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Impact of displacement demand reliability for seismic vulnerability assessment at an urban scale

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Abstract

This paper addresses seismic vulnerability assessment at an urban scale by focusing on the displacement demand determination for building damage prediction.
The study is based on the comparison of urban seismic damage distributions obtained by the displacement demand computed using non-linear time-history analysis (NLTHA) with three simplified methods. These methods include the N2 method, the Lin & Miranda proposal and an optimized version of the N2 method. Comparing the different damage distributions from the three simplified methods with the one obtained by time-history analysis helps understanding the reliability of displacement demand determination. The study is carried out on Sion and Martigny, two typical Swiss cities.
For the case of Sion, results clearly show that using N2 method may lead to significant overestimation of damage grade distribution. The use of Lin & Miranda method and optimized version of N2 improves the damage prediction in both cases. For the other studied case of Martigny, N2 method and Lin & Miranda proposal are not accurate. The optimized version of N2 method provides stable and reliable results.

Keywords: N2 method, seismic vulnerability assessment, Lin & Miranda proposal, N2 method optimization, non-linear time-history analysis, damage distribution, displacement demand

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1. Introduction

Several methods for large-scale seismic risk assessment have emerged within the past few decades, especially after destructive earthquakes occurred in Europe. In regions affected by earthquakes, direct evidence of seismic effects on structures is useful for building typology classification and damage scale definition. Methods have been developed in Italy (Benedetti and Petrini, 1984; GNDT, 1993; Seismocare, 1998; Dolce et al., 2003), Turkey (Ergunay and Gulkan, 1991), US (FEMA 178, 1997; HAZUS, 1999), Japan (Otani, 2000), Portugal (Oliveira, 2003), Switzerland (Lang and Bachmann, 2003), Canada (Ventura et al., 2005; Onur et al. 2005), Spain (Roca et al., 2006) and France (Guéguen et al., 2007).

Main goals of these works are to provide methods for reliable urban risk analysis and to generate possible earthquake scenarios useful in seismic risk and damage management as well as in urban planning. The final aim of such investigations is to plan programs for seismic risk mitigation and management of emergency in the case of the occurrence of an earthquake. Seismic vulnerability assessment is also central for urban planning even for cities subjected to moderate earthquake hazard. Therefore, a well-formed damage scenario helps to determine focus areas for urban development and areas to regenerate.

In the last few years, research focused on procedures to accelerate urban seismic vulnerability assessment. Introduction of data-mining to reduce the costly process of drawing up an inventory of building characteristics on the field (e.g. Guettiche et al., 2017) and the application for rapid risk evaluation of pre-populated databases of seismic, building inventory and vulnerability parameters for nearly real-time analysis (e.g. Nollet et al., 2018) have been proposed.

Although for the analysis of a single building damage is deliberately overestimated, such an overestimation is not desirable at an urban scale. An unreliable urban seismic vulnerability assessment leads to incorrect building damage predictions with several problems in risk management.

Most approaches available for seismic vulnerability assessment of buildings are based on empirical methods and mechanical methods. Empirical methods combine observed statistical post-earthquake damage with a predefined value of macroseismic intensity. By contrast, mechanical methods apply parameters that define the structural response to results of the refined hazard analysis. Mechanical methods determine the damage a structure suffers for a given earthquake. Within the framework of mechanical based vulnerability approaches, some methods, such as displacement-based methods, describe the response of structures with capacity curves of structural behaviour in non-linear domain. Each point on the capacity curve is associated with a given level of damage. Assessment of the seismic response is achieved by identifying the displacement required (performance point) from a comparison of the capacity curve and the displacement demand curve. The distribution of building damage states can be evaluated by defining damage thresholds on the capacity curve corresponding to predefined displacement values.

The Risk-UE methodology is composed of the empirical method, called LM1, and the mechanical method, LM2 (Mouroux and Le Brun, 2006). The empirical method, LM1, involves macroseismic intensity according to EMS98 (Grünthal et al., 2001) and vulnerability indexes. The mechanical method, LM2, involves the use of standard capacity curves and capacity spectrum method to determine the performance point (Lagomarsino and Giovinazzi, 2006). The main drawback for macroseismic methods is that an a-priori determination of the macroseismic intensity is required, so that the computed damage is reported to this entry choice. On the other hand, the LM2 method produces conservative predictions with overestimation of damage distribution, especially for low strength reduction factors (Lestuzzi et al., 2016).

This paper discusses only mechanical methods. The main challenge of mechanical methods is the behaviour prediction of existing buildings in a non-linear domain. Calculation of the seismic displacement demand is fundamental to the mechanical-based model. Although displacement demand may be determined throughout non-linear time-history analysis (NLTHA), displacement demand in the inelastic domain is usually estimated by simplified static approaches. The aim of this paper is to compare three different displacement demand determination methods and to evaluate their reliability in the damage prediction. Reliability is evaluated by comparing damage distributions related to the displacement demand provided by the three methods analysed with the value of true displacement provided by a NLTHA method.

2. Simplified seismic demand determination

The three simplified seismic demand determination methods here compared are: the N2 method, the method proposed by Lin & Miranda (2008) and an optimized version of N2 method recently proposed by Diana L, Manno A and Lestuzzi P (in press).

The N2 method is one of the most widespread methods in Europe. It combines the pushover analysis of a multi-degree-of-freedom (MDOF) model with the response spectrum analysis of an equivalent single-degree-of-freedom (SDOF) system. The method is formulated in ADRS (acceleration-displacement response spectrum) format (Fajfar

and Gašperšič, 1996) and applies to inelastic spectra, rather than elastic spectra with equivalent damping and period, representing the major difference with the Capacity Spectrum Method (Fajfar, 2000).
As prescribed in EC8, the displacement demand determination for short periods is based on the N2 method. For periods longer than T_C, the inelastic and the elastic displacement are considered as the same (Velestos and Newmark, 1960; Lestuzzi and Badoux, 2003).
As a whole, in EC8 the displacement demand is determined as:

$$\begin{cases} S_d = \frac{S_{de}}{R_\mu} \cdot \left[(R_\mu - 1) \cdot \frac{T_C}{T} + 1 \right], & T < T_C \text{ and } R_\mu > 1 \\ S_d = S_{de}, & T \geq T_C \text{ or } R_\mu \leq 1 \end{cases} \quad (1),$$

where the parameters T_C , S_{de} and S_{ae} are the corner period limiting the zone of the spectrum of maximum acceleration (i.e. plateau), the displacement of the structure with an unlimited elastic behaviour and the elastic spectral acceleration respectively. These parameters define the seismic demand (S_d). The period T (period of vibration of the structure) and the strength reduction factor R_μ $\left(R_\mu = \frac{S_{ae}}{S_{ay}}\right)$ are parameter defining building capacity. The value S_{ay} represents the yielding acceleration of the structure. The lack of accuracy of N2 method, especially on the plateau range, has been observed by others (Michel et al., 2014). The effect of inaccuracy on building damage distribution in a seismic vulnerability assessment at an urban scale has however not yet been extensively examined.
The second method to be evaluated is by Lin & Miranda (2008) and based on a particular version of the Capacity-Spectrum Method (CSM). This version is based on equivalent linearization. Therefore, the displacement demand of a non-linear SDOF system is estimated from the displacement demand of a linear-elastic SDOF system. The elastic SDOF system, referred to as an equivalent system, has a period and a damping ratio larger than those of the initial non-linear system (ATC, 2005). The inelastic displacement demand of the non-linear SDOF system is determined as:

$$S_d = S_d(T_{eq}; \xi_{eq}) = S_d(T_{eq}; \xi_{=5\%}) \cdot \eta = S_a(T_{eq}; \xi_{=5\%}) \cdot \frac{T_{eq}^2}{4\pi^2} \cdot \eta \quad (2),$$

where: the value $S_d(T_{eq}; \xi_{eq})$ is the spectral displacement demand of the equivalent system; T_{eq} is the equivalent period of vibration of the equivalent system; ξ_{eq} is the equivalent viscous damping ratio; $S_d(T_{eq}; \xi_{=5\%})$, the displacement demand of the linear system with 5%-damping elastic ratio; η a reduction factor depending from the damping modification factor ξ. The reduction factor η can be determined as:

$$\eta = \sqrt{\frac{1}{0.5 + 10\,\xi_{eq}}} \quad (3)$$

The equivalent period T_{eq} and the equivalent damping ratio ξ_{eq} are functions of the strength reduction factor R_μ of the non-linear SDOF system and, respectively, of the initial period of vibration and of the damping ratio. The various equivalent linear methods differ from each other mainly for functions used to compute T_{eq} and ξ_{eq}.
In their work (2008), Lin & Miranda give the equivalent period and the equivalent damping ratio as follows:

$$T_{eq} = \left[1 + \frac{m_1}{T^{m2}} \cdot \left({R_\mu}^{1.8} - 1\right)\right] \cdot T \quad (4)$$

$$\xi_{eq} = \xi_{=5\%} + \frac{n_1}{T^{n_2}} \cdot (R_\mu - 1) \quad (5)$$

Coefficients m_1, m_2, n_1 and n_2 depend on the post-yield stiffness ratio α (Table 1), R_μ and T are respectively the strength reduction factor and the initial period of vibration of the non-linear SDOF and $\xi_{=5\%}$ is the 5%-damping elastic ratio.

α	m_1	m_2	n_1	n_2
0%	0.026	0.87	0.016	0.84
5%	0.027	0.65	0.027	0.55
10%	0.027	0.51	0.031	0.39
20%	0.024	0.36	0.030	0.24

Table 1 Coefficients for calculating equivalent period and damping (Lin & Miranda, 2008)

The third method evaluated was originally proposed by Diana et al. (in press) and is based on an optimization of the original N2 method. An exponent correction to the classical N2 formulation has also been proposed by Graziotti et al. in 2014, based on shaking table tests but valid exclusively for masonry stiff structures. The proposal here evaluated, referred to as N2 OPT, enhances the N2 formulation to include an additional exponent for correction and multiplicative coefficients. Improvement of N2 OPT is achieved by statistical evaluation of NLTHA results on EC8 ground-classes (A, B, C and D) with the aim of minimizing the discrepancy in displacement demand prediction. This evaluation assumes single-degree-of-freedom systems with different periods ranging from T_B to T_C and strength reduction factors ranging from 1.5 to 5.0. The T_B and T_C periods are the lower and the higher corner periods limiting the plateau zone of the spectrum. The new formula has been obtained by a global optimization metaheuristic employing a genetic algorithm to minimize differences obtained between the formula and the NLTHA. The approach of the N2 OPT method preserves the mathematical compatibility with the preceding N2 method. The goal is to reduce the uncertainty in seismic displacement demand assessment in a non-linear domain. The formula is defined starting from (1), including three coefficients, as follows:

$$\begin{cases} S_d = \dfrac{S_{de}}{\frac{R_\mu}{1.48}} \cdot \left[\left(\dfrac{R_\mu}{1.45} - 1 \right)^{1.35} \cdot \dfrac{T_C}{T} + 1 \right], & T < T_C \text{ and } R_\mu > 1 \\ S_d = S_{de}\,, & T \geq T_C \text{ or } R_\mu \leq 1 \end{cases} \quad (6).$$

2.1 NLTHA Methodology

Displacement demands provided by the previous mentioned methods are compared with the displacement demands (true values) provided by the non-linear time-history analysis (NLTHA). The methodology used in this study is identical to that in previous investigations by Michel et al. (2014). Non-linear responses were computed for SDOF systems subjected to acceleration time-histories. The non-linear SDOF systems deemed in this study are defined by the relative initial natural period, the yield displacement and the hysteretic model according to which the structure behaves in the non-linear domain.
The modified Takeda-model (Takeda at al. 1970) is used here as hysteretic model to describe non-linear structural response. An adequate approximation of material behaviour is attained by integrating the real condition for unloading and reloading phases (Lestuzzi, 2002).

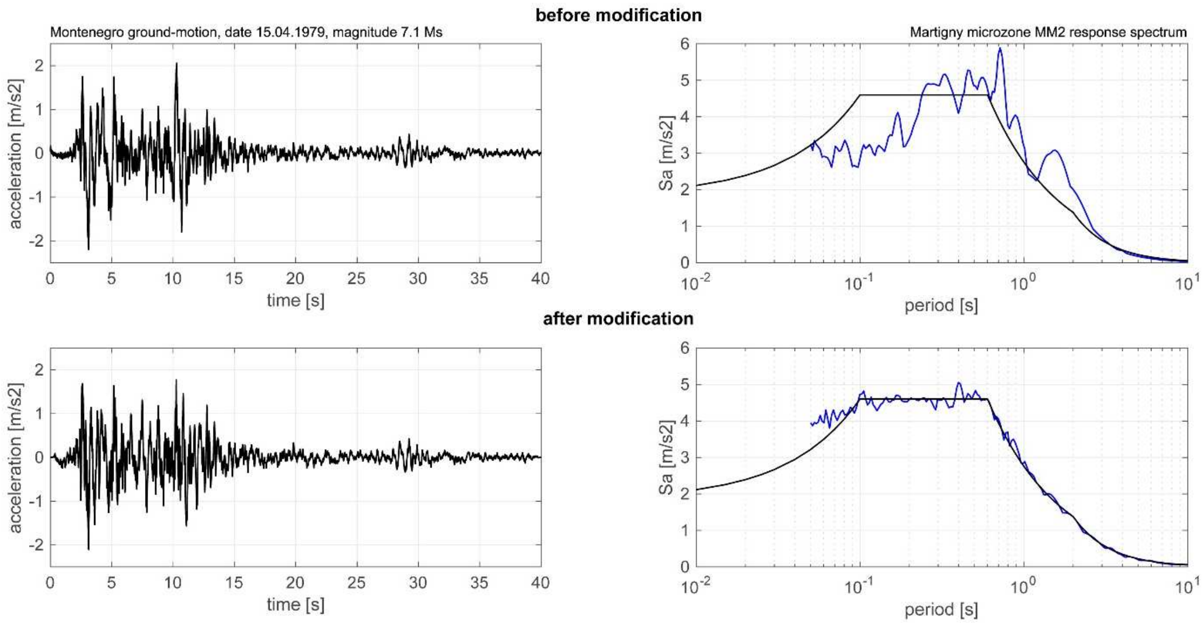


Figure 1 Ground-motion of Montenegro (15.04.1979, magnitude 6.9 M_w) before modifications and after modification to match the response spectrum of Martigny microzone MM2.

A set of twelve ground-motion recordings (see Appendix I) is selected from the European Strong Motion Database (Ambraseys et al., 2002). Recordings from analog instruments, such as ESM Database, may mask or distort the original ground-motion signal (Boore and Bommer, 2005). Beyond such a rather sismological issue, ground-motions have been here considered only for investigating structural response of structures. Each recording is adjusted using non-stationary spectral matching method proposed by Abrahamson (1992) in order to individually match the different response spectra. Adjustments preserve the non-stationary property of the reference ground-motion (Linda and Abrahamson, 2010). Modifications of records are small enough to ensure that related structural responses in the non-linear domain are not significantly affected. This procedure allows the exclusion of the variability due to ground-motion to evaluate variability due to structural response (Diana et al., in press). In Figure 1, the ground motion of Montenegro (15.04.1979, Magnitude 6.9 M_w) before modifications and after modifications to match the response spectrum of Martigny microzone MM2 (see section 4.2.2) is shown. The true value for each simulation is defined by the mean value of non-linear peak displacements provided by the twelve ground-motion recordings. The difference between the mean and displacement demands predicted by simplified methods was then assessed.

3. Test cities: SION and MARTIGNY, typical Swiss cities in moderate seismicity area

The accuracy of damage prediction linked to the investigated displacement demand determination methods is tested on two typical Swiss cities (Sion and Martigny) in moderate seismicity area. These tests provide real building stock distributions and seismic conditions.
The seismic vulnerability assessment 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.
Both cities are situated in the main seismic zone of Switzerland (zone 3b), with a peak ground acceleration of 1.6 m/s^2. Soils conditions and seismic actions are defined by soil class of EC8 (CEN, 2004) and related response spectra.

3.1 Building typologies

The cities of Sion and Martigny are the subject of an ongoing study, performed in collaboration between Canton du Valais, the EPFL, the University of Genova and CREALP (Centre de Recherche sur l'Environnement Alpin), dealing with the urban seismic vulnerability assessment. Building stock of the two cities have been analysed with different methods and surveys.
A first rapid survey has been performed by conducting visual screenings to identify the main Risk-UE types. This survey concerned nearby 3000 buildings in Sion and 1600 buildings in Martigny.
An additional detailed survey was also performed for a limited number of buildings in both cities. The Risk-UE classification based on the main European constructions, does not fully match with the Swiss built environment. The goal of this further survey was indeed to develop specific types for Swiss buildings with stiff floors. This detailed survey was performed on the construction drawings of each building obtained from city archives. This detailed work has included 206 buildings in Sion and 306 in Martigny. The new typical Swiss-building typology is intended to be a better description of the building stock of Sion and Martigny. The introduced types have been: A1, A2, B2, C and D2 (Fig. 2).
Type A1 is for unreinforced masonry (URM) buildings with a basement floor in reinforced concrete (RC). Type A2 is for mixed URM-RC buildings for all the height of the structure. Type B2 is for buildings with RC pillars in the base floor. Type C is for buildings with RC shear walls. Type D2 is for buildings with URM shear walls (Lestuzzi et al, 2017; Luchini 2016). The related capacity curves, called typological curves, were also developed. In this paper, only typical Swiss-buildings typological curves have been considered, neglecting Risk-UE capacity curves. Typological curves have been developed to fit with existing characteristics of real building stock since every building has been surveyed and construction drawings analysed. Furthermore, typological curves are more reliable than Risk-UE capacity curves since each curve corresponds to the behaviour of buildings with a well-defined number of storeys. On the contrary, Risk-UE capacity curves are related to less precise height categories (low-rise, mid-rise, high-rise buildings).

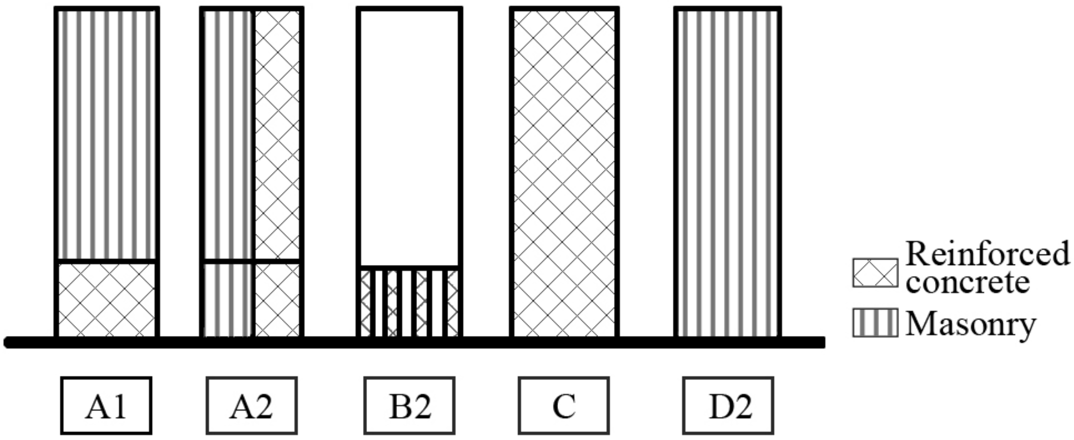
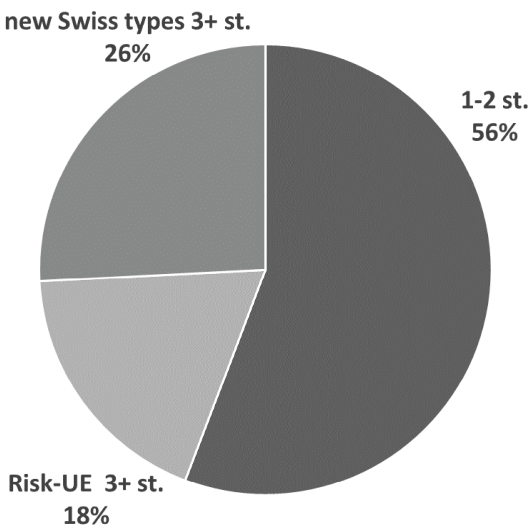


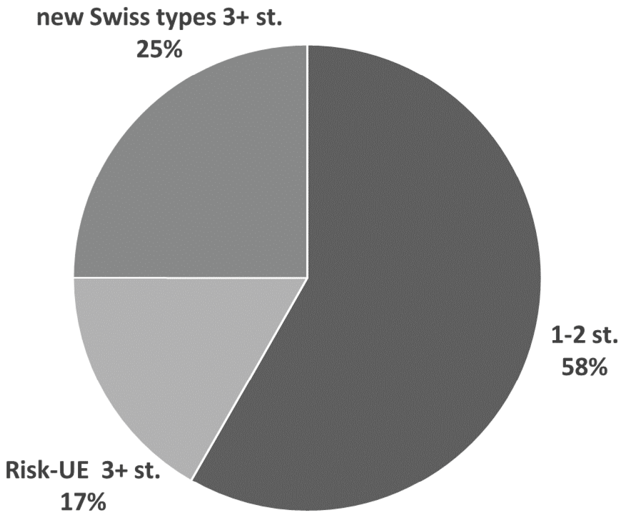
Figure 2 Specific types for typical Swiss-buildings (figure adapted from: Lestuzzi et al, 2017)

3.2 Distributions

Specific types for typical Swiss-buildings (Figure 2) do not encompass all building stock of Sion and Martigny. For example, steel and timber buildings with flexible floors and buildings of less than three storeys are not included. The study considers only buildings equal or higher than 3 storeys. In this paper, 1164 buildings belonging to these specific typologies have been selected: 773 for the city of Sion and 391 for the city of Martigny. These buildings correspond to the 512 detailed surveyed buildings in both cities augmented by buildings which were surveyed by rapid visual screening that belong to these specific Swiss types. Typical Swiss-buildings are an important and sensible part of the entire stock of the two cities as shown in Figure 3. The major part (56% for Sion and 58% for Martigny) of the building stock is composed of low-rise buildings including 1 and 2 storeys. This building category is known to be less vulnerable than mid-rise and high-rise buildings. The new Swiss types represent approximately 25% of the total building stock in both cities.
The global distribution of specific types is different for Sion and Martigny (Figure 4). In Sion type C is dominant (38%), followed by type A2 (28%). Types D2 and A1 are present in approximately equal parts (15% and 16%). Type B2 is not significant and thus irrelevant. In Martigny, type D2 is dominant (57%), followed by type C (15%). Types A2, A1 and B2 are present in approximately equal small parts (10%, 9% and 9%).

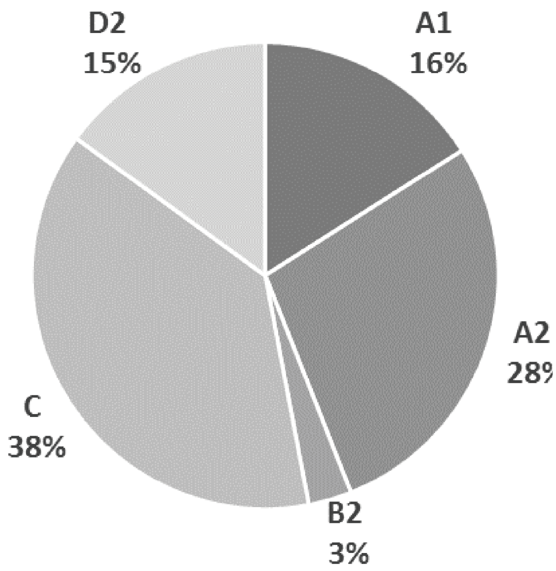


(a) Sion

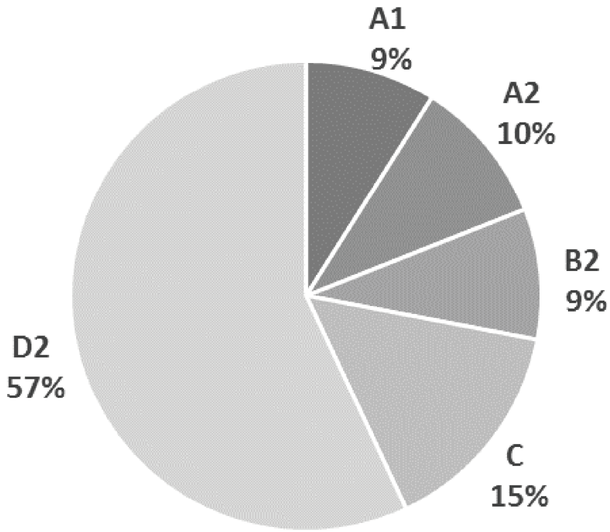


(b) Martigny

Figure 3 Distribution of the total suveyed buildings of (a) Sion (2994 buildings) and (b) Martigny (1564 buildings) in three main sets: new Swiss types ≥ 3 storeys; Risk-UE types ≥ 3 storeys; buildings of 1 and 2 storeys.



(a) Sion



(b) Martigny

Figure 4 Typical Swiss-building global distribution: (a - Sion) 773 buildings; (b - Martigny) 391 buildings

3.3 Typological curves

The structural response of typical Swiss-buildings, in line with the performance-based approach, is described by a typological curve of an equivalent inelastic SDOF system. Using a few mechanical and geometrical parameters, the typological curve defines the response of a structure in a non-linear domain. The typological curve provides a simplified assessment of the overall strength for each type and number of storeys.

For an assessment at an urban scale, several methods are available in literature to define typological curves. The mechanical method known as Displacement Based Vulnerability (DBV) method (Lagomarsino et al., 2010; Cattari et al., 2012; Lagomarsino and Cattari, 2013) has been chosen. The structural response of buildings is idealized by a bilinear elastic perfectly-plastic SDOF system defined by three parameters: the fundamental period T, the yield acceleration A_y and the ultimate capacity D_u (as shown in Figure 5).

In a large-scale seismic vulnerability analysis, a typological curve has to be representative of different buildings belonging to the same class exhibiting similar behaviour. Parameters such as materials, geometry and drift capacity are random variables with a dispersion that is compatible with variability of analysed buildings of that class. Every typological capacity curve has a variability range that is related to two limit cases, a minimum strength case and a maximum strength case. Some slight differences can be observed also in terms of stiffness and ultimate displacement. Detailed information about the development of typological curves and the related variability for typical Swiss-buildings are discussed by others (Luchini and Podestà, 2015; Luchini, 2016; Lestuzzi et al., 2017). The influence of such variability has not been investigated and requires further study.

For the present study, the most unfavourable capacity curves (the minimum strength case) has been chosen as typological curve in order to provide conservative assessment in the damage scenario. In addition, median curves showed an underestimation related to the real damage scenario (Lestuzzi et al. 2017). Note that due to different buildings stock features, typological curves are slightly different for Sion and Martigny even for the same building class.

For the determination of the performance point for a given type and a given number of storeys, uncertainties are related to both the method used for computing the displacement demand and the uncertainties related to the typological curve used (Michel et al. 2017) (see Figure 5). Only the uncertainties related to displacement demand determination are investigated in this paper.

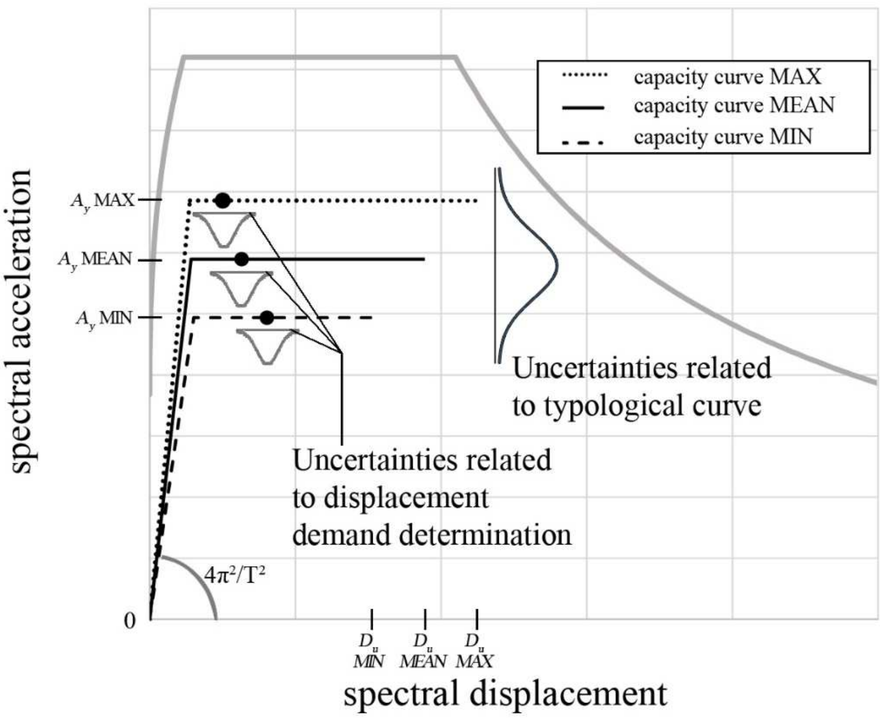


Figure 5 Uncertainties for the determination of the performance point are related to both the method used for computing the displacement demand and the uncertainties related to the typological curve used.

4. Impact on the damage distribution

Seismic damage distribution at an urban scale is a direct consequence of damage assessment on all types evaluated. Using mechanical methods and neglecting uncertainties associated with typological curves, a relationship is established between prediction of the displacement demand and the damage distribution.

In Section 4.1, displacement demands provided by the three methods introduced in Section 2 (N2; Lin&Miranda; N2 OPT) are compared with the NLTHA demand assumed as the true value. In this section, only the type 1 EC8 soil class C response spectrum is considered for both cities.

In Section 4.2, displacements are used as input values for the determination of the damage distribution. The analysis is here performed with the hypothesis that all buildings were settled on the type 1 EC8 soil class C (Section 4.2.1) as well as taking into account the real soil amplification and the expected ground shaking by considering detailed microzone spectra for both cities (Section 4.2.2). The goal is to show the influence that different methods for determination of the displacement demand have on the urban damage distribution for a real case.

4.1 Displacement demand determination with N2, Lin & Miranda and N2 OPT

The displacement demand determination is performed on the type 1 EC8 soil class C spectrum, for zone 3b (p.g.a. equal to 1.6 m/s^2) where both cities are settled. Typological curves considered are those for new Swiss types introduced in Section 3.1 (see Figure 2). Type B2 is not significant and thus irrelevant (see Figure 4).

Figure 6 illustrates typological curves for type A1 in Sion with the performance points obtained by the N2 method (solid black circles), the Lin & Miranda proposal (black crosses), the N2 optimized formula (grey triangle) and the NLTHA (unfilled circles). One standard deviation of these values is shown with a plus sign. This example shows significant differences between methods. Other typological curves for the city of Sion and Martigny are shown in figure 7 together with the different performance points obtained. For clarity in these cases only the horizontal plastic deformation region of the typological curves is shown.

The three methods are compared numerically in terms of percent difference between the displacement demand obtained ($Sd_{meth.}$)and the NLTHA average value ($Sd_{NLTHA.}$), according to expression (7):

$$\Delta_{dd\%} = \frac{S_{d_{meth.}} - S_{d_{NLTHA}}}{S_{d_{NLTHA}}} \qquad [\%] \qquad (7).$$

The N2 method leads to overestimation of displacement in both Sion and Martigny for low-rise buildings up to 5 and 6 storeys. Especially for types A1, A2 and D2, important overestimation can be observed. Overestimated and

underestimated predictions are considered as important if they are above or below the one standard deviation away from the mean of NLTHA predictions. For type C in Sion, the displacement demand determined by the three methods shows important overestimation for high rise buildings starting from 6 storeys.
In Martigny, a more stable and reliable behaviour is observed. The three methods show less significant overestimation than in Sion. Generally, Lin & Miranda and N2 OPT for both cities are more accurate than the N2 method. The N2 OPT results compared to those provided by Lin & Miranda, show overestimation for 3- and 4-storey buildings of type A2 for both cities. For type C in Martigny, the N2 OPT proposal guarantees more confident predictions with the NLTHA than Lin & Miranda for middle rise buildings (5 and 6 storeys) but with an important overestimation for 8-storey high buildings. The detailed per cent discrepancies for Sion and Martigny are reported in Table 2 and 3.
Since typological curves related to the same building class are slightly different for Sion and Martigny, therefore different displacement demands can be identified even if the response spectrum considered is the same for both cities.
Low-rise buildings have lower strength reduction factor R_μ. When low-strength reduction factor systems are analysed, the displacement demand is overestimated. This is most common when implementing the N2 method. This trend is clear for very stiff structures like type A1 and A2 for low-rise buildings. As the number of storeys and strength reduction factor increase, differences with NLTHA decrease. There is an exception for type C in Sion. In this case, high-strength reduction factors and long periods (type C is in reinforced concrete) of SDOF systems cause overestimation of the displacement demand for all three methods.

N2 method								**Lin&Miranda**								**N2 OPT**							
Sion - EC8 Soil Class C								Sion - EC8 Soil Class C								Sion - EC8 Soil Class C							
Nr of stories	3	4	5	6	7	8	9	Nr of stories	3	4	5	6	7	8	9	Nr of stories	3	4	5	6	7	8	9
A1	**114%**	**60%**	**33%**	12%	2%	0%	4%	A1	**26%**	-1%	-3%	-4%	2%	3%	**15%**	A1	**97%**	-2%	-1%	-4%	-4%	-5%	**16%**
A2	**52%**	**42%**	**44%**	**33%**	16%	9%	5%	A2	-1%	-2%	5%	5%	0%	2%	7%	A2	**43%**	**34%**	-1%	0%	-6%	-6%	-4%
C	14%	3%	1%	**11%**	**16%**	11%	**15%**	C	-3%	5%	9%	**17%**	**20%**	**15%**	**18%**	C	-4%	-4%	3%	**20%**	**16%**	**16%**	**15%**
D2	**39%**	20%	5%	-2%	-1%	1%	-	D2	-4%	-3%	0%	8%	11%	11%	-	D2	2%	-1%	-4%	-3%	4%	6%	-

Table 2 Summary of the results obtained in Sion on EC8 soil class C. In the first column, the percent differences ($\Delta_{dd\,\%}$) between N2 method displacement demand and the NLTHA average value; in the second column the Lin & Miranda method results ($\Delta_{dd\,\%}$); in the third column the N2 OPT method ($\Delta_{dd\,\%}$). Values outside of one standard deviation are bold face.

N2 method								**Lin&Miranda**								**N2 OPT**							
Martigny - EC8 Soil Class C								Martigny - EC8 Soil Class C								Martigny - EC8 Soil Class C							
Nr of stories	3	4	5	6	7	8	9	Nr of stories	3	4	5	6	7	8	9	Nr of stories	3	4	5	6	7	8	9
A1	**125%**	**51%**	**19%**	6%	-4%	-	-	A1	**24%**	-2%	-6%	0%	6%	-	-	A1	**15%**	2%	-2%	-2%	-4%	-	-
A2	**52%**	**48%**	**28%**	11%	4%	4%	-	A2	-1%	5%	2%	-1%	2%	11%	-	A2	**43%**	1%	-1%	-6%	-6%	-2%	-
C	-	9%	8%	8%	9%	**12%**	-	C	-	-1%	8%	12%	10%	11%	-	C	-	-9%	-4%	1%	7%	**12%**	-
D2	**39%**	13%	1%	-3%	2%	0%	-	D2	-4%	-5%	2%	12%	9%	15%	-	D2	2%	-3%	-3%	0%	5%	13%	-

Table 3 Summary of the results obtained in Martigny on EC8 soil class C. In the first column, the percent differences ($\Delta_{dd\,\%}$) between N2 method displacement demand and the NLTHA average value; in the second column the Lin & Miranda method results ($\Delta_{dd\,\%}$); in the third column the N2 OPT method ($\Delta_{dd\,\%}$). Values outside of one standard deviation are bold face.

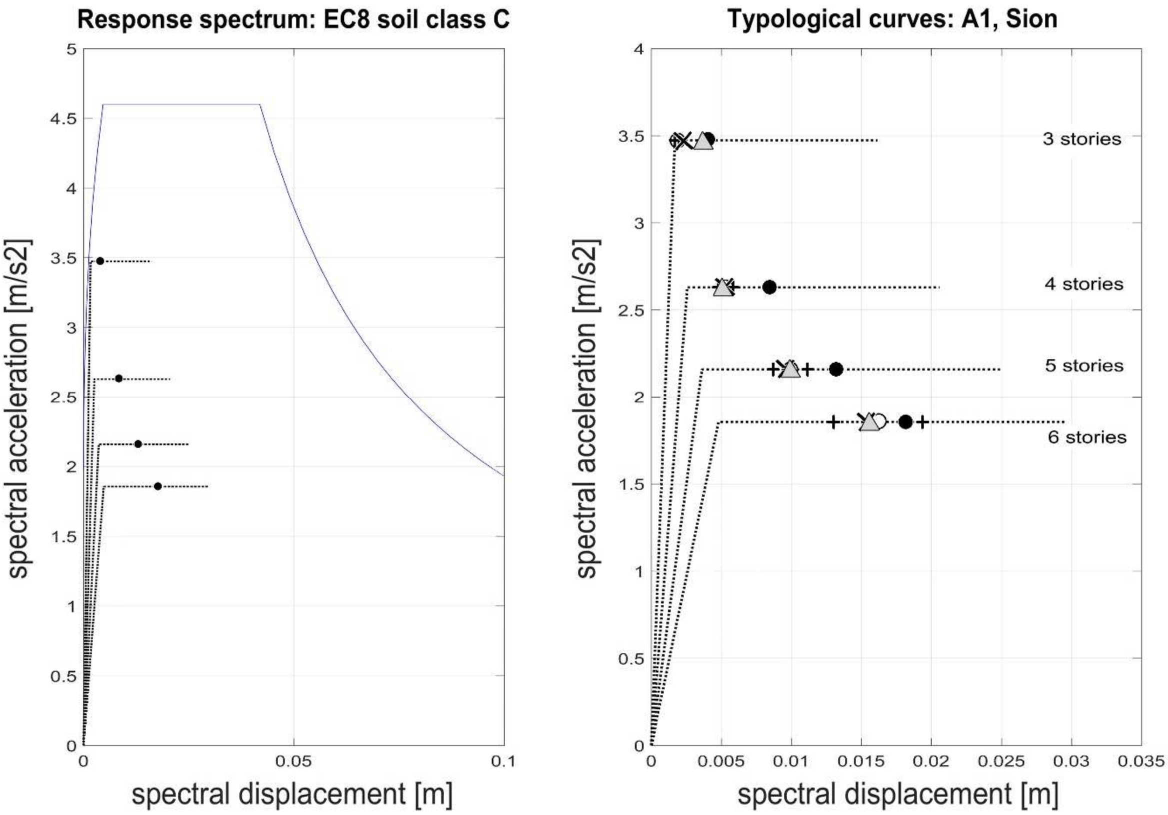


Figure 6 Typological curves for type A1 in Sion and related performance points (● = N2 method; X = Lin & Miranda; ▲ = N2 OPT) for response spectrum of EC8 soil class C and seismic zone Z3b. Unfilled circles correspond to the average value of the results of NLTHA together with a plus sign for one standard deviation. On the left part of the figure, only performance points obtained by N2 method are shown.

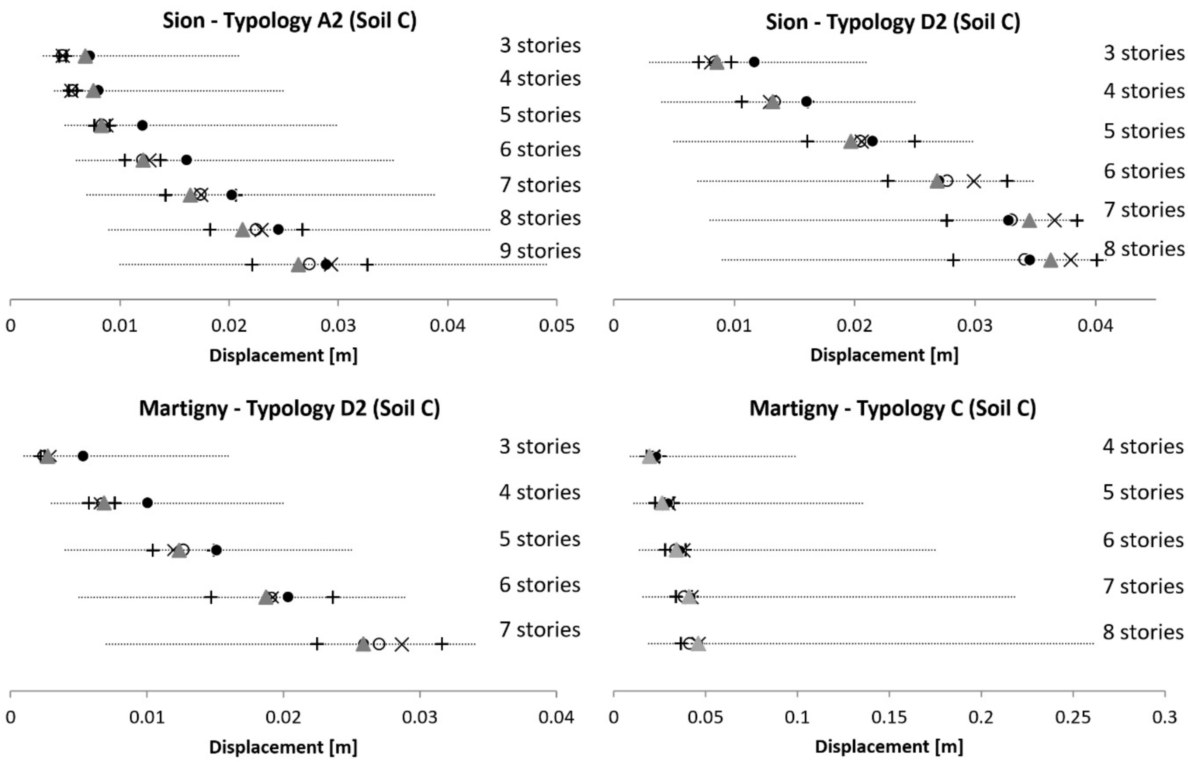


Figure 7 Displacement demand determination (● = N2 method; X = Lin & Miranda; ▲ = N2 OPT) for types A2 and D2 for Sion and types C and D2 for Martigny for response spectrum of EC8 soil class C and seismic area Z3b. Unfilled circles (○) correspond to the average value of the results of NLTHA together with a plus sign (+) for one standard deviation.

4.2 Damage distribution

Unreliable methods to compute the displacement demand could lead to significant error in the damage distribution at an urban scale. In this section, the objective is to investigate the impact of the three methods analysed to compute the displacement demand on damage distribution at an urban scale for Sion and Martigny. This comparison is provided for the Swiss-building types introduced in section 3.1, with the exclusion of type B2.

Mechanical methods for damage distribution (Lagormarsino and Giovinazzi, 2006) use a lognormal cumulative probability function (HAZUS, 1999). In this study, a different procedure has been employed related to a particular damage probability matrix. This matrix is utilized in macroseismic vulnerability methods (Lagomarsino and Giovinazzi, 2006) and is achieved by the probability mass function (PMF) of the binomial distribution. This approach is based on the binomial distribution and has been chosen for the sake of simplicity when compared to the lognormal distribution proposed in the mechanical method. Choosing a particular distribution is not the primary goal of this paper. Instead, interest is focused on how methods for prediction of displacement demand influence the damage distribution at an urban scale and not on the reliability of damage distribution. Furthermore, the binomial distribution has been also assumed as being the one successfully employed for the approximation of observed damage data (Braga et al., 1982). The probability of having a damage grade from 1 to 5 ($k = 1, \dots 5$), on the storeys distribution ($stor = 3, \dots 9$), is calculated as follows:

$$p_{(stor,k)} = \frac{5!}{k!\,(5-k)!} \cdot \left(\frac{\mu_d}{5}\right)^k \cdot (1 - \frac{\mu_d}{5})^{5-k} \qquad (8).$$

The value μ_d, is the mean damage degree, and calculated as:

$$\mu_d = \begin{cases} 0 + \dfrac{S_d - 0}{S_{d,1} - 0}, & S_d \leq S_{d,1} \\ 1 + \dfrac{S_d - S_{d,1}}{S_{d,2} - S_{d1}}, & S_{d,1} < S_d \leq S_{d,2} \\ 2 + \dfrac{S_d - S_{d,2}}{S_{d,3} - S_{d,2}}, & S_{d,2} < S_d \leq S_{d,3} \\ 3 + \dfrac{S_d - S_{d,3}}{S_{d,4} - S_{d,3}}, & S_{d,3} < S_d \leq S_{d,4} \\ 4 + \dfrac{S_d - S_{d,4}}{2 \cdot S_{d,4}}, & S_d > S_{d,4} \end{cases} \qquad (9).$$

The seismic displacement demand S_d is determined by the analysed method. Similarly to the threshold value of the LM2 method (Lagomarsino and Giovinazzi, 2006), the damage limit state $S_{d,j}$ ($j = 1 \dots 4$) are here identified on the typological curves as functions of the yielding D_y displacement and of the ultimate D_u displacement. The thresholds here considered are slightly adapted from those used by Lagomarsino and Giovinazzi in 2006. More information about the displacement thresholds adopted can be found in Luchini (2016).

The probability of having buildings with no damage is calculated as follows:

$$p_{(stor,0)} = 1 - \sum_{K=1}^{5} p_{(stor,k)} \qquad (10).$$

In the following sections, the damage distribution is achieved by the aggregation of the probability distribution multiplied by the number of related buildings obtained by the urban distribution. This explains the presence of decimal places in the number of buildings.

4.2.1 Damage distribution on Type 1 EC8 soil class C

Damage distributions have been firstly determined under the assumption that all buildings were settled on the type 1 EC8 soil class C. Soil class C is the most common soil class in the region of Sion and Martigny as well as the main soil configuration before the introduction of the detail study of microzones (see Section 4.2.2). Displacement demands obtained in Section 4.1 are input values for the determination of damage distributions (see Equation(9)). The total amount of buildings assessed by the methods and the NLTHA in a different damage grade is evaluated for comparison.

In terms of number of building, this total discrepancy is calculated as follows:

$$\varDelta_{dg} = \sum_{i=0}^{5} \left| n^{\circ}build_{d_{i_{meth.}}} - n^{\circ}build_{d_{i_{NLTHA}}} \right| \qquad (11).$$

And in terms of percent:

$$\varDelta_{dg\%} = \frac{\varDelta_{dg}}{tot\ build.} \quad [\%] \qquad (12).$$

In both cities, the distribution from the N2 method accounts for a greater number of buildings in upper damage grades compared with the NLTHA distribution. Important underestimation of buildings in damage grade from 0 to 2 and overestimation of those from 3 to 5 can be underlined (see Table 4 and 5 first column and Figure 8a and 9a). For the city of Sion, the total number of buildings assessed by N2 method in a different set than NLTHA is 104.93 ($\varDelta_{dg\%}$ = 14%). For Martigny, it is equal to 43.18 ($\varDelta_{dg\%}$ = 12%).
In Sion, Lin & Miranda and N2 OPT distributions are more consistent with NLTHA one (see Table 4 second and third columns and Figure 8b) than N2 method. The Lin & Miranda proposal shows the minimum discrepancy with 18.15 buildings ($\varDelta_{dg\%}$ = 2%) while N2 OPT arrives at 27.63 buildings ($\varDelta_{dg\%}$ = 4%).
For the city of Martigny, optimal results were obtained by the N2 OPT with only 3.36 buildings ($\varDelta_{dg\%}$ = 1%) evaluated in different sets than NLTHA. For Lin & Miranda proposal in Martigny, the underestimation of damage grade 3 and the overestimation of damage grade 5 lead to a total discrepancy $\varDelta_{dg}$ of 14.21 buildings ($\varDelta_{dg\%}$ = 4%). The two methods in Sion show a similar distribution while in Martigny only the distribution obtained from the N2 OPT matches with the NLTHA (see Table 5 second and third column and Figure 9b).

N2 method damage distribution analysis						
Sion - typ. A1+A2+C+D2 (total number of buildings = 732)						
EC8 Soil class C (total number of buildings = 732)						
damage grade	0	1	2	3	4	5
N2	47.6	150.1	217.7	189.9	101.0	25.6
NLTHA	62.6	178.6	226.6	168.6	77.6	17.9
diff.	-15.0	-28.6	-8.9	21.3	23.5	7.7
DIFF. TOT	**15.0**	**28.6**	**8.9**	**21.3**	**23.5**	**7.7**
Δ dg				**104.9**		
Δ dg%				**14%**		

Lin&Miranda damage distribution analysis						
Sion - typ. A1+A2+C+D2 (total number of buildings = 732)						
EC8 Soil class C (total number of buildings = 732)						
damage grade	0	1	2	3	4	5
L&M	58.0	174.3	228.8	172.3	79.6	19.1
NLTHA	62.6	178.6	226.6	168.6	77.6	17.9
diff.	-4.7	-4.4	2.2	3.7	2.0	1.2
DIFF. TOT	**4.7**	**4.4**	**2.2**	**3.7**	**2.0**	**1.2**
Δ dg				**18.2**		
Δ dg%				**2%**		

N2 OPT damage distribution analysis						
Sion - typ. A1+A2+C+D2 (total number of buildings = 732)						
EC8 Soil class C (total number of buildings = 732)						
damage grade	0	1	2	3	4	5
N2 OPT	56.2	171.3	230.0	176.2	80.3	18.0
NLTHA	62.6	178.6	226.6	168.6	77.6	17.9
diff.	-6.5	-7.3	3.3	7.6	2.8	0.1
DIFF. TOT	**6.5**	**7.3**	**3.3**	**7.6**	**2.8**	**0.1**
Δ dg				**27.6**		
Δ dg%				**4%**		

Table 4 Number of buildings and relative damage grade for the city of Sion, evaluated for Soil class C and with the three methods.

N2 method damage distribution analysis						
Mart. - typ. A1+A2+C+D2 (total of analysed buildings = 351)						
EC8 Soil class C (total number of buildings = 351)						
damage grade	0	1	2	3	4	5
N2	12.7	40.4	76.1	102.7	86.2	32.8
NLTHA	17.2	50.8	82.9	96.7	75.1	28.3
diff.	-4.4	-10.4	-6.8	6.1	11.1	4.4
DIFF. TOT	**4.4**	**10.4**	**6.8**	**6.1**	**11.1**	**4.4**
Δ dg				**43.2**		
Δ dg%				**12%**		

Lin&Miranda damage distribution analysis						
Mart. - typ. A1+A2+C+D2 (total of analysed buildings = 351)						
EC8 Soil class C (total number of buildings = 351)						
damage grade	0	1	2	3	4	5
L&M	16.1	50.0	81.4	93.0	76.2	34.4
NLTHA	17.2	50.8	82.9	96.7	75.1	28.3
diff.	-1.1	-0.9	-1.5	-3.7	1.0	6.1
DIFF. TOT	**1.1**	**0.9**	**1.5**	**3.7**	**1.0**	**6.1**
Δ dg				**14.2**		
Δ dg%				**4%**		

N2 OPT damage distribution analysis						
Mart. - typ. A1+A2+C+D2 (total of analysed buildings = 351)						
EC8 Soil class C (total number of buildings = 351)						
damage grade	0	1	2	3	4	5
N2 OPT	16.6	50.8	84.2	96.7	74.0	28.7
NLTHA	17.2	50.8	82.9	96.7	75.1	28.3
diff.	-0.6	0.0	1.3	0.1	-1.1	0.3
DIFF. TOT	**0.6**	**0.0**	**1.3**	**0.1**	**1.1**	**0.3**
Δ dg				**3.4**		
Δ dg%				**1%**		

Table 5 Number of buildings and relative damage grade for the city of Martigny, evaluated for Soil class C and with the three methods.

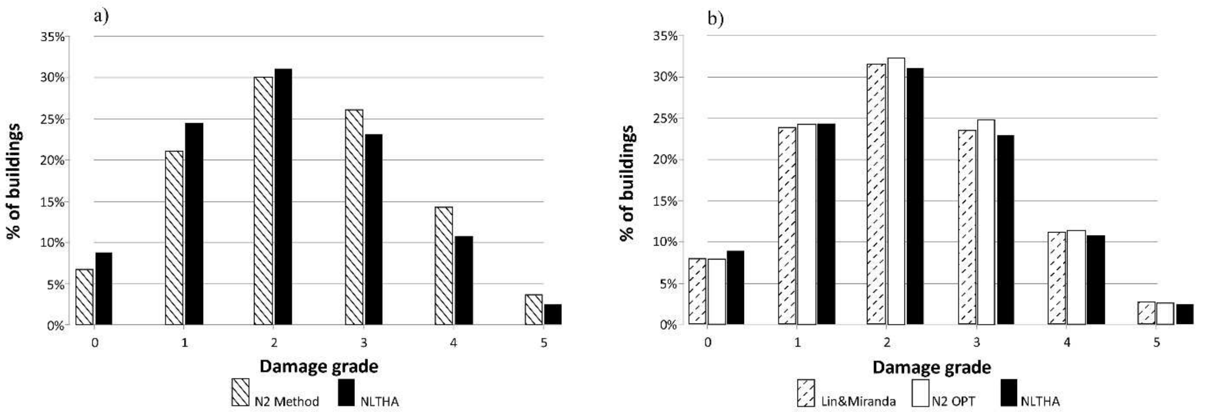


Figure 8 Damage distribution of Sion (soil C): N2 method and NLTHA distributions (a); Lin & Miranda proposal, N2 OPT formula and NLTHA distributions (b).

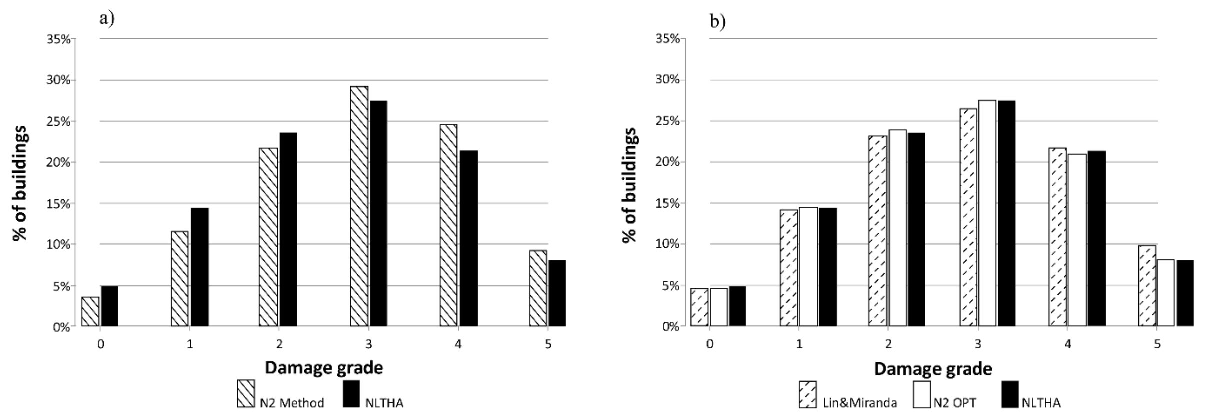


Figure 9 Damage distribution of Martigny (soil C): N2 method and NLTHA distributions (a); Lin & Miranda proposal, N2 OPT formula and NLTHA distributions (b)

4.2.2 Damage distribution on microzones

For the cities of Sion and Martigny a specific study by CREALP was performed to describe the soil amplification and the expected ground shaking. Three microzones have been defined for each city with connected response spectra. Figure 10 and Table in Appendix II show the related 5%-damped elastic spectra. The main parameters of microzones compared to EC8 soil classes are also shown.
The peak values of the response spectra of Sion are the same as EC8 soil classes. Plateau levels of microzones A1, A2 and A3 correspond to classes A, C and D. Corners of the plateau for microzones A1 and A2 are shifted towards high periods showing an increase of the seismic demands.
In Martigny, the peak values of microzones M1 and M3 are higher than Sion due to unfavourable soil conditions. The response spectrum of microzone M1 corresponds to the larger seismic demand. The microzone M2 corresponds to response spectrum of soil C, with the exclusion of period T_B shifted to a lower value. Furthermore, Sion microzone spectra show a plateau period range extended towards higher periods than EC8 soil classes and Martigny microzone spectra with the exception of microzone M1.
The distribution of the typical Swiss-building types (introduced in Section 3.1) in each microzone is in line with the global distribution of the two cities shown in Figure 4.

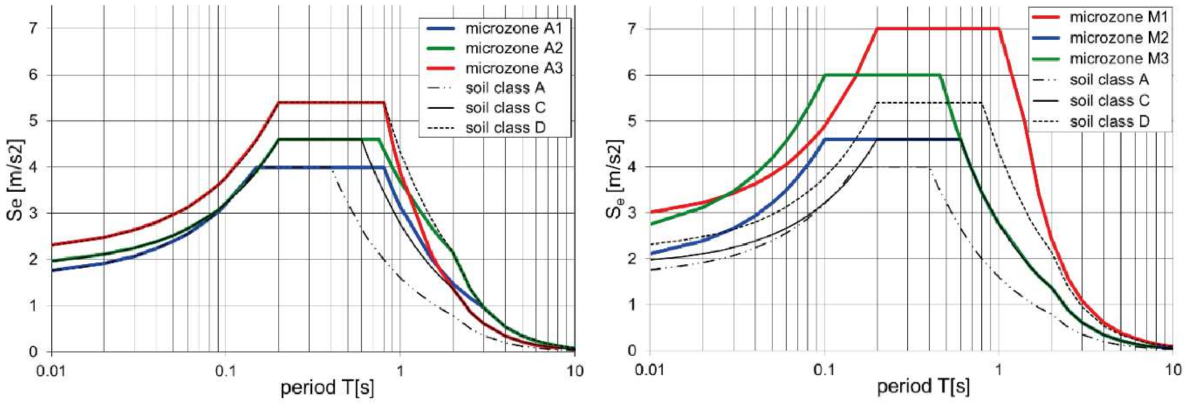


Figure 10 Elastic response spectra for a return period of 475 years and 5% damping ratio for microzones A1, A2 and A3 of Sion (on the left) and microzones M1, M2 and M3 of Martigny (on the right) (study provided by CREALP)

Appendix III shows the behaviour of the three methods in terms displacement demand and the related per cent difference values ($\Delta_{dd\ \%}$) with NLTHA results of microzones for Sion and Martigny. Error directly affects the damage distributions obtained. In Sion, considering the N2 method, overestimation in displacement demand prediction causes fewer buildings identified as damage grade 0, 1 and 2 as compared with damage grade 3, 4 and 5.
The N2 method overestimates the number of buildings with damage grade equal to 4 (+38.2 buildings more than NLTHA) and underestimates the number of buildings with damage grade equal to 1 (-35.46 buildings less than NLTHA) and equal to 2 (-25.47 buildings) (see Table 6 first column). The total discrepancy (Δ_{dg}) over the three microzones between N2 method and NLTHA is equal to 150.66 ($\Delta_{dg\%}$ = 21%). Results obtained by the NLTHA show a relocation of the distribution towards lower grade of damage (see Figure 11a).
The distributions obtained by Lin & Miranda and by N2 OPT are similar between each other and more consistent with the one provided by the NLTHA. The total discrepancy Δ_{dg} is of 50.63 buildings ($\Delta_{dg\%}$ = 7%) for Lin & Miranda and 49.18 buildings ($\Delta_{dg\%}$ = 7%) for N2 OPT (see Table 6 second and third column and Figure 11b).
The N2 method and the NLTHA do not greatly differ in terms of displacement demand in Martigny (Appendix III.c and III.d). The microzone MM1 of Martigny has not been taken into account due to few buildings present (only 32 building) and to misaligned response spectrum. The total discrepancy Δ_{dg} over the two microzones for the N2 method is 12.15 ($\Delta_{dg\%}$ = 4%). In this case, the N2 method is in agreement with NLTHA. Only a slight overestimation in the number of buildings being part of damage grade 3 is shown (3.65 buildings).
Regarding the two other methods analysed, the distribution provided by N2 OPT is accurate. The total discrepancy Δ_{dg} is equal to 11.32 ($\Delta_{dg\%}$ = 4%). Contrary to the accurate results obtained on Sion microzones, the distribution provided by Lin & Miranda in Martigny microzones accounts for more damaged buildings at higher damage grades. Underestimation of buildings being part of damage grade 2 and 3 and overestimation of building of damage grade 4 and 5 are shown. The total discrepancy Δ_{dg} is 36.88 ($\Delta_{dg\%}$ = 12%). The detailed damage distributions for Lin & Miranda and N2 OPT are shown in Table 7 second and third column and in Figure 12b).

N2 method damage distribution analysis						
Sion - typ. A1+A2+C+D2 (total number of buildings = 732)						
Microzone MA1 (total number of buildings = 121)						
damage grade	0	1	2	3	4	5
N2	7.9	24.7	35.6	31.2	17.1	4.6
NLTHA	12.2	32.4	38.1	25.7	10.5	2.2
diff.	-4.3	-7.8	-2.5	5.6	6.6	2.4
MA1 damage distribution diff. (24.15%)				29.2		
Microzone MA2 (total number of buildings = 184)						
damage grade	0.0	1.0	2.0	3.0	4.0	5.0
N2	8.7	30.6	49.5	49.9	33.4	11.8
NLTHA	10.8	36.2	52.2	44.4	28.0	12.4
diff.	-2.1	-5.7	-2.7	5.6	5.5	-0.6
MA2 damage distribution diff. (11.97%)				22.0		
Microzone MA3 (total number of buildings = 427)						
damage grade	0.0	1.0	2.0	3.0	4.0	5.0
N2	12.2	51.3	98.1	118.0	99.7	47.7
NLTHA	19.7	73.3	118.3	112.4	73.6	29.7
diff.	-7.4	-22.0	-20.2	5.6	26.1	18.0
MA3 damage distribution diff. (23.28%)				99.4		
TOT DIFF.	**13.8**	**35.5**	**25.5**	**16.8**	**38.2**	**21.0**
Δ_{dg}				**150.7**		
$\Delta_{dg\%}$				**21%**		

Lin&Miranda damage distribution analysis						
Sion - typ. A1+A2+C+D2 (total number of buildings = 732)						
Microzone MA1 (total number of buildings = 121)						
damage grade	0	1	2	3	4	5
L&M	12.0	32.7	38.7	25.7	10.0	2.0
NLTHA	12.2	32.4	38.1	25.7	10.5	2.2
diff.	-0.2	0.3	0.6	0.0	-0.5	-0.2
MA1 damage distribution diff. (1.52%)				1.8		
Microzone MA2 (total number of buildings = 184)						
damage grade	0.0	1.0	2.0	3.0	4.0	5.0
L&M	12.4	40.1	56.2	45.4	23.2	6.7
NLTHA	10.8	36.2	52.2	44.4	28.0	12.4
diff.	1.7	3.8	4.0	1.1	-4.8	-5.7
MA2 damage distribution diff. (11.41%)				21.0		
Microzone MA3 (total number of buildings = 427)						
damage grade	0.0	1.0	2.0	3.0	4.0	5.0
L&M	17.7	72.2	124.7	119.9	70.1	22.4
NLTHA	19.7	73.3	118.3	112.4	73.6	29.7
diff.	-2.0	-1.2	6.4	7.5	-3.5	-7.3
MA3 damage distribution diff. (6.51%)				27.8		
TOT DIFF.	**3.8**	**5.2**	**11.0**	**8.6**	**8.7**	**13.3**
Δ_{dg}				**50.6**		
$\Delta_{dg\%}$				**7%**		

N2 OPT damage distribution analysis						
Sion - typ. A1+A2+C+D2 (total number of buildings = 732)						
Microzone MA1 (total number of buildings = 121)						
damage grade	0	1	2	3	4	5
N2 OPT	10.1	30.0	38.8	28.0	11.7	2.4
NLTHA	12.2	32.4	38.1	25.7	10.5	2.2
diff.	-2.1	-2.5	0.7	2.4	1.3	0.2
MA1 damage distribution diff. (7.47%)				9.0		
Microzone MA2 (total number of buildings = 184)						
damage grade	0.0	1.0	2.0	3.0	4.0	5.0
N2 OPT	11.5	37.8	54.8	46.6	25.6	7.8
NLTHA	10.8	36.2	52.2	44.4	28.0	12.4
diff.	0.7	1.6	2.6	2.2	-2.4	-4.6
MA2 damage distribution diff. (7.58%)				14.0		
Microzone MA3 (total number of buildings = 427)						
damage grade	0.0	1.0	2.0	3.0	4.0	5.0
N2 OPT	16.3	66.3	115.6	117.0	79.5	32.2
NLTHA	19.7	73.3	118.3	112.4	73.6	29.7
diff.	-3.4	-7.0	-2.7	4.6	5.9	2.6
MA3 damage distribution diff. (6.13%)				26.2		
TOT DIFF.	**6.1**	**11.1**	**6.0**	**9.1**	**9.6**	**7.3**
Δ_{dg}				**49.2**		
$\Delta_{dg\%}$				**7%**		

Table 6 Number of buildings and relative damage grade for the city of Sion, evaluated for the three microzones and with the three methods.

N2 method damage distribution analysis						
Mart. - typ. A1+A2+C+D2 (total of analysed buildings = 319)						
Microzone MM2 (total number of buildings = 90)						
damage grade	0	1	2	3	4	5
N2	3.2	9.8	18.6	26.4	23.1	8.9
NLTHA	3.9	11.0	19.0	25.4	22.1	8.7
diff.	-0.7	-1.2	-0.4	1.0	1.0	0.2
MM2 damage distribution diff. (4.91%)				4.4		
Microzone MM3 (total number of buildings = 229)						
damage grade	0.0	1.0	2.0	3.0	4.0	5.0
N2	7.4	22.6	43.0	64.6	63.2	28.2
NLTHA	8.1	23.4	41.8	62.0	63.3	30.3
diff.	-0.7	-0.8	1.2	2.7	-0.2	-2.2
MM3 damage distribution diff. (3.38%)				7.7		
TOT DIFF.	**1.4**	**2.0**	**1.6**	**3.6**	**1.2**	**2.4**
Δ_{dg}				**12.2**		
$\Delta_{dg\%}$				**4%**		

Lin&Miranda damage distribution analysis						
Mart. - typ. A1+A2+C+D2 (total of analysed buildings = 319)						
Microzone MM2 (total number of buildings = 90)						
damage grade	0	1	2	3	4	5
L&M	3.8	11.4	19.5	24.6	21.3	9.4
NLTHA	3.9	11.0	19.0	25.4	22.1	8.7
diff.	-0.1	0.4	0.5	-0.8	-0.8	0.8
MM2 damage distribution diff. (3.91%)				3.5		
Microzone MM3 (total number of buildings = 229)						
damage grade	0.0	1.0	2.0	3.0	4.0	5.0
L&M	7.3	21.0	35.7	54.7	67.6	42.7
NLTHA	8.1	23.4	41.8	62.0	63.3	30.3
diff.	-0.8	-2.4	-6.2	-7.3	4.3	12.4
MM3 damage distribution diff. (14.57%)				33.4		
TOT DIFF.	**0.9**	**2.8**	**6.7**	**8.1**	**5.1**	**13.2**
Δ_{dg}				**36.9**		
$\Delta_{dg\%}$				**12%**		

N2 OPT damage distribution analysis						
Mart. - typ. A1+A2+C+D2 (total of analysed buildings = 319)						
Microzone MM2 (total number of buildings = 90)						
damage grade	0	1	2	3	4	5
N2 OPT	3.9	11.9	20.6	25.6	20.3	7.6
NLTHA	3.9	11.0	19.0	25.4	22.1	8.7
diff.	0.0	0.9	1.7	0.2	-1.7	-1.1
MM2 damage distribution diff. (6.23%)				5.6		
Microzone MM3 (total number of buildings = 229)						
damage grade	0.0	1.0	2.0	3.0	4.0	5.0
N2 OPT	7.9	23.8	42.1	60.3	62.4	32.6
NLTHA	8.1	23.4	41.8	62.0	63.3	30.3
diff.	-0.2	0.4	0.3	-1.7	-0.9	2.3
MM3 damage distribution diff. (2.50%)				5.7		
TOT DIFF.	**0.2**	**1.3**	**1.9**	**1.9**	**2.7**	**3.3**
Δ_{dg}				**11.3**		
$\Delta_{dg\%}$				**4%**		

Table 7 Number of buildings and relative damage grade for the city of Martigny, evaluated for microzones MM2 and MM3 and with the three methods.

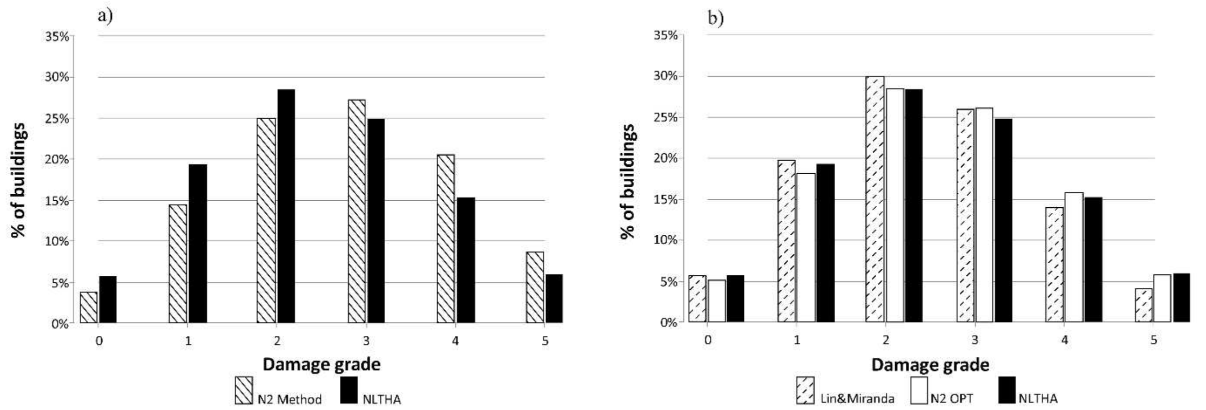


Figure 11 Damage distribution of Sion (microzones MA1+MA2+MA3): N2 method and NLTHA distributions (a); Lin & Miranda proposal, N2 OPT formula and NLTHA distributions (b).

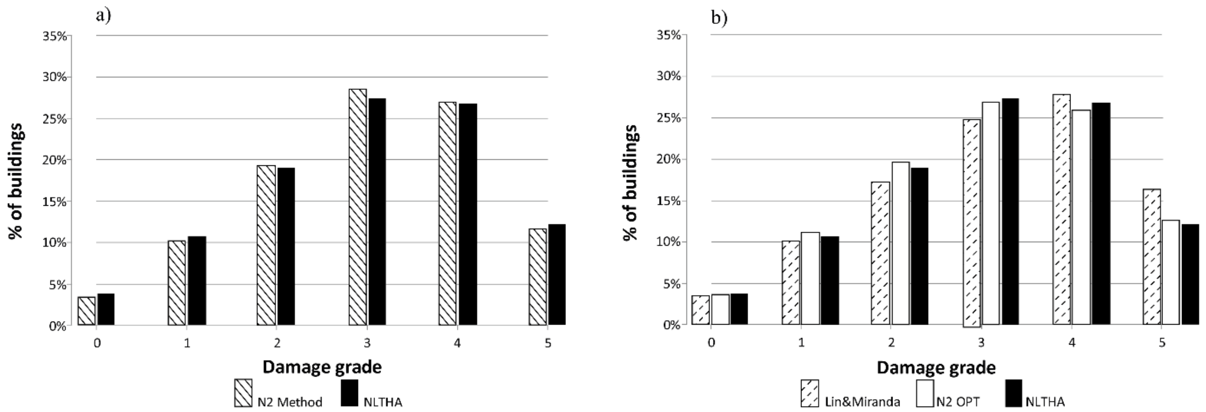


Figure 12 Damage distribution for Martigny (microzones MM2 and MM3): N2 method and NLTHA distributions (a); Lin & Miranda proposal, N2 OPT formula and NLTHA distributions (b).

4.3 Interpretation of the results

The three methods have been evaluated for the city of Sion and Martigny with response spectra of the EC8 soil class C and with inputs provided by the microzones response spectra. These three methods have been analysed for influence of different displacement demand determination in damage distributions at an urban scale for a real case. The three methods show a different behaviour (Table 8).

The N2 method generally overestimates the effect of damage. Damage distributions compared with the one provided by the NLTHA (considered as true distributions) are relocated towards higher damage grades. This trend is clear for Sion and Martigny under the assumption that all buildings were settled on the type 1 EC8 soil class C and for Sion microzones. In the case of Sion soil C, the per cent discrepancy $\Delta_{dg\%}$ arrives up to 14% while for Martigny soil C up to 12%. In the case of Sion microzones, the damage distribution is shifted of one damage grade towards higher level (see Figure 11a), with $\Delta_{dg\%}$ equal to 21%. Only for Martigny microzones, the N2 method shows results in line with the NLTHA distribution (Figure 12a) with $\Delta_{dg\%}$ equal to 4%.

Implementing N2 method, the difference between damage distributions obtained for Sion and Martigny microzones depends on shape of the spectra. For Sion microzone spectra, plateau period upper corners (T_C) are more extended towards higher period ranges than in Martigny (see Figure 10). This implies strong modifications to elastic displacement in application of N2 method. These modifications overestimates the displacement demand for structures with small strength reduction factors (Diana et al., in press) like A1 and A2 buildings as well as low-rise D2 buildings (see Appendix III.a and III.b). Moreover, type A1 and A2 as well as low-rise D2 in Sion account for more than 50% of the total stock. The overestimation increases the percent discrepancy ($\Delta_{dg\%}$ = 21%). On the contrary, plateau period extentions are limited in Martigny microzone spectra leading to lower modification of

elastic displacement. Furthermore, Martigny is characterized by a huge amount of D2 buildings (neary 60%, see Figure 4). Especially for the case of microzone MM3 (the most populated zone with 229 buildings), type D2 has several buildings of 3, 4, and 5 storeys with a strength reduction factor approximately three ($R = [2.8\ 3.8]$). Here, the N2 method provides results in line with the NLTHA (Diana et al. in press). Therefore, the related damage distribution has a small percent discrepancy $\Delta_{dg\%}$.
The N2 method results are compared with Lin & Miranda and N2 OPT results. The N2 OPT and the Lin & Miranda methods generally show similar results. In two out of four cases (Martigny soil C and Martigny microzones), the N2 OPT proposal is the most consistent with the NLTHA distribution. Especially for the case of Martigny soil C, the N2 OPT damage distribution is almost the same of NLTHA (see Figure 9b) with $\Delta_{dg\%}$ equal to 1%. The Lin & Miranda approach is the most consistent with NLTHA distribution on soil class C for the city of Sion ($\Delta_{dg\%} = 2\%$). Concerning Sion microzones, the Lin & Miranda proposal and the N2 OPT show results with the same $\Delta_{dg\%}$.
For the analysis carried out on Martigny microzones, it is not possible to observe a reliable behaviour of the Lin & Miranda proposal. It provides a per cent discrepancy of 12% with significant overestimation of damage grade 4 and 5 (Figure 12b). The source of such discrepancy is the overestimation of displacement demands shown by type D2 (see Appendix III.c and III.d). Since type D2 is the most widespread type in Martigny, assessing its displacement demand correctly becomes a central issue. In Figure 13, the damage distributions obtained by the three methods in Martigny microzones considering exclusively type D2 are shown. The Lin & Miranda distribution largely underestimates buildings in damage grade 2 and 3 and overestimates buildings in damage grade 5. In the case of microzone MM3, there is a maximum of 16% discrepancy for type D2 which explains an increased general value of $\Delta_{dg\%}$.
Therefore, the optimal behaviour is obtained by N2 OPT. In addition to providing the best results in several cases, it presents the most stable and confident distribution in every conditions. The other methods do not offer stable results with important distribution deviations. For the Lin & Miranda proposal, whose results are generally in line with N2 OPT, the per cent discrepancy ($\Delta_{dg\%}$) arrives in one case up to 12% (Martigny microzones).
For large-scale seismic vulnerability assessment, slight differences in damage distribution are considered reasonable and not misleading. Therefore, determining the method providing in different conditions stable results is a central issue. The Lin & Miranda and N2 OPT formula provide more accurate results than N2 method, but only the N2 OPT formula is always largely below a per cent discrepancy of 10%.
Obviously, the damage grade distribution depends on the response spectra considered in the vulnerability assessment. More specifically, the results depend on the relationship between response spectra and typological curves. Parameters such as strength reduction factors and initial frequency affects significantly the impact. Other issues need further research efforts such as the variability related to typological curves.

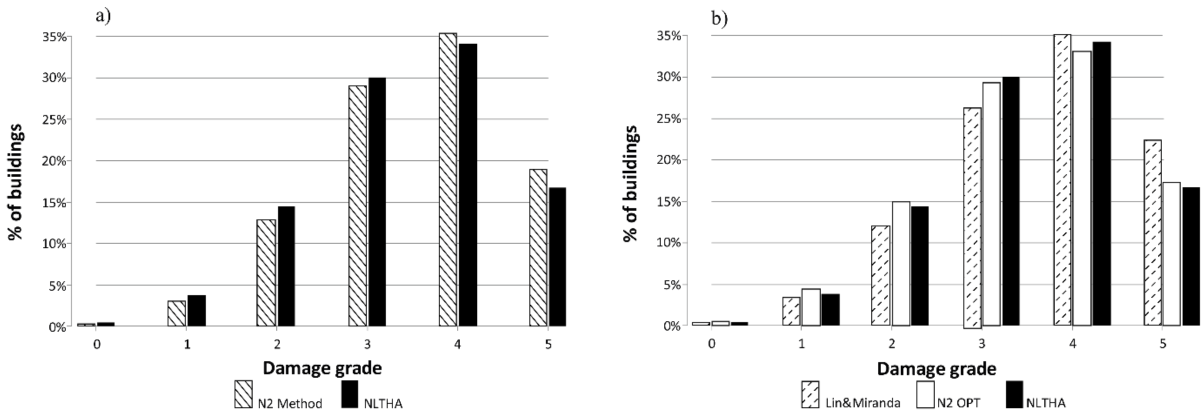


Figure 13 Damage distribution for Martigny (microzones MM2 and MM3) considering exclusively type D2: N2 method and NLTHA distributions (a.1 and a.2); Lin & Miranda proposal, N2 OPT formula and NLTHA distributions (b.1 and b.2).

	N2 method	Lin&Miranda	N2 OPT
SION - EC8 Soil class C			
$\Delta_{dg\%}$	14%	2%	4%
MARTIGNY - EC8 Soil class C			
$\Delta_{dg\%}$	12%	4%	1%
SION - Microzones			
MA1	24%	2%	7%
MA2	12%	11%	8%
MA3	23%	7%	6%
$\Delta_{dg\%}$	21%	7%	7%
MARTIGNY - Microzones			
MM1	-	-	-
MM2	5%	4%	6%
MM3	3%	15%	3%
$\Delta_{dg\%}$	4%	12%	4%

Table 8 Differences between the three methods and the NLTHA damage distribution for the city of Sion and Martigny obtained on EC8 soil class C and on the microzones.

5. Conclusions

When mechanical methods are used, urban damage distribution is directly related to the computed seismic displacement demand. Reliability of displacement demand determination is significant for accurate urban vulnerability assessment. Incorrect prediction of the displacement demand can lead to inaccurate damage distribution. Thus, the influence of using several approaches is critical to determine the seismic displacement demand of structures. Three other factors contribute to the final damage distribution: the definition of typological curves; the choice of the probability mass function; the knowledge of the seismic hazard. The influence of typological curves on damage distribution at an urban scale is related to the variability of stiffness, strength and ultimate displacement of the different structures belonging to the same building class. The choice of a particular probability mass function influences damage probabilities of different types analysed. Introduction of local seismic hazard determination (microzone) has a direct influence on damage results moving distributions towards more realistic values. In this paper, only the influence of displacement demand determination on seismic urban damage distribution is investigated. Other influences are not investigated and need further study.

Accurate displacement demand determination leads to more reliable damage distribution assessment. The urban damage distributions obtained from three methods (N2 method, Lin & Miranda proposal, N2 OPT) have been compared. Reliability of these three methods has been evaluated in the assessment of the seismic vulnerability of a selected portion of the building stock of the city of Sion and Martigny. Evaluations have been performed on the EC8 soil class C and on microzone response spectra (total of four combinations, two for Sion and two for Martigny).

The reliability of the N2 method has been here evaluated by the comparison with a non-linear time history analysis (NLTHA). Other methods, such as Lin & Miranda and an optimized version of the N2 method (N2 OPT), have also been evaluated. The comparison of the three methods has been firstly performed on the prediction of the performance point. Results showed that the N2 method leads to displacement demand overestimation for low-rise buildings (especially for 3- to 5-storey buildings) and relative underestimation for high-rise buildings (especially for 8- and 9-storey buildings). For type A1 in the microzone MA3 of Sion, the overestimation of the displacement demand are up to 198%. However, the Lin & Miranda and N2 OPT leads to more consistent displacement demand determination with respect to the NLTHA values.

The N2 OPT method shows the most stable behaviour in the four damage distributions (with a per cent discrepancy varying from 1% for Martigny soil C to 7% for Sion microzones), and is the most reliable method for vulnerability assessment at an urban scale. Although the other two methods analysed (N2 method and Lin & Miranda) can eventually get closer to the true distribution, these methods are not stable.

According to the obtained results, it is suggested to proceed with the N2 OPT method instead of the typical N2 method in order to minimize potential discrepancies. However, by using other displacement demand predictions, attention should be paid to the relationship between capacity curves and seismic action (i.e. response spectra). This issue directly influences the determination of displacement demand required to compute the damage distribution in the vulnerability assessment investigation. Potential discrepancy is controlled by strength reduction factor-plateau level ratio and initial period of equivalent SDOF system (initial slope of the capacity curves)-plateau corner period ratio. The N2 method provides accurate results if the value of the strength reduction factor is approximately three. For strength reduction factors less than three, the damage grade tends to be overestimated and underestimated for values greater than three.

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7. Appendix

Earthquake	Date	Magnitude	Dist. [km]	PGA [m/s2]	soil C	Sion			Martigny	
						A1	A2	A3	M2	M3
Friuli (as)	11.09.1976	5.5Mw	10	2.260					X	
Friuli (as)	15.09.1976	6Mw	11	1.069	X					
Basso Tirreno	15.04.1978	6Mw	18	1.585	X					
Friuli	06.05.1976	6.5Mw	27	3.499				X		
Volvi	20.06.1978	6.2Mw	29	1.430	X					
Montenegro (as)	24.05.1979	6.2Mw	33	2.652					X	
Montenegro (as)	24.05.1979	6.2Mw	8	2.624				X		
Alkion	25.02.1981	6.3Mw	25	1.176	X					
Aigion	15.06.1995	6.5Mw	43	0.911	X					
Adana	27.06.1998	6.3Mw	30	2.644			X	X		X
Montenegro	15.04.1979	6.9Mw	16	3.680						
Montenegro	15.04.1979	6.9Mw	65	2.509	X					
Montenegro	15.04.1979	6.9Mw	21	2.198		X	X	X	X	X
Montenegro	15.04.1979	6.9Mw	24	2.880						
Campano Lucano	23.11.1980	6.9Mw	23	1.776		X	X			
Campano Lucano	23.11.1980	6.9Mw	26	0.903	X					
Campano Lucano	23.11.1980	6.9Mw	16	1.725		X	X		X	
Campano Lucano	23.11.1980	6.9Mw	32	3.166					X	X
Alkion	24.02.1981	6.6Mw	33	3.036		X	X	X		X
Alkion	24.02.1981	6.6Mw	33	2.256					X	X
Alkion	24.02.1981	6.6Mw	34	2.838		X	X	X	X	
Spitak	07.12.1988	6.7Mw	36	1.796		X				
Tabas	16.09.1978	7.4Mw	11	3.779						X
Manjil	20.06.1990	7.4Mw	131	1.341		X	X			
Izmit	17.08.1999	7.6Mw	113	2.580			X	X	X	X
Izmit	17.08.1999	7.6Mw	110	1.698	X					
Izmit	17.08.1999	7.6Mw	99	3.542						
Izmit	17.08.1999	7.6Mw	48	2.334	X	X			X	
Izmit	17.08.1999	7.6Mw	78	1.040	X					
Izmit	17.08.1999	7.6Mw	96	1.120	X					
Izmit	17.08.1999	7.6Mw	10	2.192		X	X			
Izmit	17.08.1999	7.6Mw	39	1.266		X	X			
Izmit	17.08.1999	7.6Mw	34	3.542		X		X	X	X
Izmit	17.08.1999	7.6Mw	20	2.903			X	X		
Izmit	17.08.1999	7.6Mw	20	2.903				X		
Izmit	17.08.1999	7.6Mw	103	0.871	X					
Duzce 1	12.11.1999	7.2Mw	22	2.902						X
Kalamata	13.09.1986	5.9Mw	10	2.909		X	X	X	X	X
Umbria Marche	26.09.1997	5.7Mw	3	3.382						X
Umbria Marche	26.09.1997	5.7Mw	3	3.382				X	X	X

Appendix I Main characteristics of the selected records and their distribution in the six different sets of twelve records each (as=aftershock) for the non-linear time-history analysis (NLTHA)

City	Soil	Microzone	$S_{e,max}$	T_B	T_C	T_D	S
Sion	-	A1	4.0	0.15	0.80	3.00	-
Sion	-	A2	4.6	0.20	0.75	2.00	-
Sion	-	A3	5.4	0.20	0.80	2.00	-
Martigny	-	M1	7.0	0.20	1.00	1.40	-
Martigny	-	M2	4.6	0.10	0.60	2.00	-
Martigny	-	M3	6.0	0.10	0.46	2.00	-
-	A	-	4.0	0.15	0.40	2.00	1.00
-	C	-	4.6	0.20	0.60	2.00	1.15
-	D	-	5.4	0.20	0.70	2.00	1.35

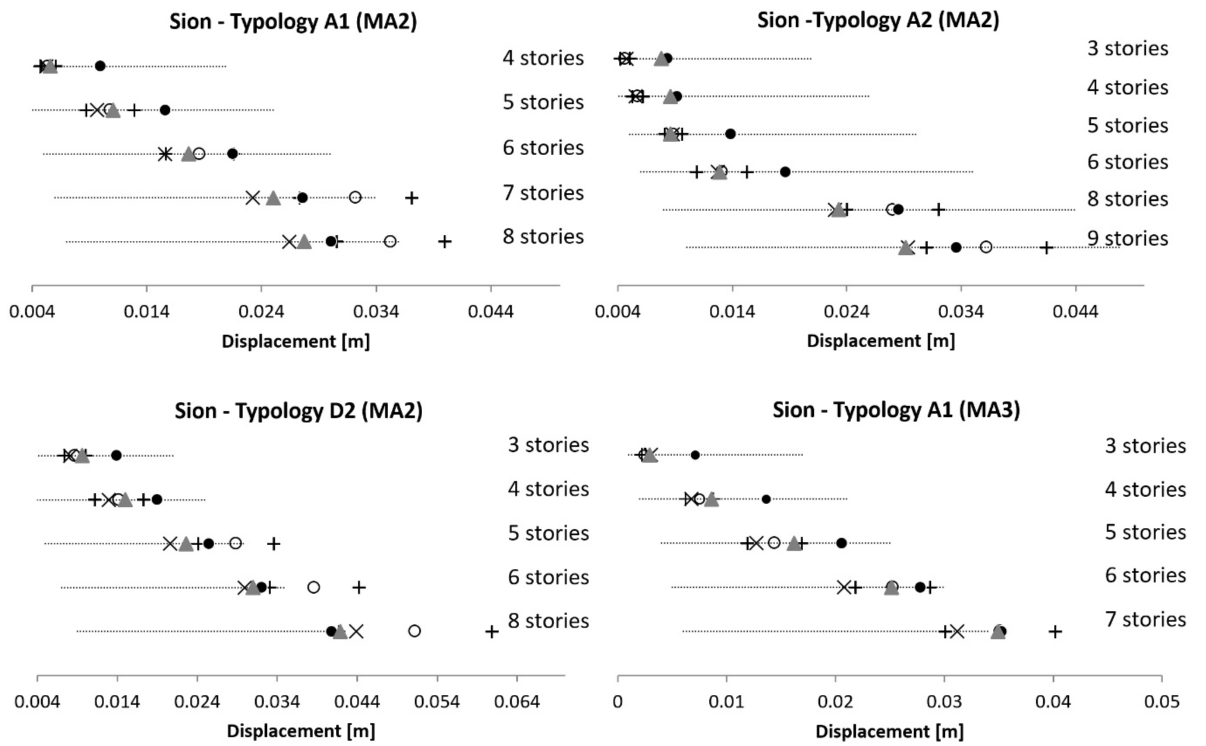
Appendix II - Table Main parameters of the microzone response spectra (study provided by Centre de Recherche sur l'Environnement Alpin) and of the response spectra type 1 EC8 soil classes

N2 method							
Sion - MA1							
Nr of stories	3	4	5	6	7	8	9
A1	-	-	**93%**	**59%**	**50%**	**13%**	-
A2	**60%**	**50%**	**54%**	**51%**	-	**26%**	**23%**
C	**48%**	-	10%	-1%	-1%	6%	0%
D2	**69%**	**45%**	**15%**	7%	5%	5%	-
Sion - MA2							
Nr of stories	3	4	5	6	7	8	9
A1	-	**85%**	**44%**	16%	-14%	**-15%**	**-24%**
A2	**80%**	**59%**	**57%**	**43%**	-	2%	-7%
C	**20%**	-11%	**-17%**	-18%	-17%	-15%	-17%
D2	**60%**	**34%**	-12%	**-17%**	-	**-20%**	-
Sion - MA3							
Nr of stories	3	4	5	6	7	8	9
A1	**198%**	**82%**	**43%**	10%	0%	-	-
A2	**105%**	**88%**	**54%**	**43%**	**17%**	-	-
C	**15%**	5%	8%	10%	15%	14%	11%
D2	**46%**	**21%**	1%	0%	4%	-	-

Lin&Miranda							
Sion - MA1							
Nr of stories	3	4	5	6	7	8	9
A1	-	-	-7%	0%	**-14%**	-10%	-
A2	2%	1%	0%	1%	-	-4%	0%
C	0%	-	2%	3%	15%	4%	8%
D2	-7%	-8%	**-16%**	-11%	-2%	0%	-
Sion - MA2							
Nr of stories	3	4	5	6	7	8	9
A1	-	-2%	-11%	**-16%**	**-28%**	**-25%**	17%
A2	3%	-3%	-1%	-3%	-	**-18%**	**-19%**
C	**-14%**	**-23%**	-14%	-6%	-4%	11%	2%
D2	-7%	-9%	**-29%**	**-23%**	-	-14%	-
Sion - MA3							
Nr of stories	3	4	5	6	7	8	9
A1	**27%**	-9%	-12%	**-18%**	-11%	-	-
A2	4%	0%	-9%	-6%	**-14%**	-	-
C	**-16%**	-6%	18%	**39%**	**65%**	**32%**	**45%**
D2	-14%	**-16%**	-15%	-1%	20%	-	-

N2 OPT							
Sion - MA1							
Nr of stories	3	4	5	6	7	8	9
A1	-	-	0%	11%	-6%	-3%	-
A2	**47%**	**37%**	**45%**	-2%	-	-5%	-1%
C	7%	-	1%	-3%	3%	0%	-1%
D2	3%	3%	-7%	-	-	0%	-
Sion - MA2							
Nr of stories	3	4	5	6	7	8	9
A1	-	3%	2%	-5%	**-22%**	**-21%**	-16%
A2	**65%**	**49%**	-3%	-1%	-	**-17%**	**-19%**
C	-5%	**-20%**	**-18%**	-14%	-7%	-14%	-11%
D2	10%	5%	**-22%**	**-20%**	-	-18%	-
Sion - MA3							
Nr of stories	3	4	5	6	7	8	9
A1	**23%**	15%	13%	-1%	-1%	-	-
A2	8%	2%	1%	6%	-4%	-	-
C	0%	3%	14%	**25%**	**37%**	**24%**	**27%**
D2	14%	5%	-2%	5%	16%	-	-

Appendix III.a - Table Summary of the results obtained for the microzones of Sion. In the first column, the per cent differences ($\Delta_{dd\,\%}$) between N2 method displacement demand and the NLTHA average value; in the second column the Lin & Miranda method results ($\Delta_{dd\,\%}$); in the third column the N2 OPT method ($\Delta_{dd\,\%}$). Values outside of one standard deviation are bold face.



Appendix III.b - Figure Displacement demand determination: solid black circle (●) for N2 method; bla□k □ross (X) for Lin & Miranda; grey triangle (▲) for N2 OPT) for types A1, A2 and D2 compared to the response spectra of Sion microzone MA2 and for type A1 related to the response spectrum of Sion microzone MA3. The unfilled circles (○) correspond to the average value of the results of NLTHA together with a plus sign (+) for one standard deviation

N2 method

Martigny - MM2							
Nr of stories	3	4	5	6	7	8	9
A1	**97%**	**46%**	16%	-2%	-1%	-	-
A2	-	**45%**	-	3%	4%	-	-
C	-	7%	-	-	13%	6%	-
D2	**40%**	4%	-4%	3%	1%	1%	-

Martigny - MM3							
Nr of stories	3	4	5	6	7	8	9
A1	**45%**	10%	-4%	-10%	-2%	-	-
A2	**35%**	**14%**	7%	-1%	1%	4%	-
C	-	5%	7%	6%	8%	7%	-
D2	4%	-5%	-8%	-1%	-1%	0%	-

Lin&Miranda

Martigny - MM2							
Nr of stories	3	4	5	6	7	8	9
A1	9%	-6%	-9%	-8%	9%	-	-
A2	-	3%	-	-8%	2%	-	-
C	-	-3%	-	-	14%	6%	-
D2	-3%	-12%	-3%	21%	**35%**	**36%**	-

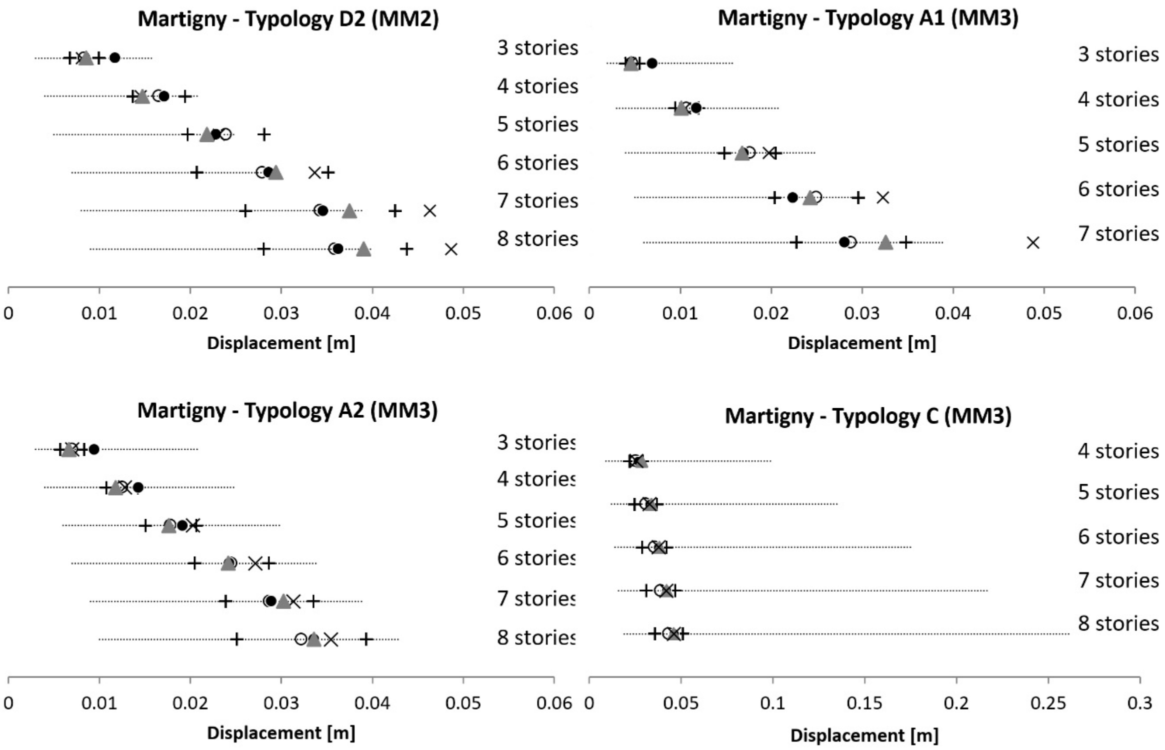
Martigny - MM3							
Nr of stories	3	4	5	6	7	8	9
A1	-5%	-2%	12%	**29%**	**70%**	-	-
A2	0%	2%	14%	11%	9%	10%	-
C	-	12%	9%	8%	8%	6%	-
D2	1%	16%	9%	15%	12%	10%	-

N2 OPT

Martigny - MM2							
Nr of stories	3	4	5	6	7	8	9
A1	1%	-1%	-6%	-11%	-2%	-	-
A2	-	-1%	-	-15%	-7%	-	-
C	-	-13%	-	-	10%	6%	-
D2	3%	-12%	-10%	5%	9%	9%	-

Martigny - MM3							
Nr of stories	3	4	5	6	7	8	9
A1	-4%	-6%	-5%	-3%	12%	-	-
A2	-6%	-6%	-1%	-2%	5%	4%	-
C	-	1%	6%	6%	7%	6%	-
D2	-6%	-3%	3%	15%	-1%	0%	-

Appendix III.c - Table Summary of the results obtained for the microzones of Martigny. In the first column, the percent differences ($\Delta_{dd\,\%}$) between N2 method displacement demand and the NLTHA average value; in the second column the Lin & Miranda method results ($\Delta_{dd\,\%}$); in the third column the N2 OPT method ($\Delta_{dd\,\%}$). Values outside of one standard deviation are bold face.



Appendix III.d - Figure Displacement demand determination: solid black circle (●) for N2 method; black cross (X) for Lin & Miranda; grey triangle (▲) for N2 OPT) for type D2 compared to the response spectrum of Martigny microzone MM2 and for typologies A1, A2 and C compared to the response spectra of Martigny microzone MM3. The unfilled circles (○) correspond to the average value of the results of NLTHA together with a plus sign (+) for one standard deviation