Proc. of the 6th Intl. Symposium on Reliability Engineering and Risk Management (6ISRERM)
31 May – 1 June 2018, Singapore
Editor(s) Xudong Qian, Sze Dai Pang, Ghim Ping Raymond Ong, Kok-Kwang Phoon

SEISMIC DISPLACEMENT-DEMAND AND URBAN DAMAGE DISTRIBUTION: THE IMPACT OF DIFFERENT METHODS ON VULNERABILITY ASSESSMENT

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This paper addresses seismic vulnerability assessment at urban scale. Particularly, it focuses on the differences in damage distribution obtained from the application of several simplified methods for displacement demand determination. The results obtained for two cities of Switzerland (Sion and Martigny) highlight the related impact. Displacement demands predicted using three simplified methods are compared with “reference” seismic demands obtained from non-linear time-history analysis (NLTHA). Comparing the urban seismic damage distributions from the three simplified methods with the one from NLTHA helps in understanding the reliability of displacement demand determination. The following three methods are compared: the usual N2 method, the Lin & Miranda proposal and an optimized version of the N2 method. These methods are evaluated based on the real seismic hazard (microzones), showing furthermore the importance of considering the real soil conditions in the general damage assessment.

Keywords: displacement demand, seismic vulnerability, urban scale, N2-method optimization.

1 Introduction

Several methods for large-scale seismic risk assessment have emerged within the last decades, especially after earthquakes have occurred in Europe. The main goals of such methods are to develop techniques for accurate urban analysis in seismic risk and damage management as well as in urban planning. Although some safety margins are typically added for seismic analysis of single buildings, overestimation is not desirable at an urban scale for damage predictions. Most procedures available for seismic vulnerability assessment of buildings are based on mechanical methods and in this paper their reliability is investigated. Mechanical methods involve parameters that define the response of a structure to a seismic event. The response of structures is described by capacity curves of non-linear structural behavior. Each point on the capacity curve is associated with a level of damage. Assessment of the seismic response is achieved by identifying the required displacement (performance point). The influence of several factors that contribute to the determination of damage distributions is studied. Generally, factors for accurate damage distributions based on mechanical methods are: (i) defining of an adequate damage scale; (ii) defining of an appropriate building typology classification; (iii) determining of the real seismic structural behavior of different building types; (iv) knowledge of the seismic hazard. Damage grades (i) have been largely investigated in EMS98. Earthquake damage in EMS98 is based on classifications of vulnerability classes, types of structures and grade (1 to 5) of damage suffered by structures. The damage grades introduced in EMS98 are taken as reference. The definition of an appropriate building type classification (ii) is not trivial as the building stock differs between regions. The building stock of Northern Europe differs from that of South Europe for which available methods have been calibrated. Existing building types have not been adapted for northern European cities (and in general for regions with moderate seismicity). Specific capacity curves for the application of a mechanical approach should be developed even for northern Europe. Using mechanical approaches, damage grade is directly related to the computed seismic displacement demand (iii) (Lagomarsino and Giovinazzi, 2006). Simplified procedures, used to determine displacement demands, have been developed for seismic design and thus include a safety margin thus decreasing the accuracy of predictions. Moreover, according to several research investigations, simplified static procedures are less accurate than commonly supposed, as in certain conditions they may lead to unsafe underestimations. Improving displacement-demand determination is required for reliable seismic vulnerability assessment. Another important task is the local seismic hazard determination (microzones) (iv). Specific studies on potential soil amplifications are needed to specify expected ground shaking and associated response spectra. The paper shows the importance of introducing microzone spectra in order to have more reliable damage distributions results than those obtained using standard soil classes of Eurocode 8. The paper focuses only in understanding the consequences on damage distributions of the application of different simplified methods for determining the displacement demand (iii) and microzones spectra (iv). The accuracy of damage prediction is tested on two typical Swiss cities (Sion and Martigny) in a moderately seismic area where a detailed seismic hazard study has been developed and accurate building types have been introduced.

2 Simplified seismic demand determination

The effect of inaccurate seismic demand determination on building-damage distributions at urban scale has not been extensively examined yet. In this paper is three different simplified methods are compared and their reliability in the damage prediction is evaluated. The reliability is evaluated by comparing the damage distributions obtained from the displacement demand provided by the three analyzed methods with the value of reference displacement calculated using a non-linear time-history analysis (NLTHA) method. The three methods compared are: the N2 method (Fajfar, 2000), the method proposed by Lin & Miranda (2008) and an optimized version of the N2 method recently proposed by Diana L. et al. (accepted).

The N2 method is one of the most widespread methods in Europe for displacement demand determination. It combines pushover analysis of a multi-degree-of-freedom model with response spectrum analysis of an equivalent single-degree-of-freedom (SDOF) system. The lack of accuracy of N2 method has been observed by several studies (Michel et al., 2014). Despite this inaccuracy, the N2 method remains the reference for calculation damage distribution in mechanical method among Europe.

The second method evaluated is by Lin & Miranda (2008) and is based on a particular version of the Capacity-Spectrum Method. This version is based on equivalent linearization. Therefore, the displacement demand of a non-linear SDOF system is estimated from the displacement demand of an equivalent linear-elastic SDOF system. The equivalent system has a period T_{eq} and a damping ratio ζ_{eq} larger than those of the initial non-linear system. The various equivalent linear methods mainly involve different computing of T_{eq} and ζ_{eq}. In this paper, the version proposed by Lin&Miranda (2008) is taken into account.

The third method, proposed by Diana et al. (accepted), is based on an optimization of the original N2 method. This method (N2 OPT) enhances the N2 formulation by including an additional exponent and multiplicative coefficients. The approach of the N2 OPT method preserves the mathematical compatibility with the preceding N2 method. The goal is to reduce the uncertainty in displacement assessment in a non-linear domain. The formula is defined starting from the N2 method formula, including three new coefficients, as follows (for the definition of terms, see Fajfar, 2000):

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

Damage distributions obtained using displacement demands provided by the methods mentioned above are compared with the "true" distribution provided by the NLTHA. Non-linear responses were computed for SDOF systems subjected to 12-acceleration time-histories. The modified Takeda-model (Takeda at al. 1970) is used here as hysteretic behavior model. The mean value of the 12 displacement demand predictions from NLTHA is used as entry-value for determining the damage distribution that is considered to be the "true" distribution.

3 Building typology of Sion and Martigny

The cities of Sion and Martigny are subject of an ongoing study, performed in collaboration between the Canton of Valais, the EPFL, the University of Genova and CREALP, aiming to improve the seismic vulnerability assessment at an urban scale. Building stocks of both cities have been analyzed with different methods and surveys. A first rapid survey has been performed by conducting visual screenings. This survey involved 3000 buildings in Sion and 1600 buildings in Martigny. The standard classification based on typical European constructions, does not fully match with the Swiss built environment. Therefore, specific types have been developed for Swiss buildings with stiff floors. The introduced typologies are (see Fig. 1): type A1 for unreinforced masonry (URM) buildings with a basement floor in reinforced concrete (RC); type A2 for mixed URM-RC buildings for all the height of the structure; type B2 for buildings with RC pillars in the base floor; type C for buildings with RC shear walls; type D2 for buildings with URM shear walls (Lestuzzi et al, 2017). In this paper, 732 buildings for Sion and 351 buildings for Martigny are considered.

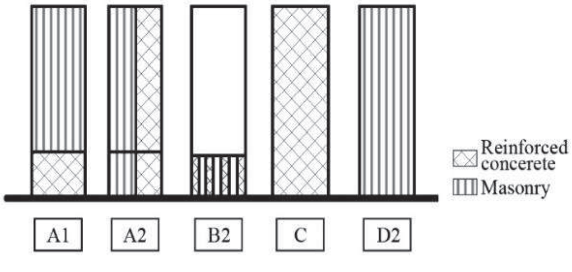

Figure 1. Specific types for typical Swiss buildings (figure adapted from: Lestuzzi et al, 2017).

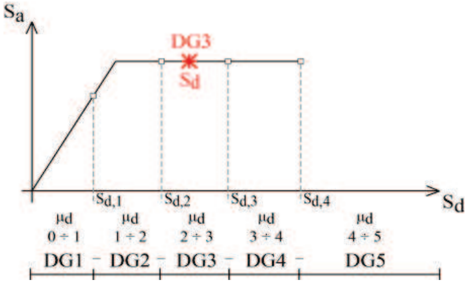

Figure 2. Displacement demand and damage grade.

4 Damage distribution

Unreliable methods for predicting displacement demand lead to significant errors in the damage distribution at urban scale. The displacement demand obtained for each type of structure is the entry value to determine the damage (Fig. 2). The objective is to investigate the impact of damage distribution at an urban scale for Sion and Martigny using the three methods mentioned above. Mechanical methods for damage distribution (Lagomarsino and Giovinazzi, 2006) use a lognormal cumulative probability function. However, this study relies on a particular damage probability matrix. This matrix is based on the probability mass function of the binomial distribution. This approach has been chosen for the sake of simplicity. The probability of having a damage grade from 1 to 5 (*k*), on the stories distribution (*stor*), is calculated using Eq. (2):

$$p_{(stor,k)} = \frac{5!}{k!(5-k)!} \cdot \left(\frac{\mu_d}{5}\right)^k \cdot \left(1-\frac{\mu_d}{5}\right)^{5-k} \qquad (2).$$

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

$$\mu_d = j + \frac{S_d - S_{d,j}}{S_{d,j+1} - S_{d,j}} \qquad (3).$$

The displacement demand S_d is calculated using the three methods analyzed. The damage limit state $S_{d,j}$ ($j = 0 \ldots 4$) are here identified on the capacity curves as functions of the yielding displacement D_y and of the ultimate displacement D_u (Luchini, 2016). The threshold $S_{d,0}$ corresponds to a displacement equal to zero while the threshold $S_{d,5}$ is equal to $3 \cdot S_{d,4}$.

5 The importance of microzones spectra

The cities of Sion and Martigny are situated in the main seismic zone of Switzerland, with a peak ground acceleration of 1.6 m/s^2. Soils conditions and seismic actions are defined by soil classes of EC8 and related response spectra. A specific study was performed to describe the soil amplification and the expected ground shaking. Three microzones have been defined for each city with corresponding response spectra. The peak values of the response spectra of Sion equal those of EC8 soil classes but the corners of the plateau are shifted towards high periods resulting in higher seismic demands. In Martigny, the peak values of microzones are higher than in Sion due to unfavorable soil conditions. In Fig. 3, damage distributions based on NLTHA are shown. The NLTHA is applied to obtain the damage distribution for Sion and Martigny with the hypothesis of EC8 soil class type C, as prescribed by previous soil classification. These distributions are compared to those obtained with microzone spectra. As a first consequence, it is possible to see how the introduction of refined seismic hazard determination in the vulnerability assessment moves the distributions towards higher damage grades. The center of the new distribution passes from an x-value of 2.10 to 2.42 for Sion and from 2.70 to 2.99 for Martigny underlining how the distribution with standardized soil classes largely underestimates damage. Considering the total amount of buildings assessed in different damage grade sets by the two distributions, allows for the introduction of the total discrepancy value ($\Delta_{tot} = (\Sigma|\Delta_i|)$ / (*tot. build.*) [%]). The different discrepancies $|\Delta_i|$ for each damage grade ($i = 0, \ldots, 5$) are the number of building assessed in a different set for every damage grade. The total discrepancy value reaches 20.4% for Sion and 19.1% for Martigny. In these cases, distributions obtained with microzones are considered as the “true” value. In conclusion, taking into account the real seismic hazard and considering the potential soil amplification is an important first step for reliable seismic vulnerability assessments.

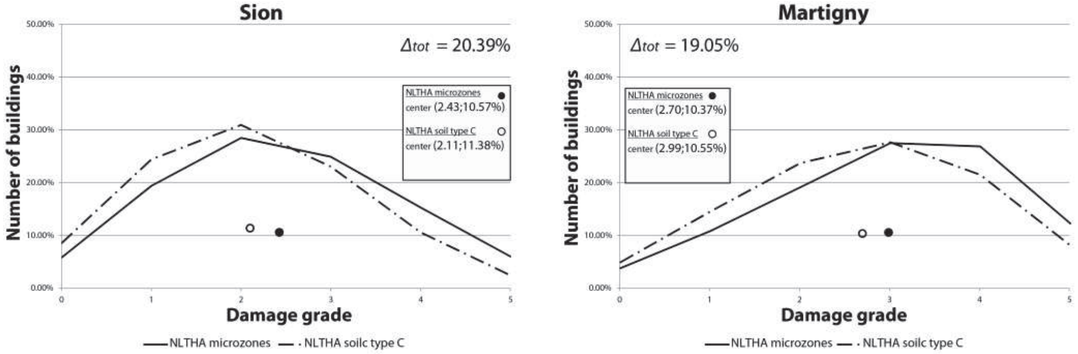

Figure 3. Damage distributions obtained with NLTHA for Sion (a - left) and Marigny (b - right): hypothesis of soil class C (black line) and microzones (dash-dot line).

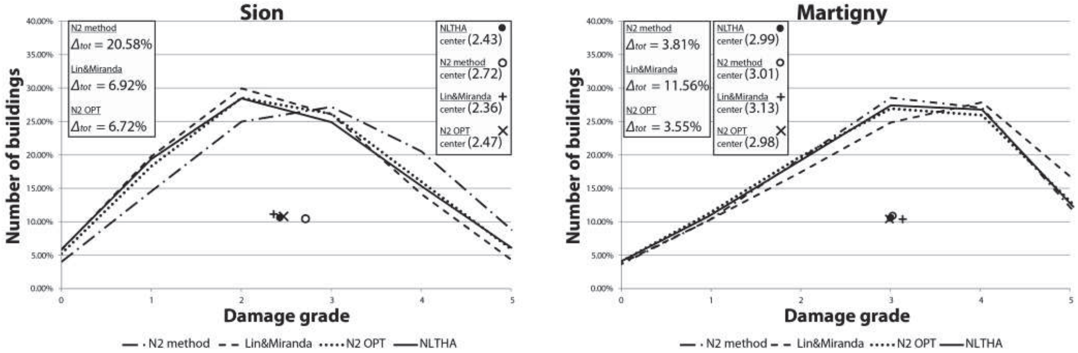

Figure 4. Damage distribution of Sion (a - left) and Martigny (b - right): NLTHA; N2 method; Lin & Miranda proposal; N2 OPT.

6 Displacement demand determination and damage distribution

The reliability of the three simplified methods in determining displacement demand is evaluated based on the damage distributions. These damage distributions are compared to the NLTHA results. In Sion, the N2 method overestimates the number of buildings with damage grade equal to 4 and underestimates the number of buildings with damage grade equal to 1 and 2. The number of buildings assessed by N2 and NLTHA in different sets of the damage distribution (Δ_{tot}) is equal to 20.6%. Results obtained by the NLTHA show a relocation of the distribution towards lower damage grades (Fig. 4a). The center of the distribution moves towards higher x-values passing from 2.43 (for NLTHA) to 2.72 (N2 method), underling the huge overestimation. The distributions obtained by Lin & Miranda and by N2 OPT are similar and are more consistent with the one provided by the NLTHA. The total discrepancy Δ_{tot} is 6.9% for Lin & Miranda and 6.7% for N2 OPT (Fig. 4a). The center of the Lin&Miranda distribution is 2.36, slightly under the NLTHA value, while the N2 OPT is 2.47. The N2 method and NLTHA do not greatly differ in terms of damage distribution in Martigny (Fig. 4b). The number of miss-categorized buildings assessed by N2 is equal to 3.8%. 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. The center of the distribution is: 2.99 for NLTHA and 3.01 for N2 method. The distribution provided by N2 OPT is accurate as well. The total number of divergent buildings Δ_{tot} is equal to 3.6%. Contrary to the accurate results obtained on Sion, the distribution provided by Lin & Miranda in Martigny 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 number of miss-categorized buildings is 11.6%. The center of the Lin&Miranda distribution is 3.11, underling an important overestimation of the distribution. The center of the N2 OPT distribution is 2.98, almost the same value of the NLTHA distribution center (Fig. 4b).

7 Conclusions

Reliability of displacement demand determination is important for accurately assessing urban vulnerability. The EC8 proposes to determine displacement demand using a simplified version of the N2 method, which in some conditions provides unreliable results. It is necessary to provide a new approach to predict the non-linear behavior with reduced uncertainties. In addition to the appropriate knowledge of the structural features of the building stock, the reliability of the seismic demand determination is one of the main topics to be considered. The reliability of the N2 method has been 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 damage distributions obtained from the three methods have been compared on two Swiss cities (Sion and Martigny). The evaluation has been performed on microzone response spectra. Considering the local influence of the soil conditions in the damage assessment moves the damage distributions towards higher levels than those obtained with the standard EC8 soil types. The damage results show that using the N2 method leads to a significant overestimation of urban seismic damage distributions in the case of Sion. The use of the Lin & Miranda method and an optimized version of N2 increases the accuracy of damage predictions. For the case-study of Martigny, the N2 method is in line with NLTHA predictions while Lin & Miranda leads to less reliable results. The optimized version of the N2 method on the contrary, provides most accurate damage distributions in both cases and thus, stable and reliable predictions. According to the obtained results, it is suggested to proceed with the N2 OPT method instead of the typical N2 method or Lin&Miranda in order to minimize potential errors.

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