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CONTROLLING PARAMETERS IN THE ASSESSMENT OF THE SEISMIC VULNERABILITY OF BUILDINGS

L. Yamin(1), A. Hurtado(2), R. Rincón(3)

(1)Associate Professor , Universidad de los Andes, Bogotá, Colombia, lyamin@uniandes.edu.co
(2)Research Engineer, Universidad de los Andes, Bogotá, Colombia, ai.hurtado77@uniandes.edu.co
(3) Research Engineer, Universidad de los Andes, Bogotá, Colombia, jr.rincon3391@uniandes.edu.co

Abstract

The probabilistic seismic risk assessment in terms of economic losses for building portfolios requires the seismic hazard assessment, the definition and characterization of the building portfolio and the estimation of the expected economic losses of specific building typologies for increasing seismic intensities. The probability distribution function of economic losses for different seismic intensities can be estimated by integration of individual building component´s repair costs. By means of Monte Carlo simulations, all relevant variables that influences the final repair cost can be introduced into the analysis. The results of the analysis are integrated and represented through specific vulnerability functions for each building typology, which relates the expected economic losses and its corresponding uncertainty measure with the seismic intensity level. The integration of losses considers the uncertainties associated with the hazard assessment, the dynamic response of the model, the expected damage level for each one of the components and the corresponding repair cost and time. Using this methodological approach, a sensitivity analysis is performed in order to identify the most relevant variables in the loss assessment process. The following main variables have been considered for the analysis: the set of seismic records which represent a particular seismological and geotechnical setting, the number of stories for the prototype building models; the seismic code level used for the design of main structural elements, the type and relative cost of non-structural components and the type of building content components. In addition, other parameters have also been considered such as the number of realizations for the Monte Carlo simulations and the consideration or not of efficiency and scaled economy to estimate repair costs and times depending on the number of simultaneous interventions that has to be performed for each damage scenario. Comparing the resulting vulnerability functions, the sensibility to usual variations in the above-mentioned variables and parameters can be established. With this, the controlling parameters for seismic vulnerability assessment of buildings are defined. In a general case, the final specification of any building vulnerability or fragility shall include as a minimum parameters such as the building typology itself, the building fundamental period of vibration, the seismic design level, and the type and relative costs of non-structural components. Additional parameters such as irregularity, overloads, type of soil deposit where it is located and the type of non-structural components should also be considered for a more detailed typological characterization.

Keywords: Vulnerability; Risk; Losses; sensibility analyses

1. Introduction

The probabilistic assessment of seismic risk for building portfolios can be expressed in terms of the probability distribution functions (PDF) of economic losses for a set of stochastic seismic events representing the seismic hazard at a particular geographic zone. The main components of the analysis include the seismic hazard assessment, the definition and characterization of the building portfolio and the definition of the seismic vulnerability of particular building typologies in terms of economic losses. Possible applications of the risk assessment of building portfolios include insurance or reinsurance schemes, risk management of private or public infrastructure, financial protection, selection of optimum risk mitigation schemes and design of post-earthquake emergency plans or reconstruction programs [1, 2].

Several methodologies have been proposed in order to estimate probabilistic losses for building portfolios. Those methodologies have been implemented in platforms such as Hazus [3], CAPRA [4], Risk-UE [5], and others, still under development, such as GEM [6]. All these methodologies have been designed for risk assessment of building portfolios, where hundreds or thousands of buildings have to be analyzed simultaneously in order to estimate integrated financial risk figures such as a loss curve, the average annual loss, or the maximum probable losses. Hazard is usually estimated through stochastic earthquake scenarios, each one represented by means of the geographical distribution of any seismic intensity parameters such as PGA, PGV, PGD, spectral accelerations or interstory drift. The building typology vulnerability is usually estimated through simplified or detailed nonlinear response history analyses (RHA). The estimation of damages is usually based in fragility formulations at component or building level, which in turn depend on engineering demand parameters such as maximum interstory drift or absolute story acceleration. Other models simply use spectral intensity parameters and pre-established fragility or vulnerability functions in order to obtain damages and losses. Recently, performance-based earthquake engineering (PBEE) has been integrated into the analysis to estimate loss in terms of dollar amounts, down time, and fatalities [7].

This paper uses the methodology proposed by Yamin [8] in order to assess vulnerability functions under different conditions of analysis. For this, the total economic losses in a building subjected to a seismic event are considered including both the direct repair costs and the indirect costs associated with the downtime or business interruption. The results of the analysis are integrated and represented through specific vulnerability functions for each building typology, which relates the expected economic losses and its corresponding uncertainty measure with the seismic intensity level. The integration of losses considers the uncertainties associated with the hazard assessment, the dynamic response of the model, the expected damage level for each one of the components and the corresponding repair cost and time. The calculation algorithm includes the most relevant variables that can affect the results.

A sensibility analysis is performed in order to identify controlling parameters which generate significant variations in the vulnerability results of particular building typologies. In order to obtain representative indicative results, a series of reinforced concrete moment resisting framed buildings are evaluated with the following characteristics: multiple stories, multiple-bay, regular and symmetric and designed for different seismic design levels. For the sensibility analysis, variables such as story height, design code level and type and relative costs of structural and non-structural components in the building are considered. Vulnerability and/or fragility classification of building typologies shall include at least the specification of the controlling parameters identified.

2. Loss estimation methodology

Different methodologies have been proposed for the estimation of economic losses in buildings subjected to earthquakes. For example, Scholl and Evernden [9] and Kustu et al. [10] proposed a methodology to estimate economic losses in buildings for urban zones. Later, Porter et al. [11, 12] proposed a methodology for vulnerability assessment of buildings based on the accumulation of losses of individual building components for different seismic intensities. For the UNISDR´s Global Assessment Report (GAR), Yamin et al. [13] proposed a methodology to estimate vulnerability functions based on fragility functions proposed in the Hazus project [14] or any other, for different building typologies. Those functions were used for the GAR global risk assessment project [15, 16]. In addition, Yamin et al. [17] proposed a methodology for vulnerability assessment based on nonlinear RHA and integrating the individual damage factors for all structural elements at selected seismic intensities. More recently, D'Ayala et al. [18] presented a methodological guide for the analytical vulnerability assessment for low and medium rise buildings in the framework of the Global Earthquake Model (GEM) project. Fragility functions of repair costs at different intensity levels and for several damage states were proposed by ATC-58 [19]. Fragility functions were estimated based on Hazus [13] or "Fracas", a methodological approach which uses the capacity curve of the building to estimate its fragility [20].

In the present assessment, the methodology proposed by Yamin [8] is used in order to assess vulnerability functions under different conditions of analysis. For this, the total economic losses in a building subjected to a seismic event are considered including both the direct repair costs and the indirect costs associated with the downtime or business interruption. According to that, the total losses shall be estimated as the summation of the direct losses PD and the indirect losses PI as follows:

$$P_T = P_D + P_I \tag{1}$$

$$P_D = \sum_{n=1}^{N_c} P_n \tag{2}$$

Pn is considered as a random variable representing the repair or replacement direct cost for component k, and Nc is the total number of components defined for each building (structural, non-structural and contents). PI corresponds to the indirect costs associated to business interruption (BI) which are calculated based on the downtime or time required to complete the repair or replacement of the building, and a corresponding cost per unit of time (based in the cost to rent an equivalent building or the net income that will be lost during the repair period).

By means of Monte Carlo simulations in a methodological approach implemented by Hurtado [21], all relevant variables that influences the final repair cost can be introduced into the analysis including the following: (1) a set of seismic records which represent a particular seismological and geotechnical characteristics setting; (2) the use of prototype building models designed according to a particular set of seismic specifications and design parameters; (3) the evaluation of the seismic response of building structures through detailed nonlinear RHA; (4) the definition of a component-based model potentially susceptible to damage with its corresponding fragility specification in terms of cost and time of repair; (5) the independent consideration of structural, non-structural and building content components; (6) the use of an integration methodological approach, which adequately considers uncertainties for each one of the random variables; (7) the possibility to consider practical aspects such as geographical variations, scale economy, special commercial conditions, minimum or total intervention costs, and business interruption costs.

In addition to the previous aspects, the following parameters are also included into the methodological approach: (1) residual drift to decide the demolition of the building (2) the repair costs limit above which a total replacement value would be assigned to the building; (3) the minimum seismic intensity level below which damages are not usually reported; (4) specific considerations for estimation of indirect costs such as: business interruption cost per unit of time as a percentage of the building replacement cost; (5) level of seismic intensity below which no business interruption costs are generated; (6) consideration or not of efficiency and scaled economy to estimate repair costs and times depending on the number of simultaneous interventions; (7)

maximum time frame for repairs; and (8) the number of simultaneous laborer teams for structural and non-structural repair works. The detailed description of the methodological approach used can be found in Yamin [8].

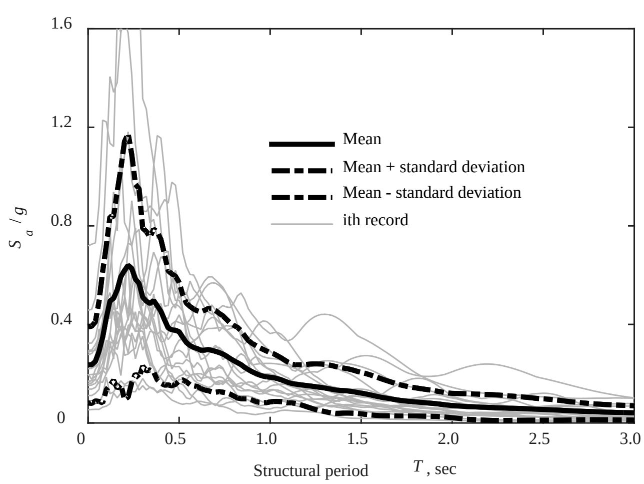
Both inherent and epistemic uncertainties are considered for all random variables. The selection of a considerable number of records for different soil conditions accounts for the hazard uncertainty. A log normal probability function with a general dispersion between 0.2 and 0.5 is included to account for uncertainty in the dynamic response following recommendations from FEMA [19]. This allows the consideration of uncertainties in aspects such as the analytical modelling process, the geometric dimensions, the material properties, the load intensity and distribution, particular analytical considerations (embedment, cracked sections, rigid zones and others), numerical precision, mass distribution, stiffness and damping assumptions and general quality of the construction. Damage levels are assigned uncertainty according to the fragility specification of the different damage states of the individual components. Finally repair and replacement costs are assigned either a normal or a lognormal distribution with published accepted values of dispersion depending on each type of component (see reference [19] for more details). In this study it is considered independency among all random variables.

3. Parameters considered for the sensibility analyses

3.1 Ground motions selection

Several input motions are selected for the nonlinear RHA, representing a specific seismic, tectonic and geotechnical setting. They, as a group, represent the hazard uncertainty. The seismic intensity for the analysis is the spectral acceleration at the fundamental period of vibration T1 for 5% damping coefficient, Sa(T1).

The PEER database [22] was used to select ground motions for the vulnerability analysis. A total of 18 ground acceleration records from 7 different earthquakes, with magnitudes ranging from 6.0 to 7.3, were selected according to the following criteria, based on a proposal by Haselton [23]: (1) effective peak ground acceleration >0.2 g; (2) effective peak velocity >15 cm/sec; (3) recording distance from the hypocenter >10 km; (4) maximum useful frequency <0.25 Hz to guarantee the inclusion of low frequency content; (5) records from intra-plate seismic events; (6) free field records; (7) records on soil type C, D and F according to FEMA [24]. Fig. 1 presents the elastic acceleration response spectra for 5% damping coefficient for four different group of records corresponding to different soil types represented by G1(soil type C), G2 (soil type D) and G3(soil type F). G4 corresponds to the collection of all previous records.



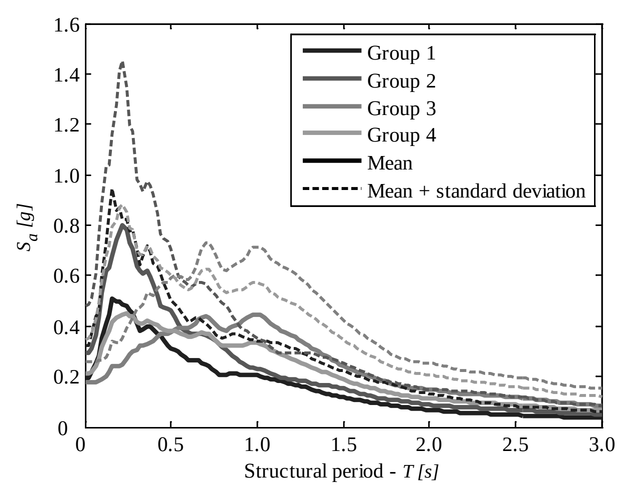
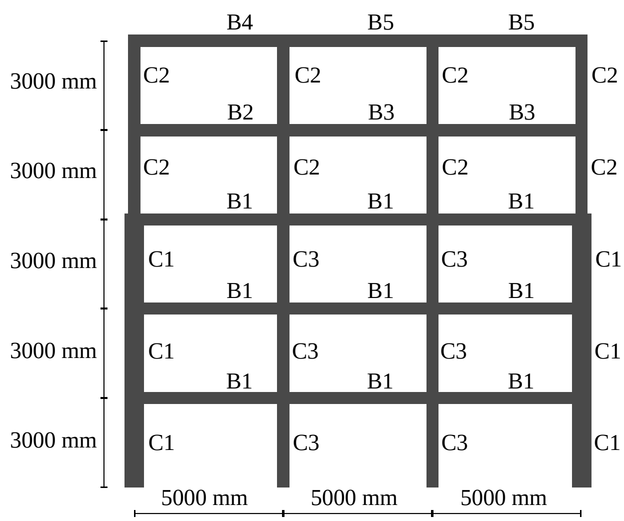


Fig. 1 – Elastic acceleration response spectra (ξ=5%); (a) for selected records on group G2 (soil type D); (b) for groups G1, G2, G3 and G4.

3.2 Prototype building

Prototype models, representing the actual characteristics of the building typology, were designed in detail using standard seismic building code requirements. For the design of each prototype model, the following parameters are controlled: general design considerations such as support conditions, design regulations, material properties, and others; geometric properties such as number of stories, number of bays, irregularities and others; load configurations; seismic design parameters; type of non-structural elements; and nonlinear analysis considerations such as model type, type of nonlinear considerations, p-delta effects and others.

A 5-story, multiple-bay, regular and symmetric reinforced concrete moment resisting framed building is designed considering a special seismic design level, according to the Colombian building code NSR-10 [25] which maintain certain consistency and similarity with the ASCE/SEI 41-13 [26]. This building is designed in accordance with the seismic conditions of Bogotá, Colombia, and is considered representative of a typical medium-high socio-economic residential level (for details, see Rincón [27]). Partitions and facades are designed as representative of typical Colombian and other Latin American cities by means of confined masonry walls isolated from the main structure. Other non-structural elements are designed with special seismic considerations and, therefore, fragility specifications are to be assigned accordingly. Although the structural model is 3D, the vulnerability analysis and damage assessment is performed in one of the main directions of analysis only. Fig. 2 illustrates the geometric distribution for the 5-story building typology for one typical interior frame in the direction of analysis. Definition of geometry and reinforcement parameters are the following: height h, width b, ratio of longitudinal steel reinforcement in tension ρ, ratio of longitudinal steel reinforcement in compression ρ', ratio of total area of longitudinal steel reinforcement (tension + compression) ρ_{total}, ratio of transverse steel reinforcement ρ_{sh}, and spacing of transverse steel reinforcement s. Equivalent 2 and 10-storey building are also designed for the sensibility analysis.



Beam type	B1	B2	B3	B4	B5
h, mm	400	400	400	400	400
b, mm	350	350	350	250	250
ρ/1000	6.98	69.8	93.1	9.77	13.0
ρ'/1000	4.65	46.5	46.5	6.51	6.51
ρ_{sh}/1000	4.30	43.0	43.0	6.02	6.02
s, mm	95.0	95.0	95.0	95.0	95.0

Column type	C1	C2	C3
h, mm	650	400	400
b, mm	400	400	650
ρ_{total}/1000	6.33	7.24	6.68
ρ_{sh}/1000	5.63	5.63	3.47
s, mm	95.0	95.0	95.0

Fig. 2 Five story prototype building model.

3.3 Parameters selected for the sensibility analysis

For the sensibility analysis the following parameters are selected:

- Site characteristics: seismic records associated to different type of soil deposits.
- Building typology: number of stories, the seismic design level, the type of non-structural components and their relative cost as compared with the total cost of the structure.

- Conditions of analysis: the number of realizations for the Monte Carlo Analysis and the consideration or not of efficiency and scaled economy to estimate repair costs and times depending on the number of simultaneous interventions.

A reference model and type of analysis is selected in order to have a reference for sensibility comparison. The reference case selected for the sensibility analysis is the 5-story building, high seismic design code, non-structural components designed with seismic specifications, masonry partition walls isolated from the structure as well as the façade. This model is analyzed with the following reference parameters: uncertainty in the dynamic response analysis, βm=0.3; a total number of 27000 realizations to consider uncertainty in the EDP, in the unit repair cost, and in the unit repair time for each damage state.

4. Results of the analysis

4.1 Sensibility of results

For each of the abovementioned list of parameters, expected and reasonable variations are considered in order to identify those that have more influence in the resulting vulnerability functions. Following, Fig. 3 to Fig. 8 illustrate representative results on variations of specific variables and parameters. In all figures, the x-axis corresponds to the spectral acceleration for the fundamental vibration period of the particular building typology and the y-axis is the relative repair/replacement cost in (%) with respect to the total estimated replacement value of the building.

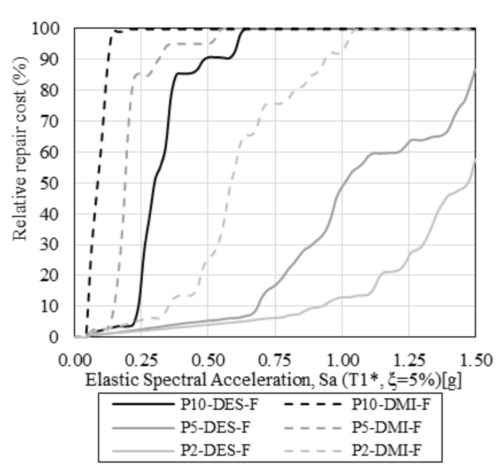


Fig. 3 – Variations with the number of stories and the seismic design level (P is the number of stories, DES is Special moment resistant frames, DMI is ordinary moment resistant frames, F refers to fragile non-structural elements

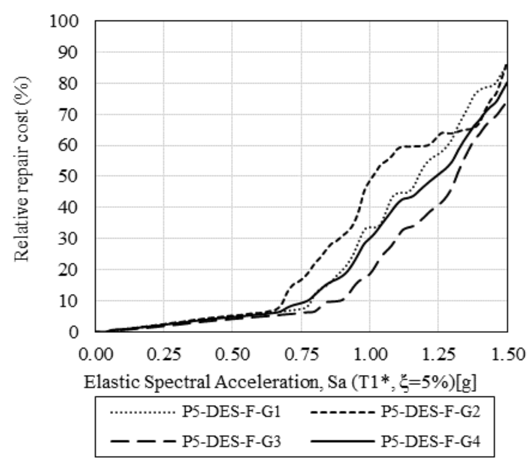


Fig. 4 – Variation for different set of seismic records corresponding to different soil types (G1 to G4 are the four different groups of records for different soil types

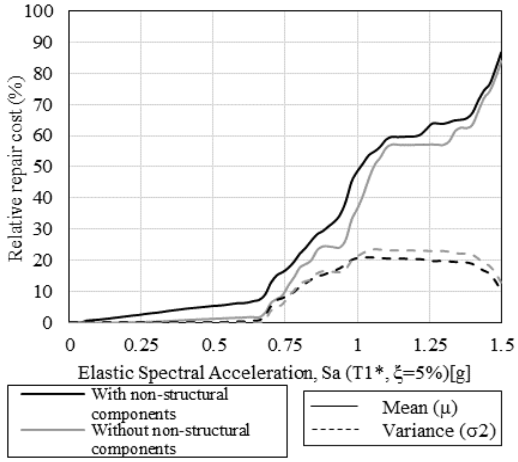


Fig. 5 – Reference typology with and without non-structural components

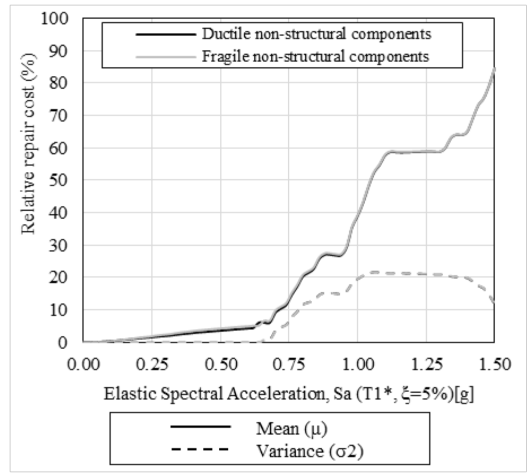


Fig. 6 – Variation with the type of non-structural components (fragile or ductile) for standard residential buildings

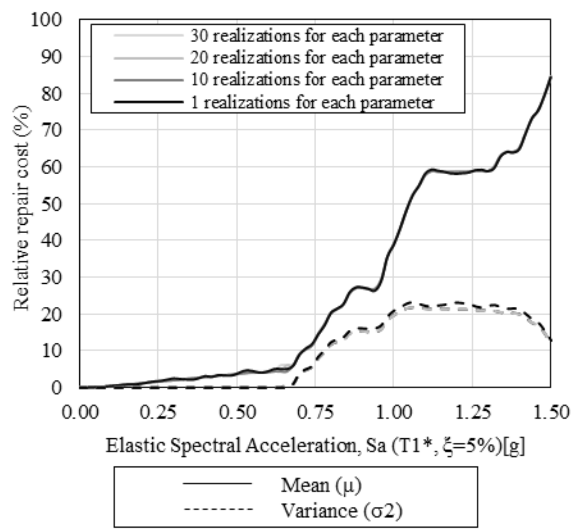


Fig. 7 – Variations with the number of realizations in the Monte Carlo simulation in order to consider the uncertainty in the analysis

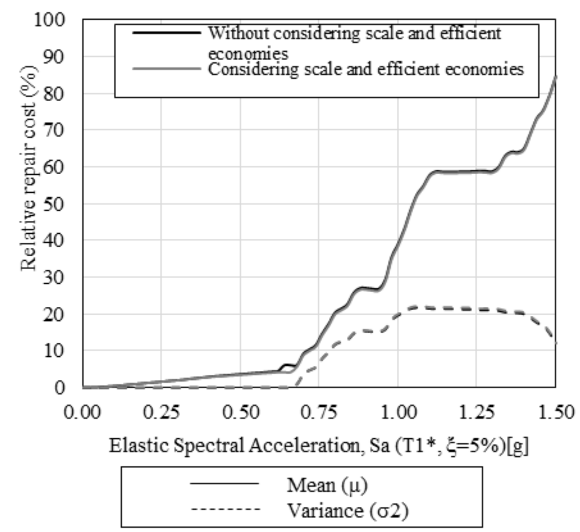


Fig. 8 – Variations when considering scale and efficient economies

4.2 Analysis of results

The following categorization can be established based on the previous analysis. The vulnerability functions and therefore the estimated repair/replacement losses for different seismic intensities present different degrees of sensibility to the different variables analyzed as follows:

- High sensibility: the building height and the corresponding fundamental period of vibration, the seismic design level and the consideration of non-structural components especially when they represent a significant portion of the total cost of the building and have a fragile behavior.

- Medium sensibility: soil type associated to the group of seismic record used in the analysis, the type of non-structural components (fragile vs. ductile).
- Low sensibility: number of realizations used in the Monte Carlo simulations to consider the once, as long as a minimum of 10 realizations are considered and the consideration or not of the optimization of costs and times of repair in order to consider scale and efficiency effects in the cost estimation.

5. Conclusions

Using a consistent and rigorous methodological approach for the estimation of economic losses, it was possible to assess the sensibility in vulnerability functions upon expected variations in different variables and parameters. For the sensibility analysis a series of parameters characterizing the building typology were considered. In addition a set of parameters related to the conditions of analysis were also considered in order to establish their relevance in the final repair/replacement cost estimates.

For the sensibility analysis a reference model is selected consisting in a 5-story reinforced concrete moment resisting framed building designed for the following characteristics: high seismic design level for structural and non-structural components, located on soil type D or similar; residential use and loads, medium to high socio-economic class, confined masonry facades and partitions isolated from the structure. Construction characteristics and repair or replacement costs corresponds to the city of Bogotá, Colombia, in the year 2015. This reference model is analyzed with the following reference parameters: uncertainty in the dynamic response analysis, $\beta m=0.3$; a total number of 27000 realizations to consider uncertainty in the EDP, in the unit repair cost, and in the unit repair time for each damage state; and the cost per unit of time due to business interruption is 1.0% of the commercial value for 30 days.

The sensibility analyses demonstrate that there are certain parameters that can affect dramatically the final repair cost estimates. These corresponds mainly to the building height, its corresponding fundamental period of vibration, the seismic design level and the consideration of non-structural components especially when they represent a significant portion of the total cost of the building and have a fragile behavior. Also to consider as relevant the group of seismic records used to estimate the demand parameters and the economic impact on the building. Sensible differences where obtained using groups of records associated to different type of soil deposits.

In conclusion, in order to adequately classify and associate building typologies, the abovementioned parameters are to be used as descriptors of the vulnerability and/or fragility specification. Failure to do so, will generate sensible variations in the vulnerability/fragility functions and therefore in the final risk assessment. The following parameters are recommended to be used as the minimum classification variables: the building typology itself, the building fundamental period of vibration, the seismic design level, and the type and relative costs of non-structural components. Additional parameters such as irregularity, overloads and the type of soil deposit where the building is to be located should also be considered for a more detailed typological characterization.

Other parameters such as the level of residual drift to decide a total replacement cost, the level of seismic intensity below which no significant damages are considered and the business interruption costs associated with the different damage states can also have a significant effect in the final repair/replacement costs and its influence is still to be estimated.

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