REDUCTION IN COLLAPSE SAFETY OF BUILDING STRUCTURES LOCATED IN EPICENTRAL AREAS IN COLOMBIA

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Abstract

Experimental observations from recent earthquake sequences, as well as recent analytical research, has shown that, in epicentral areas, the probability of exceeding elastic design spectral accelerations increases as the source-to-distance is reduced; and that, this probability is not negligible, even for earthquakes of moderate magnitudes. Research has also identified as other controlling variables the fundamental period of the system, the local soil deposits and the expected hazard level in the region. The increasing probability of exceeding the design actions, as the source-to-site distance is reduced, translates into a larger probability of exceeding structural/seismic performance objectives and, consequently, a lower reliability under frequent and moderate events (expected during the lifetime of the system) and a lower collapse safety margin under rare (low probability) ground motions. In this research work, the reduction in structural safety of a 5-story code-conforming, archetype building located at 2.5, 7.5, 12, 15 and 20 km from the Romeral fault, in the Aburrá Valley, Colombia, is explored. For the building, such a reduction in structural safety is quantified as the increase in the annual probability of collapse (or any other limit state) vs. the source-to-site distance, using a stochastic risk analysis approach. This increase in the annual probability is expected to be higher for low-rise buildings and to grow as the site-to-source distance declines, and thus a minimum site-to-source distance should be ensured. The results are intended to show that the design elastic spectra used in the code-conforming structures is not an upper threshold and local conditions in epicentral areas could influence the estimation of the demand parameters of the structure.

Keywords: Probability of exceedance; annual probability of collapse; source-to-site distance; stochastic risk analysis.

1. Introduction

Most seismic design codes around the globe have at their core a probabilistic seismic hazard analysis, where seismic design demands are computed as probabilities of exceedance of a specific intensity measure in a predefined period, which is usually taken as the life span of a building: 50 years. The life safety limit state has been the benchmark for many of the worldwide design codes, where design demand is computed as that of the 475-year return period (or a 10% probability of exceedance in 50 years intensity). However, research conducted after some of the most significant seismic events over the last decade, where recorded ground motions have been available, has shown that this design probability has been, in many cases, widely exceeded for near-source events [1] and thus, for buildings possibly subjected to these events, safety is basically warranted by the rarity with which the epicenter occurs close to the structure. [2].

Additionally, when analyzing the recorded data for near-source areas, it has been seen that the events producing exceedance of the design spectra are often events whose magnitudes are relatively far from the maximum deemed possible in hazard assessment. For this reason, there has been an increasing interest in research conducted on epicentral areas, in order to establish the effect of near-fault events in the seismic behavior and safety of buildings located in these zones.

Studies such as Iervolino et al. 2018 [1], where a calculation of the peak over the design threshold is computed, have been widely treated the topic; however, they have mainly focused on the hazard (calculation of probabilities of exceedance of certain S_a values). This paper intends to take one step further and estimate the safety of a code conforming building located in different points of an epicentral area, at different distances from the seismic source, by using locally derived fragility curves and a set of stochastic events for the nearby active fault. For doing this, an analysis regarding the safety of the structure at different distances is carried out, in order to establish if there is a diminution of the safety margin as the site under analysis comes closer to the source.

In the following sections, a thorough description of the methodology for the study is presented, focusing on the structural modeling, ground motion selection and damage state definition for the fragility curve derivation. Afterward, an explanation of the procedure to calculate the safety margin for the structure is given and the results are presented and commented upon.

2. Case study building

The analytical study presented in this paper considers a 5-story reinforced concrete archetype office building designed according to the Colombian Building Code for earthquake-resistant buildings, NSR-10 [4]. For research purposes, the building is considered to be located in cities with source-to-site distances less than 20 km from the Romeral Fault System, within the region of the Aburrá Valley, Colombia (La Estrella, 2.5 km; Envigado, 7.5 km; Medellin, 12 km; Bello, 15 km; Copacabana, 20 km - Fig. 1). The building has the following characteristics and requirements: *i)* soil profile type B. *ii)* seismic coefficients representing the peak horizontal acceleration and velocity at the cities: $A_a=0.15$, $A_v=0.20$. *iii)* specified compressive strength of concrete: $f'_c=21$ *MPa* for beams and $f'_c=28$ *MPa* for columns. *iv)* superimposed dead load: $SD=6.2\ kN/m^2$; *v)* live load: $L=2.0\ kN/m^2$; *vi)* importance factor: $I=1.0$; *vii)* R-factor: $R=5.0$.

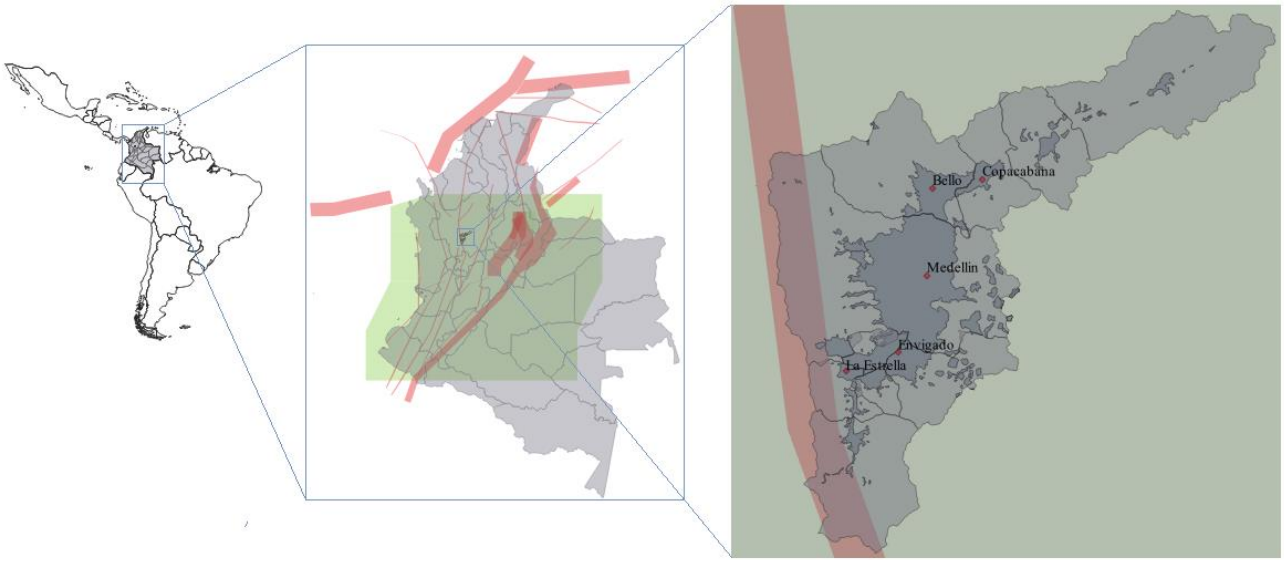

Fig. 1 - Seismic sources of the hazard model used (red: active shallow-crust; green: subduction [3]) and location of cities under study

For analysis purposes, only the central 3-bay frame along the X-axis (Fig. 2) is studied. This simplification is valid as rigid diaphragm is considered and the building structure is regular in both plan and elevation. The structure is modeled in the software OpenSees [5] as a 2D frame, as shown in Fig. 3. Concentrated plasticity models are used for beams and columns and a quadrilateral shear-distortion element [6] is used to account for the behavior of the beam-column joints. The monotonic backbone curves and the hysteretic properties for plastic hinges in beams and columns are defined according to [7]. The monotonic backbone curve for beam-column joints is defined as stated in [8] and their hysteretic properties conforming to [9]. Equivalent viscous damping is modeled in line with the formulation presented in [10], which is appropriate for degrading-strength systems whose response approximates a collapse condition (numeral instability). P-Delta effects are also considered in the analysis model.

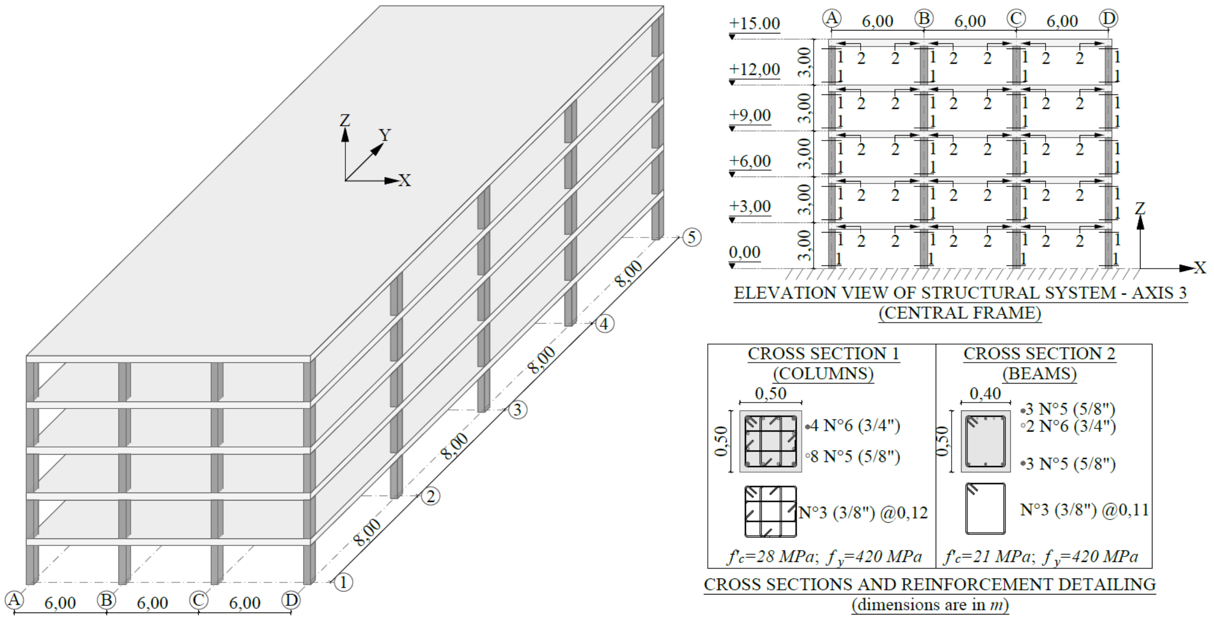

Fig. 2 - Characteristics of the case study building.

With the above-mentioned loads and mathematical model, a modal analysis is carried out, identifying a building fundamental period of vibration $T_1=1.35$ s. Likewise, when performing a non-linear static analysis (pushover), a maximum strength $V_{b,max}$ $=574$ kN and a global displacement ductility $\mu=3.8$ are calculated.

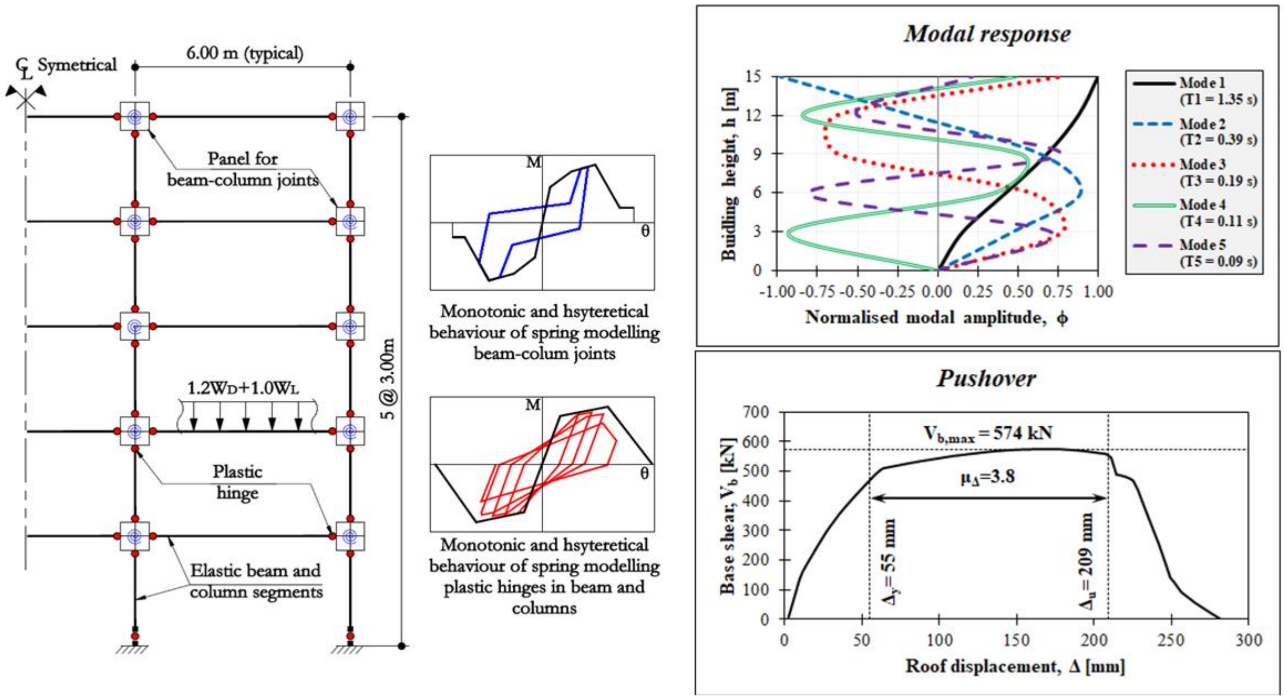

Fig. 3 - Analytical model scheme (left) and main features of the structural response of the case study structure (right).

3. Seismic hazard disaggregation and record selection

The seismic sources considered in the Colombian national seismic hazard assessment study [3] (shallow-crust and subduction) are illustrated in Fig. 1, which are the base for the current building code at the time of preparing this document, NSR-10 [4], and also the reference for this study. However, some modifications in terms of the ground-motion prediction equations (GMPEs) were carried out from the original seismic hazard model in order to consider a newer state of the art in this regarding the country. The attenuation laws proposed by Bernal, G.A. (2014) [11] for the different tectonic regions in Colombia came from a source spectrum model that was adjusted by means of an optimization procedure to fit the acceleration records of the National Strong Motion Network in Colombia.

The hazard curves at the spectral acceleration of interest, $S_a(T=1.35s)$, for the five cities (La Estrella, Envigado, Medellin, Bello and Copacabana), as well as the uniform hazard spectra for return periods of 475 and 2475 years are depicted in Fig. 4. As can be seen, there is a slight increase in the seismic hazard demand as getting closer to the Romeral fault (Fig. 1). The hazard curves and the uniform hazard spectrum were computed considering soil class B (rock).

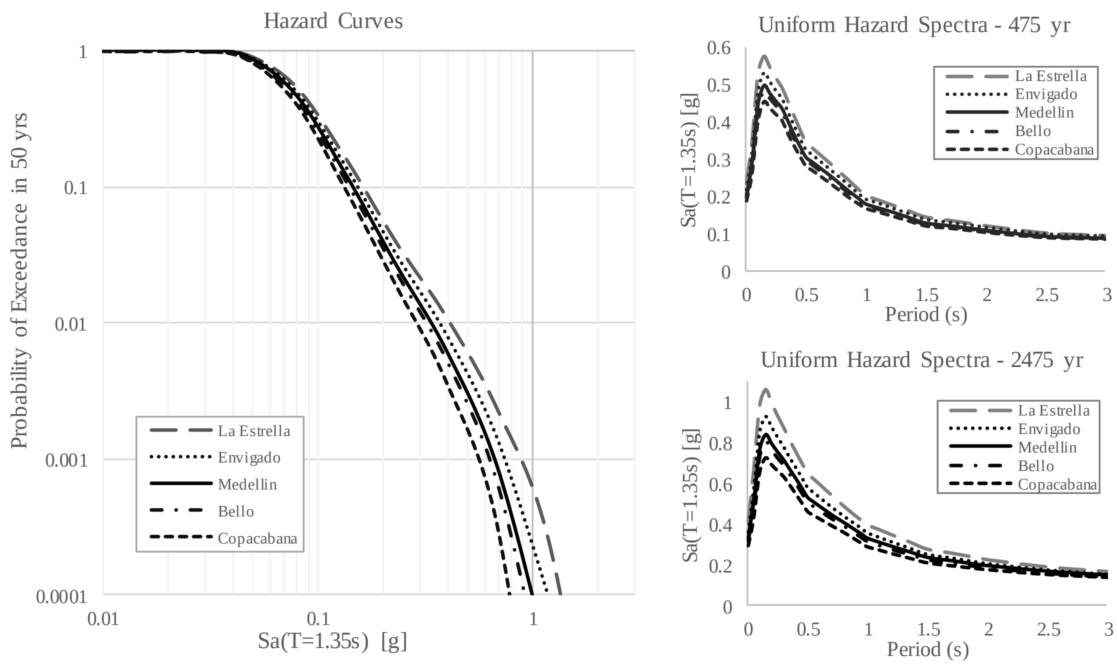

Fig. 4 - Hazard curves for the five cities and uniform hazard spectra for return periods of 475 and 2475 years.

Seismic hazard disaggregation was carried out for the five cities in order to have a hazard-consistent record selection for nonlinear time-history analysis. The disaggregation is a procedure, in the PSHA framework, used to determine the earthquake scenarios that most likely cause the occurrence or exceedance of a specific spectral acceleration (S_a) [12]. This disaggregation of source contributions tells us about the most likely magnitude, M, and distance, R, contributing in a mean annual sense to the probability of exceedance, as well as the quantile of S_{ao} on the conditional S_a distribution given M and R, represented by the Greek letter epsilon, ε [13]. In other words, ε, is the number of standard deviations by which a given S_a value differs from the mean predicted S_a value for a given pair magnitude and distance.

The seismic hazard disaggregation for the cities considered in the analysis and the mean values of (M,R,ε), for all sources contained into the area of study, is presented in Fig. 5. As can be seen from the figure, there is a clear contribution of two types of sources: one below 60 km and one after 80 km, approximately. The Romeral fault, mentioned before, is within the first source-type contribution. Therefore, values of (M,R,ε) for each source and their contribution were computed.

With the knowledge of magnitude, distance and epsilon values at the structural period of interest (*T=1.35s*), a conditional mean spectrum (CMS) [14] was computed for six different return periods (73, 225, 475, 975, 1404, 2475 years). The correlation model of spectral acceleration values from [19] was used to estimate the CMS. Due to the contribution of different sources, two sets of CMS were calculated for the shallow-crust tectonic regime (Near-field: Romeal fault. Far-field: Murindo fault).

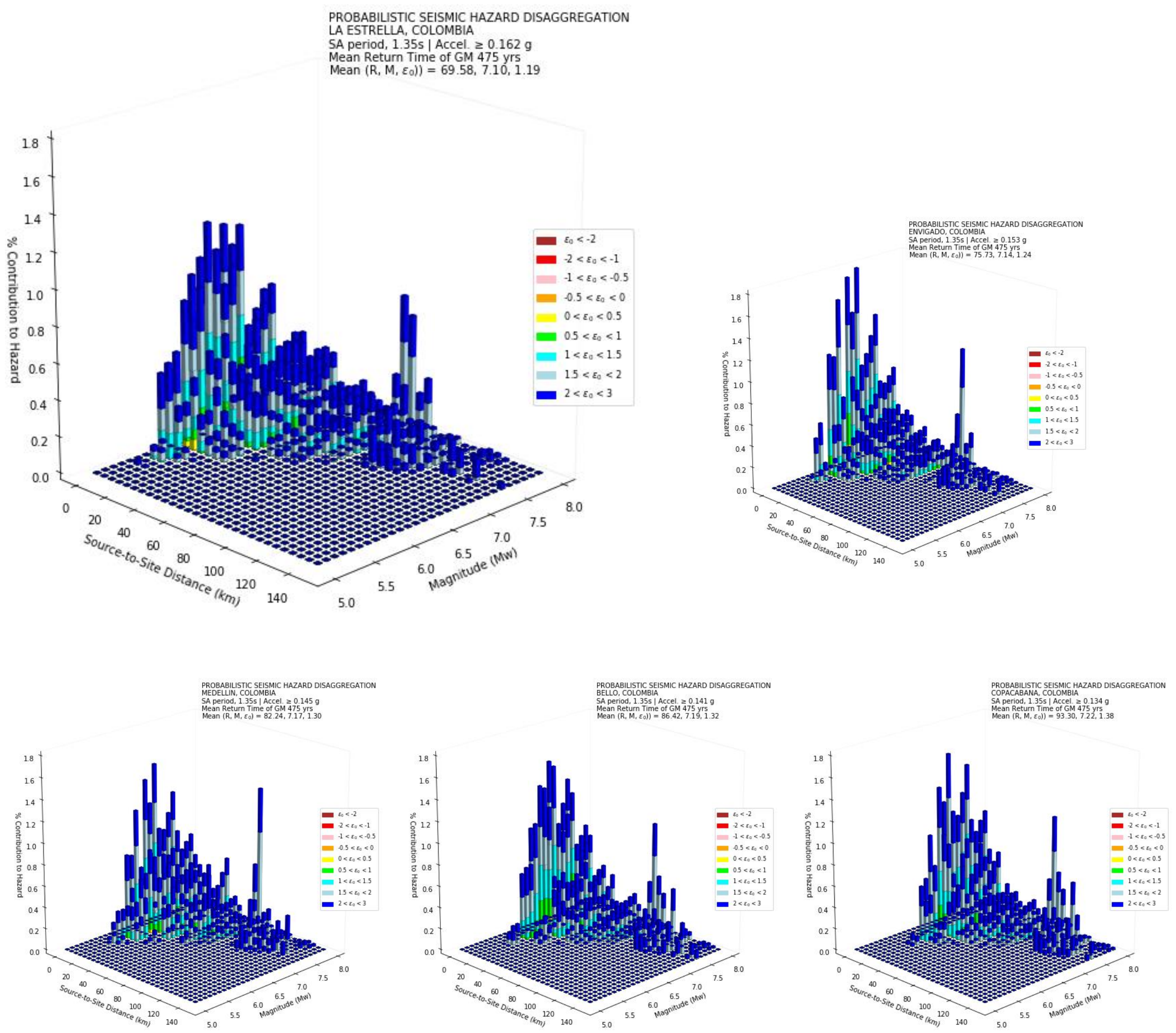

Fig. 5 - Seismic hazard disaggregation for the five cities, La Estrella, Envigado, Medellin, Bello, and Copacabana, at Sa(T=1.35s) for 475 year return period.

The conditional mean spectra for the cities of interest, return periods of 73, 475 and 2475 years, and mean values of (M,R,ε) related to the most contributed source, Romeral fault, are depicted in Fig. 6. Along with them, the relative dispersion, the uniform hazard spectrum, the spectrum computed with the GMPE [11] for the mean values of (M,R,ε) and the GMPE ± εσ are also illustrated.

Moreover, in order to perform nonlinear dynamic analysis over the case study building, a selection of seismic records was made consistent with the hazard-based spectral shape and source features (M,R,ε), previously computed for the five cities and different return periods. Therefore, the results of the conditional mean spectrum were the inputs to select and scale appropriately a set of 24 records per each case (i.e. five cities, two tectonic regimes, six return periods).

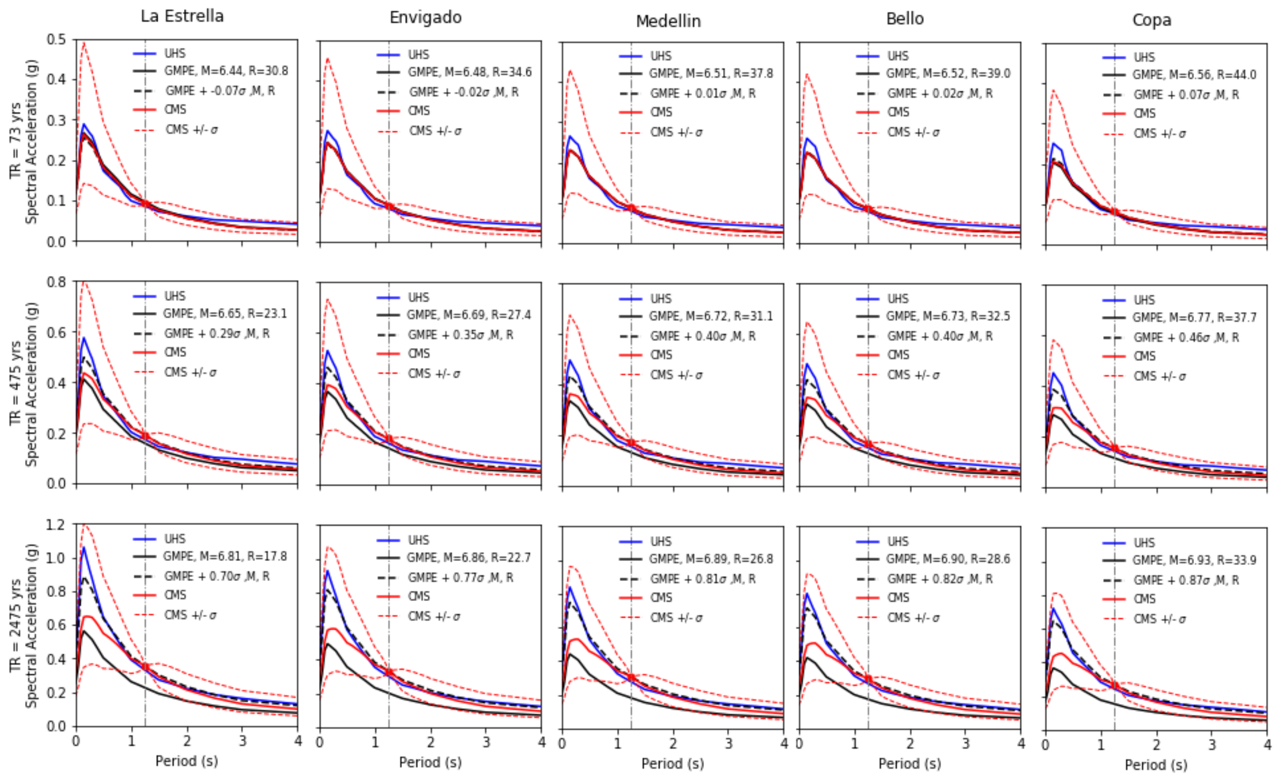

Fig. 6 - Conditional Mean Spectrum for the cities of La Estrella, Envigado, Medellin, Bello y Copacabana, return periods of 73, 475 and 2475 years, Romeral fault source at $T^* = 1.35s$.

However, with the idea to get the full behavior of the structure under collapse, some return periods were added scaling the intensities of the uniform hazard spectra up to a return period of 100,000 years, thus, considering a total number of 15 return periods. Finally, the selected records were extracted from the NGA West2 [18] ground motion database resulted in 150 pairs of records for each city and a tectonic regime, which means, a total number of 1,500 pairs of records. The scaled records for the city of Medellin, for return periods of 73, 225 and 2475 years under the tectonic regime of shallow-crust, near field: Romeral fault, are presented in Fig. 7.

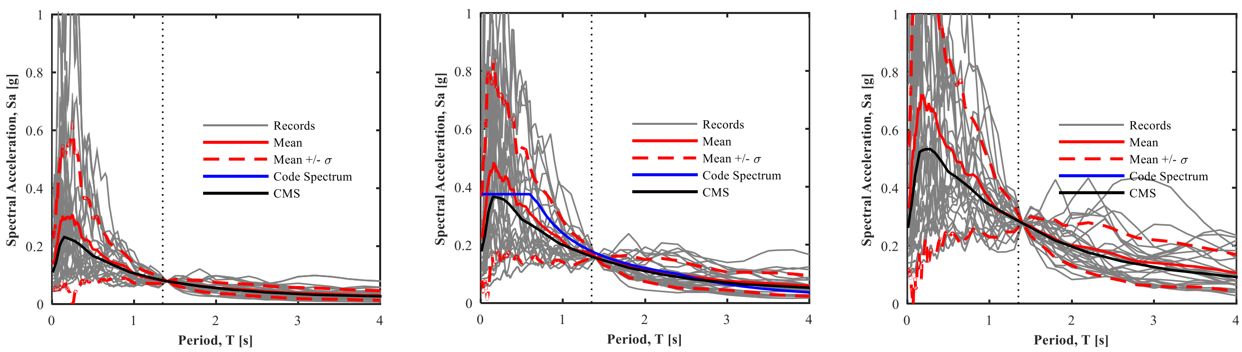

Fig. 7 - Scaled records for three different return periods (73, 475, 2475 years), for Medellin city, Romeral fault contribution at $T^* = 1.35s$.

4. Fragility Functions

Sets of fragility functions are derived by subjecting the case-study building to nonlinear time-history analyses (NTHA) using site hazard-consistent ground motion sets selected and scaled, for each city, as explained in

Section 3. Each set of fragility functions is derived for four damage states: slight, moderate, extensive and collapse. The performance limits for the slight, moderate and extensive damage states are set at drift values of 0.9%, 1.5%, and 2.7%, respectively, following the recommendations in [15]. The collapse limit is defined at a 4.5% drift, corresponding to a 20% drop in base-shear capacity [16].

Fragility functions are fitted with a log-normal cumulative density function, and the regression parameters (median and dispersion) are calculated using the maximum likelihood method as proposed in [17]. The set of fragility functions for each city is shown in Fig. 8, and the model parameters are summarized in Table 1. By comparing the median values corresponding to the collapse limit state, it is noticed that the median collapse capacity appears to reduce as one moves from the city closest to the fault (La Estrella) to the farthest (Medellin, Bello and Copacabana). This reduction is attributed to the ground motion sets of Medellín, Bello and Copacabana selected for larger mean magnitudes and distances that might bring along larger durations and frequency contents that affect negatively the building response.

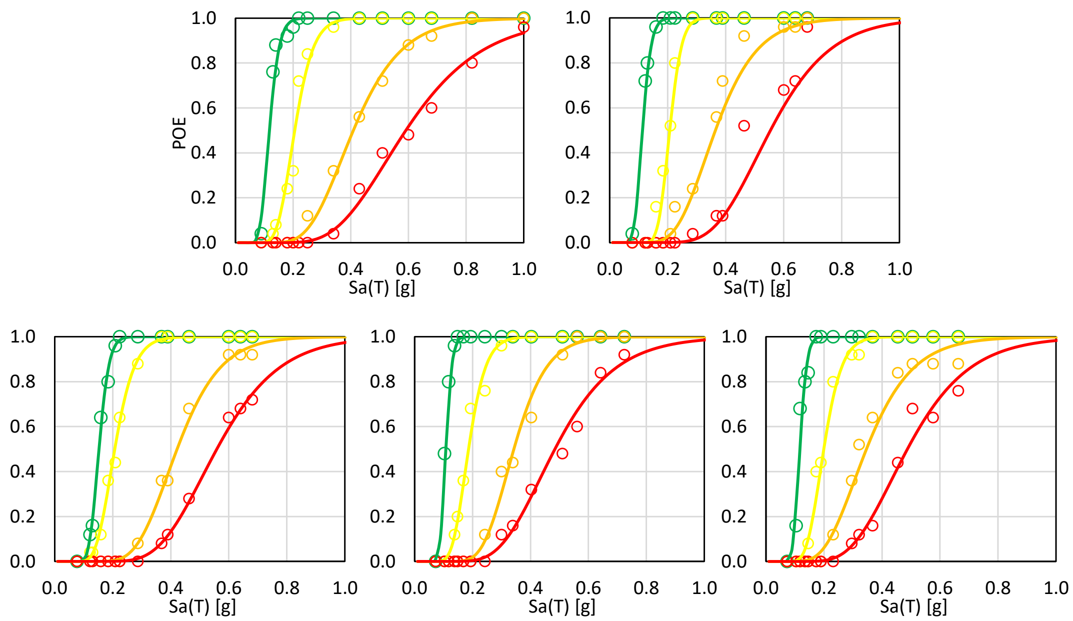

Fig. 8 - Fragility functions for the five cities under study

Table 1 – Summary of statistical model parameters for the Fragility functions

Limit State	La Estrellla		Envigado		Medellin		Bello		Copa	
	$Sa_{50\%}$ [g]	β [-]	$Sa_{50\%}$ [g]	β [-]	$Sa_{50\%}$ [g]	β [-]	$Sa_{50\%}$ [g]	β [-]	$Sa_{50\%}$ [g]	β [-]
LS1: Slight Damage	0.118	0.226	0.113	0.205	0.153	0.178	0.108	0.155	0.116	0.163
LS2: Moderate Damage	0.206	0.245	0.207	0.157	0.207	0.256	0.186	0.250	0.199	0.245
LS3: Severe Damage	0.409	0.321	0.365	0.311	0.422	0.277	0.343	0.260	0.346	0.355
LS4: Collapse	0.591	0.349	0.555	0.293	0.559	0.300	0.484	0.333	0.488	0.339

5. Results

A stochastic events catalog with magnitudes M_w between 4.0 and 7.6, and focal depths between 8 km and 40 km was generated for the Romeral fault. Each event in the catalog is used to predict a spectral acceleration in each of the cities, and from it, to determine the probability of exceeding the code or design spectral acceleration (DSA), and the probability of exceeding a damage state.

The probability of exceeding the DSA in a 50-year interval is shown in Fig. 9a as a function of the site-to-source distance. It is observed that as the site-to-source distance decreases from 20 km (Copacabana) to 2.5 km (La Estrella), the probability of exceeding DSA doubles from 4.5% to 8.3% for the 50-years interval. In addition, it is noted that, at least for the cases considered here, there is a linear relation between site-to-source distance and probability of exceedance.

In accordance with [1], the seismic demand a structure would experience under a strong earthquake is better correlated with the expected spectral acceleration (ESA) conditioned on the exceedance of the DSA value. The ESA is computed for the five cities as proposed in [1], and the results are presented in Fig. 9b as the ratio ESA/DSA. As observed, the ESA/DSA ratios tend to reduce as the source-to-site distance increases, and the expected values are not negligible, even for the case of Copacabana (20 km) with a 1.5 amplification over the code design-value. Although these values might appear high from an engineering perspective, it is recalled that the analyses presented here have considered a single fault (Romeral) out of the multiple ones that contribute to the seismic hazard of the Aburrá Valley; and whose contributions, once considered, will most likely tend to reduce the expected accelerations conditioned on the exceedance of DSA.

Although the analysis presented before in terms of hazard is insightful as to the likely performance of the building, it lacks objectivity regarding the seismic safety or the vulnerability of the building and, in consequence, it is not sufficient to assess the effect of the proximity to the Romeral fault on the vulnerability and safety of the structure. Thus, in this study, the seismic vulnerability of the building is defined as the probability of exceeding each of the four damage states in a time interval of 50 years (i.e., annual risk of exceeding a damage state). The results are plotted in Fig. 10a as a function of the site-to-source distance for the four damage states considered. A close-up view is shown in Fig.10b for the severe damage and collapse limit states.

In a general sense, the results in terms of risk display similar trends as those in terms of hazard, with increasing probabilities of exceedance as the distance to the fault decreases. Nonetheless, differences are detected for the cities of Medellin (12.5 km), Bello (15 km) and Copacabana (20 km), for which the probabilities of exceedance of the four damage states appear to be constant. This effect is attributed to the shifting of the fragility functions to the left (lower median capacity values) as one moves from Medellin (12.5 km) to Copacabana (20 km), for the reasons mentioned in Section 4. Yet, in terms of collapse probability, it is obtained that the structure located in the city closest to the fault (La Estrella) is almost two times more likely to collapse as compared to the farthest cities of Medellin, Bello and Copacabana; and similar proportions are observed for other limit states.

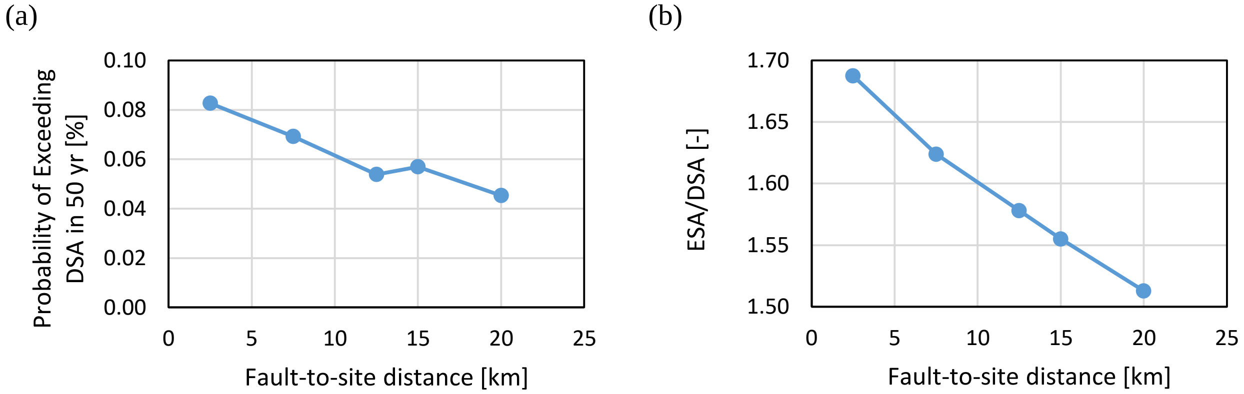

Fig. 9 – (a) Probability of exceeding the design spectral acceleration in 50 yr and. (b) Expected over design spectral acceleration as a function of the distance to the fault.

(a) (b)

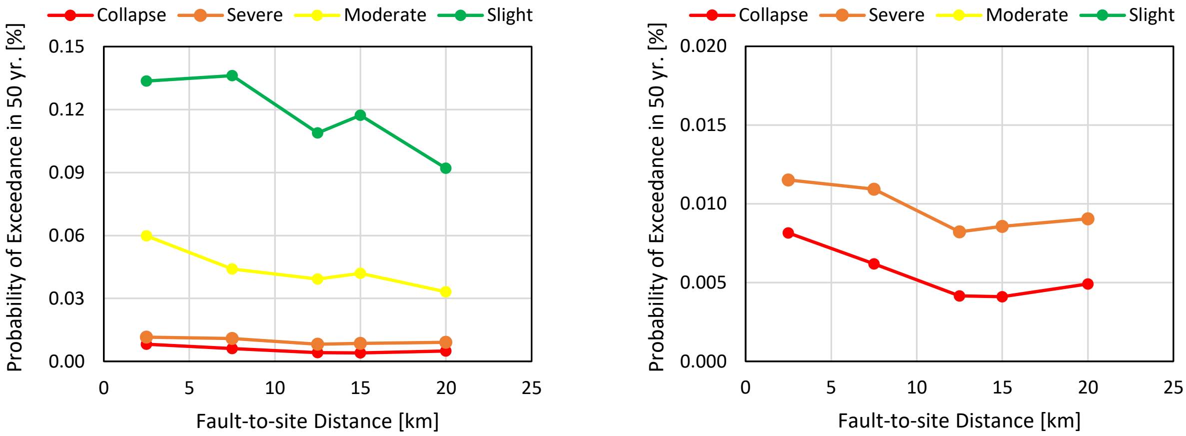

Fig. 10 – Probability of exceeding the slight, moderate, severe and collapse limit states in 50 years.

6. Conclusions

The reduction in structural safety of a 5-story code-conforming, archetype building located at 2.5, 7.5, 12, 15 and 20 km from the Romeral fault, in the Aburrá Valley, Colombia, was explored. For the building, such a reduction in structural safety was quantified as the increase in the annual probability of collapse (and some other limit states) vs. the source-to-site distance, using a stochastic risk analysis approach. As expected, the structural safety of the analyzed building did decrease as the distance between the seismic source and the site of analysis decreased and was totally conditioned on the occurrence of seismic events in this nearby source. For the case presented in this work, a linear-decreasing relation between site-to-source distance and probability of exceedance of the considered damage states was observed for closer sites to the source, while for further sites, that probability of exceedance appeared to be constant. This effect might be attributed to a shifting of the fragility functions to the left (lower median capacity values) as one moves from the site located at 12.5 km to that at 20 km, which was related to the ground motion sets selected for larger mean magnitudes and distances that might have brought along larger durations and frequency contents that affected negatively the building response.

Based on this study, it could be seen how, for sites that are considered to have the same hazard, the safety threshold can vary considerably, establishing a reason to ask for more detailed analysis for a site close to seismic sources, regarding the effects of that specific source.

This study is a first approximation to the topic, which still needs to be more carefully looked at. Even when similar trends are expected to be seen for different structures, their effects are expected to be dependent on the type of structure and the characteristics of the events that can happen on the investigated seismic source. Thus, the analysis for buildings with different structural types is a topic that needs to be further studied. Another factor that can significantly condition the results of the analysis is the inclusion of site-effects, which was left for future development, as the frequency content and characteristics of the ground motions that could be experienced in the site and its effects on the structural safety may vary significantly.

The work presented here was conducted specifically for the case of a nearby shallow crust source. However, the contribution of other faults to the site should be also investigated in particular taking into account that they may have an important contribution to the site hazard and the consideration of another tectonic regime, or even the same tectonic regime, but from a source with different characteristics, would certainly draw different results, given the considerable variations in disaggregation, record selection, and fragility curve derivation. It must also be stated that the previous analysis is site-dependent, which means that closeness to sources with other seismic characteristics may present results following the same trend, but with significant differences regarding the contribution or effect of the distance for the specific source.

The computation of the Conditional Mean Spectrum is a limited procedure in Colombia because the input parameters to determine the seismic hazard disaggregation (seismic hazard model) are not freely available for any site of the national territory. This previous becomes more relevant when mean values of magnitude, distance, and epsilon (M,R,ε) must be determined, which came from the contributions of the all sources at the site of analysis.

Local events must be evaluated in order to formulate local expressions of spatial acceleration values that represent the seismicity of the region, or at least, a deep analysis in this regard should be performed when correlations from other latitudes are used. This is a further analysis of this study.

Nonlinear time-history analyses were carried out employing ground motion records properly selected and scaled according to the hazard of the site. However, it is worth mentioning that the frequency content of each set of records, which came from pairs magnitude-distance of the disaggregation, could affect the building in some sites more than in others. In other words, a deep analysis of the possible contribution of the frequency content of the records selected in the final response of the structure should be performed.

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