions with moderate seismicity.

From a qualitative point of view, obtained results of the LM1 and LM2 methods correlate well. The relative damage grade level distributions inside the investigated areas are similar. In other words, both methods lead to the same identification of the most vulnerable parts of the cities. Moreover, a significant difference by relative global vulnerability at urban scale appears for both methods. In this study, Martigny is more seismically vulnerable than Sion, regardless of the method LM1 or LM2.

For qualitative case, both methods result in similar levels of accuracy. The empirical method LM1 and the mechanical method LM2 are able to identify the most vulnerable parts of a city and the most vulnerable city among a group of investigated cities. However, quantitative results should be considered with care. The LM1 method requires an initial value of macroseismic intensity to be used for reliable expected damage computation. The mechanical LM2 method is not directly linked to macroseismic intensity, but several issues, such as accuracy of the displacement demand determination, are critical and may significantly affect the reliability of the corresponding results. Results obtained in this study indicate that damage prediction values may be overestimated by using mechanical method LM2.

Results obtained in the reported study are the first steps of a more general investigation dealing with seismic risk in the state (canton) of Valais in Switzerland. They provide background for preparation of the expected next seismic event and the seismic risk reduction by the urban development of the considered municipalities.

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