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Seismic and wind vulnerability assessment for the GAR-13 global risk assessment

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ABSTRACT

A general methodology to evaluate vulnerability functions suitable for a probabilistic global risk assessment is proposed. The methodology is partially based in the methodological approach of the Multi-hazard Loss Estimation Methodology (Hazus) developed by the Federal Emergency Management Agency (FEMA). The vulnerability assessment process considers the resolution, information and limitations established for both the hazard and exposure models adopted. Seismic and wind vulnerability functions are estimated for each one of the building classes defined in typical global exposure databases. They consider possible variations according to the design level in different regions of the world which accounts for variations of the expected quality of construction and the design code compliance level. In addition, a consistent, expert opinion based methodology is proposed in order to assign particular vulnerability functions to building classes according to the development level of each country, the city complexity and the hazard level of the region. The proposed set of vulnerability functions and the assignment procedure were used for the probabilistic global risk assessment made in the framework of the UNISDR's Global Assessment Report on Disaster Risk Reduction, GAR 2013. Recommendations for the refinement of the methodological approach are included for future global or scaled regional risk assessments.

1. Introduction

The global risk assessment made in the framework of the UNISDR's Global Assessment Report on Disaster Risk Reduction, GAR 2013 [1,2] uses a set of vulnerability curves suitable for a probabilistic global risk assessment. These functions establish the relation between the intensity of the hazard event and the mean damage ratio, MDR, of the particular building class which it represents. One set of particular functions has been estimated for each one of the building classes defined in the exposure database in order to consider variations in the design level. The loss probability distribution function for each building class can then be estimated using both the MDR and its corresponding variance for each hazard intensity.

Building classes in the exposure database correspond to general building classifications proposed in Refs. [3,4] complemented with particular local information in several countries worldwide. The vulnerability representation of typical building classes shall consider the expected effects of the construction quality and the design code compliance level for different city categories of each country. Therefore modifications of the characteristic vulnerability functions are proposed to consider those factors.

The vulnerability assessment process considers the resolution, information and limitations established for both the

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hazard and exposure models adopted for the global risk assessment. The intensity parameter for the seismic hazard assessment corresponds to the elastic spectral acceleration. The one for cyclonic extreme wind corresponds to the maximum wind velocity sustained for five seconds at a reference height of 10 m above the ground level on a relatively flat terrain. On the other hand, the Global Exposure Database (GED) for the global risk assessment was developed at a global scale with a resolution at urban areas of 5 km × 5 km cells [5]. Exposure values were assigned using the country capital stock and the geographical distribution of the population [6]. Representative building classes are assigned at each location taking into consideration dominant building use groups (residential, commercial, industrial, and institutional for both private and public sectors), [7].

This paper proposes a methodological approach to develop consistent seismic and wind vulnerability functions which adequately represent the expected losses for different building classes considering variations associated with the expected quality of construction and code level compliance at a regional scale. A methodological approach partially based on the Hazus probabilistic risk assessment model was adopted [8]. Simultaneously, a consistent methodology to assign such vulnerability functions to particular building classes according to the development level of each country, the city complexity and the hazard level is proposed. Illustrative examples of the resulting seismic and wind vulnerability functions as well as the results of the vulnerability function assignment process are presented. The vulnerability functions developed in this paper are to be used under the risk assessment methodology adopted by the Central America Probabilistic Risk Assessment initiative, the CAPRA [9]. Additional related information can be found in Refs. [1,2,10–15].

2. Methodology

2.1. General approach for vulnerability assessment

Different approaches have been proposed to consider the physical vulnerability in the development of probabilistic risk assessment models [16–19]. Seismic fragility functions estimates the probability of reaching or exceeding a specific limit state given hazard intensity. Limit states for damage are usually defined in qualitative and descriptive terms (e.g. *S*: slight, *M*: moderate, *E*: extensive and *C*: collapse). On the other hand, probabilistic seismic vulnerability functions relate a given risk figure, as for example the expected economic loss or the MDR, to a hazard intensity parameter (Fig. 1).

The formulation for the fragility curves requires the consideration of *N* identified damage states, *ds*, for a structural system. Then the probability of reaching or exceeding the *i*th damage state P_i, given a hazard intensity *S* is as follows:

$$P_i = \Pr(DS \geq ds_i | S) \tag{2.1}$$

where *DS* is a damage random variable on the damage state vector $\{ds_0, ds_1, \ldots, ds_N\}$. According to Ref. [8], P_i can be estimated using the following function:

$$P_i = \Phi\left[\frac{1}{\beta_{ds_i}} \ln\left(\frac{S}{\overline{S}_{ds_i}}\right)\right] \tag{2.2}$$

where $\overline{S}_{ds_i}$ is the median value of the hazard intensity parameter at which the building reaches the threshold of damage state, ds_i; β_{ds_i} is the standard deviation of the natural logarithm of the hazard intensity parameter for damages state, *dsi*, and Φ is the standard normal cumulative distribution function.

The formulation of vulnerability functions requires the definition of the loss *L* as a random variable. In that case the vulnerability function describes the variation of the loss statistical moments (mean and variance) for different values of the hazard intensity. The vulnerability function provides all the necessary information to calculate the probability of reaching or exceeding a loss value, given the hazard intensity. Loss is defined using numerical scales instead of qualitative scales as for damage states (for example the ratio of repair cost to the component replacement value, also known as the mean damage ratio, MDR), which allows its direct use in probabilistic risk and loss calculations. The probability of reaching or exceeding a loss value is calculated as follows:

$$\Pr(L \geq l | S) = \int_l^{\infty} p_{L|S}(L) d\, L \tag{2.3}$$

where *l* is a loss value in the random variable *L* dominium, *S* is the hazard intensity demand and $p_{L|S}$ (*L*) is the loss probability distribution function usually assumed as Beta.

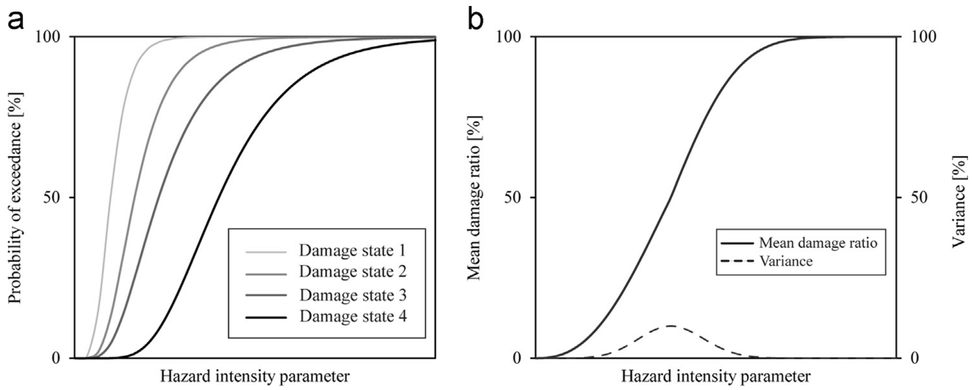

Fig. 1. Typical representation of (a) fragility and (b) vulnerability formulations.

Table 1
Design levels for vulnerability assessment.

Design Level	Description
High (H)	Good quality of construction which fully complies with the earthquake or wind resistance requirements of representative international building codes for high hazard zones.
Moderate (M)	Good quality of construction complying with earthquake or wind resistance requirements for intermediate hazard zones.
Low (L)	Minimum basic quality of constructions not designed for earthquake or wind considerations.
Poor (P)	Low quality of construction with no earthquake or wind resistance considerations.

It is possible to obtain the vulnerability function once the fragility formulation is available [2]. For this, a repair cost L_i must be assigned to each one of the defined damage states, ds_i. Therefore, the loss statistical moments given a certain hazard intensity can be calculated as follows:

$$E(L|S) = \sum_{i=0}^{N} L_i \Pr(DS = ds_i|S) \tag{2.4}$$

$$SD^2(L|S) = \sum_{i=0}^{N} (L_i - E(L|S))^2 \Pr(DS = ds_i|S) \tag{2.5}$$

where $E(L|S)$ is the loss mean and $SD(L|S)$ is the loss standard deviation given a hazard demand S, and Pr $(DS=ds_i|S)$ is the discrete probability of reaching a damage state ds_i. These equations correspond to the MDR of the vulnerability function and its corresponding variance [20].

2.2. Vulnerability functions for different design levels

In order to consider variables such as the quality of construction and code compliance level, different design levels are considered according to Table 1.

2.3. Seismic vulnerability assessment

The seismic vulnerability functions developed in this paper are based on the same methodological approach of Ref. [8] modified and complemented with some considerations and parameters proposed in Ref. [21]. The elastic spectral acceleration for 5% damping at the estimated structural vibration period of each representative building class is selected as the controlling hazard intensity parameter. Ref. [22] is used to transform maximum roof drift ratio to elastic spectral acceleration S_a as follows:

$$S_a = \frac{4\pi^2 \delta H}{g\beta_1\beta_2\beta_3\beta_4 T_e^2} \tag{2.6}$$

where:

δ = roof drift ratio
g = gravity acceleration
β_1 = participation factor ratio between the maximum roof displacement and the spectral displacement
β_2 = participation factor ratio between the maximum IDR and the roof drift ratio
β_3 = inelastic displacement ratio
β_4 = inelastic ductility ratio
T_e = fundamental vibration period
H = total building height

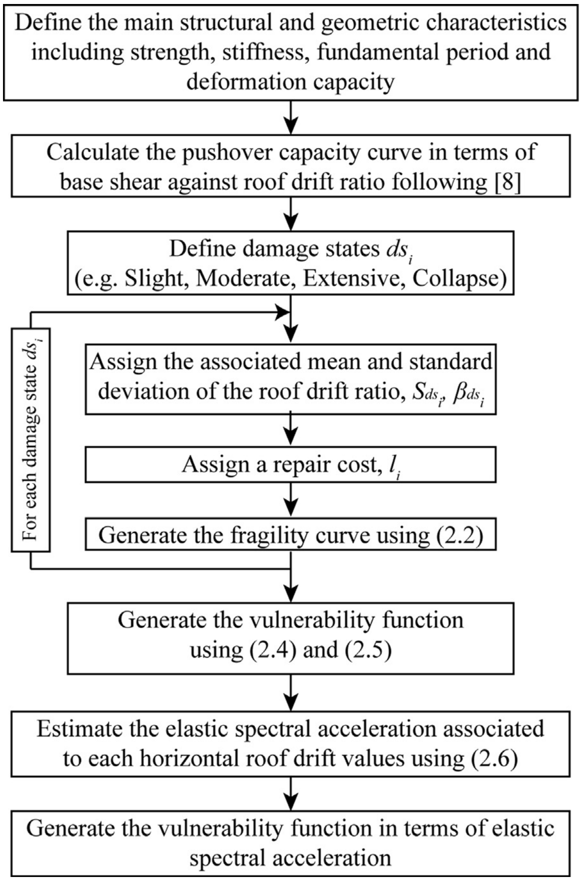

Fig. 2. Main steps to generate vulnerability functions.

The methodology comprises the main steps described in Fig. 2 which have to be applied for each design level under consideration.

2.4. Wind vulnerability assessment

For cyclonic extreme wind vulnerability assessment the maximum wind velocities sustained for 5 s at a reference height of 10 m above the ground level on a relatively flat terrain is selected as the controlling intensity parameter.

Given that, for a global risk assessment, the exposure data resolution is very limited and does not allow the level of detail required for considering all the variables necessary to estimate the wind damage for different hazard intensities, representative wind vulnerability functions have been assigned to the building classes, using the information available in [23]. Furthermore, in order to complete the required catalog of wind vulnerability functions for global building classes, expert opinions have been used to propose the parameters required to generate vulnerability functions for building classes predominant in developing countries in order to complement the already proposed functions.

The vulnerability functions for cyclonic wind are formulated using a beta distribution function, as it was originally proposed in Ref. [24] to represent damage factors as a function of the seismic intensity parameters:

$$E[\beta] = E[1 - 0.5^{(V/\gamma)^{\rho}}] \tag{2.7}$$

where $E[\beta]$ is the expected mean damage ratio value expressed as a percentage, V is the hazard intensity, γ is the intensity for the mean damage ratio $E[\beta] = 0.50$ and ρ is the curvature parameter.

2.5. Building classes

Vulnerability functions are developed for the different design levels of a group of selected building classes in order to develop a complete catalog of functions necessary in the risk assessment. The building classes include those most commonly used in developed as well as in developing countries, like those included in Refs. [3,4].

The building typologies for vulnerability classification were defined with some modifications with respect to the original ones [3,4] because of the following reasons:

- The design level is considered in the present approach as an additional qualifier to each one of the building classes. In Refs. [3,4] the design level usually generated new building classes.
- The building typologies proposed in these references were originally defined using mainly seismic resistance considerations. Modifications were made herein to account for wind specific building classes, especially for developing countries.
- According to Ref. [2], the assignment of relative building classes in each country or region and in each use group corresponds to the classification proposed in Ref. [7] which do not exactly correspond to building classes from Refs. [3,4].

Table 2 presents the building classes used for the global assessment and their corresponding basic parameters, including the design level considered in each case.

2.6. Vulnerability parameters

According to the previous methodological approach, a general parameter assessment is required to calculate seismic and wind vulnerability functions. To complete the catalog required in risk assessment studies, it is necessary to estimate parameters for new building classes for which vulnerability functions are still not available, especially for those representative of developing countries. In some other cases, parameters have to be estimated for different design levels of previously defined building classes.

Experimental information, analytical models, observed behavior of specific building classes subjected to different hazard levels and expert opinion were used as strategies to complete the required parameters. Refs. [4,21,25–37] are illustrative of the type of information available to complete the required parameters for specific building classes such as tilt-up walls, confined masonry, unreinforced masonry, warehouses, adobe and mud walls.

3. Results

3.1. Seismic vulnerability functions

All the vulnerability functions developed in this paper were calculated using the abovementioned methodological approach. Fig. 3 presents a comparison of some representative seismic vulnerability functions developed for building classes such as adobe (AD1L), unreinforced masonry (URML), reinforced masonry (RM1L), low-rise reinforced concrete frames (C1L) and low-rise steel frames (S1L). Fig. 4 illustrates the variation in the developed vulnerability functions considering different design levels for two different representative building classes: reinforced masonry (RM1L) and reinforced concrete frames (C1L). The complete set of seismic vulnerability functions used for GAR 2013 is reported in Ref. [2].

3.2. Wind vulnerability functions

All the vulnerability functions developed in this paper were calculated using the abovementioned methodological approach. Figs. 5 and 6 illustrate some representative wind vulnerability functions developed for selected building classes. The complete set of wind vulnerability functions used for GAR 2013 are reported in [2].

3.3. Assigning vulnerability functions to building classes

The assignment process of vulnerability functions to the building classes corresponding to particular regions or countries worldwide involves the assessment of the local quality of construction and compliance with the construction code requirements, for both the seismic and the wind hazards. The following variables and criteria are considered to assign a particular design level to each geographical location:

- *Building class and height*: building classes which require more specialized engineering skills (reinforced concrete or steel frames as opposed to unreinforced masonry) and tall buildings (with five or more stories) are more likely to have higher design levels than non-engineered low rise buildings (wooden, adobe, and unreinforced masonry buildings).
- *Country development level*: the classification used in the analysis follows the World Bank country classification,

Table 2
Building classes and general characteristics.

No.	Building class ID	Description	Height				Structural period Te (s)	Design level			
			Range		Typical						
			Name	Stories	Stories	Height (m)		H	M	L	P
1	W1	Wood, light frame (≤450 m2)	–	1–2	1	4.3	0.35	X	X	X	X
2	W2	Wood, commercial and industrial (>450 m2)	–	All	2	7.3	0.40	X	X	X	X
3	S1L	Steel moment frame	Low-rise	1–3	2	7.3	0.50	X	X	X	X
4	S1M		Mid-rise	4–7	5	18.3	1.08	X	X	X	X
5	S1H		High-rise	8+	13	47.5	2.21	X	X	X	X
6	S2L	Steel braced frame	Low-rise	1–3	2	7.3	0.40	X	X	X	X
7	S2M		Mid-rise	4–7	5	18.3	0.86	X	X	X	X
8	S2H		High-rise	8+	13	47.5	1.77	X	X	X	X
9	S3	Steel light frame	–	All	1	4.6	0.40	X	X	X	X
10	S4L	Steel frame with cast-in-place concrete shear walls	Low-rise	1–3	2	7.3	0.35	X	X	X	X
11	S4M		Mid-rise	4–7	5	18.3	0.65	X	X	X	X
12	S4H		High-rise	8+	13	47.5	1.32	X	X	X	X
13	S5L	Steel frame with unreinforced masonry infill walls	Low-rise	1–3	2	7.3	0.35	X	X	X	X
14	S5M		Mid-rise	4–7	5	18.3	0.65	X	X	X	X
15	S5H		High-rise	8+	13	47.5	1.32	X	X	X	X
16	C1L	Concrete moment frames	Low-rise	1–3	2	6.1	0.40	X	X	X	X
17	C1M		Mid-rise	4–7	5	15.2	0.75	X	X	X	X
18	C1H		High-rise	8+	12	36.6	1.45	X	X	X	X
19	C2L	Concrete shear walls	Low-rise	1–3	2	6.1	0.35	X	X	X	X
20	C2M		Mid-rise	4–7	5	15.2	0.56	X	X	X	X
21	C2H		High-rise	8+	12	36.6	1.09	X	X	X	X
22	C3L	Concrete frame with unreinforced masonry infill walls	Low-rise	1–3	2	6.1	0.35	X	X	X	X
23	C3M		Mid-rise	4–7	5	15.2	0.56	X	X	X	X
24	C3H		High-rise	8+	12	36.6	1.09	X	X	X	X
39	C4L	Reinforced concrete frames and concrete shear walls	Low-rise	1–3	2	6.1	0.35	X	X	X	X
40	C4M		Mid-rise	4–7	5	15.2	0.56	X	X	X	X
41	C4H		High-rise	8+	12	36.6	1.09	X	X	X	X
44	C5L	Flat slab structure	Low-rise	1–3	2	6.1	0.40	X	X	X	X
45	C5M		Mid-rise	4–7	5	15.2	0.75	X	X	X	X
46	C5H		High-rise	8+	12	36.6	1.45	X	X	X	X
25	PC1L	Precast concrete tilt-up walls	Low-rise	1–3	1	4.6	0.35	X	X	X	X
42	PC1M		Mid-rise	4–7	5	15.2	0.56	X	X	X	X
43	PC1H		High-rise	8+	12	36.6	1.09	X	X	X	X
26	PC2L	Precast concrete frames with concrete shear walls	Low-rise	1–3	2	6.1	0.35	X	X	X	X
27	PC2M		Mid-rise	4–7	5	15.2	0.56	X	X	X	X
28	PC2H		High-rise	8+	12	36.6	1.09	X	X	X	X
47	SC1L	Reinforced concrete frames and steel truss girder (warehouses)	–	All	1	4.6	0.32	X	X	X	X
29	RM1L	Reinforced masonry bearing walls with wood or metal deck diaphragms	Low-rise	1–3	2	6.1	0.35	X	X	X	X
30	RM1M		Mid-rise	4+	5	15.2	0.56	X	X	X	X
31	RM2L	Reinforced masonry bearing walls with precast concrete diaphragms	Low-rise	1–3	2	6.1	0.35	X	X	X	X
32	RM2M		Mid-rise	4–7	5	15.2	0.56	X	X	X	X
33	RM2H		High-rise	8+	12	36.6	1.09	X	X	X	X
34	URML	Unreinforced masonry bearing walls	Low-rise	1–2	1	4.6	0.35	–	X	X	X
35	URMM		Mid-rise	3+	3	10.7	0.50	–	X	X	X
38	CM1L	Confined masonry walls	Low-rise	1–3	3	9.1	0.40	–	X	X	X
36	AD1L	Adobe	Low-rise	1–2	2	6.1	0.50	–	X	X	X
37	TA1L	Tapia	Low-rise	1–2	2	6.1	0.50	–	X	X	X

Note: H=high, M=medium, L=low, P=poor; “X” refers to the design levels which were considered in each case to generate a particular vulnerability function. All vulnerability functions are presented in Ref. [2].

[38,39] using the following development levels: H=high, MH=medium-high, ML=medium-low, L=low.

- *The complexity level of the city or town*: it is usually associated with the size of the urban hub. High complexity cities usually boast more demanding regulatory agencies and therefore better compliance with construction code levels can be expected. The complexity level classification for each urban hub was made

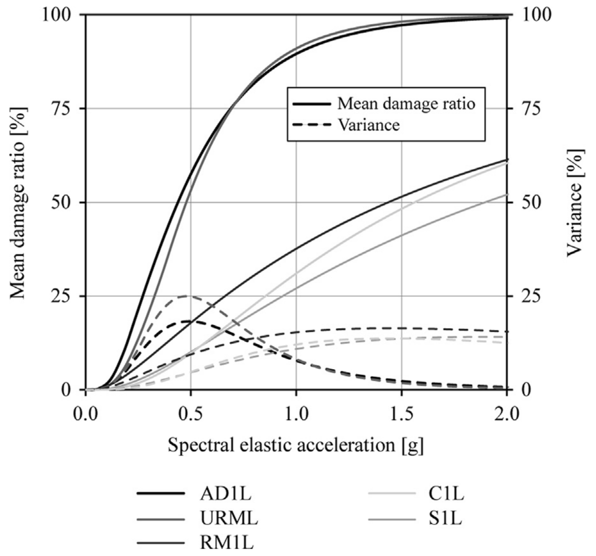

Fig. 3. Seismic vulnerability functions for different building classes (design level: M).

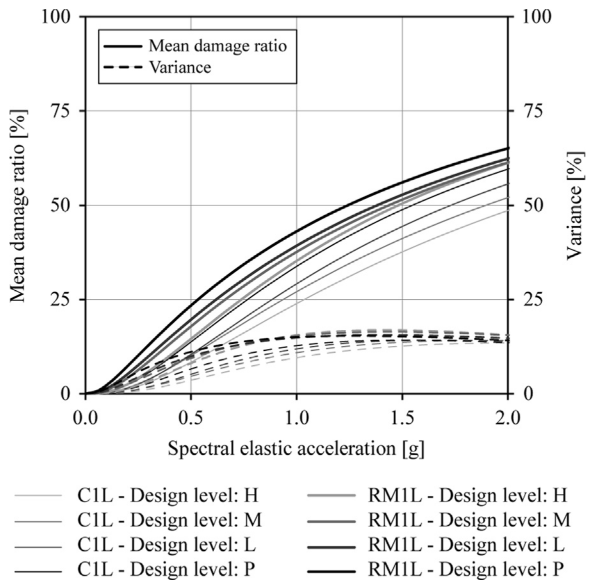

Fig. 4. Seismic vulnerability functions for different design levels of selected building classes.

according to Refs. [2,40] in the following categories: H=high, M=medium, L=low.

- *The regional hazard level*: regions with relatively high frequency of medium or high intensity events are more likely to have better construction quality and higher design levels. The regional hazard level was assigned according to the parameters indicated in Table 3 obtained from the global hazard models [2].

In order to perform a rigorous assignment process, specific vulnerability information of the different building classes would be required in a regional basis. To overcome this limitation, an assignment methodology based on expert opinions was adopted, which enabled obtaining a consistent and reasonable set of results in terms of vulnerability variations, according to the main variables under study. Table 4 illustrates a suggested design level assignment process for representative building classes. The complete table is available in Annex 16 of Ref. [2].

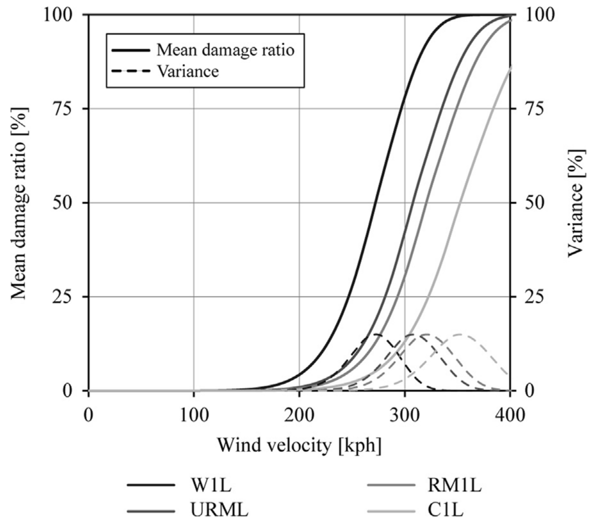

Fig. 5. Representative wind vulnerability functions for different building classes.

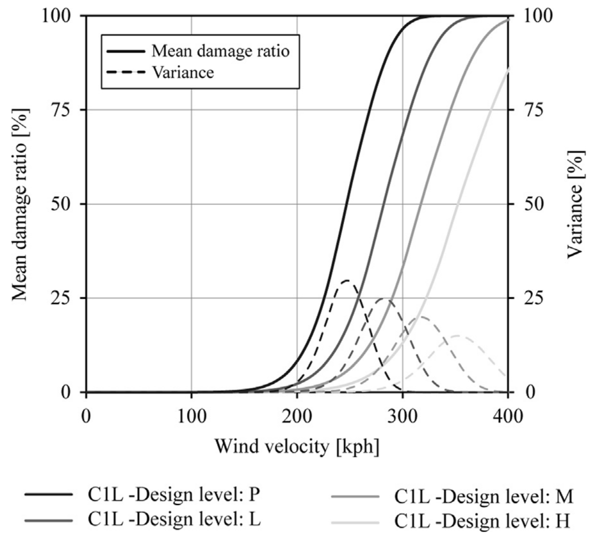

Fig. 6. Representative wind vulnerability functions for different design levels of selected building classes.

Table 3
Seismic and wind hazard levels.

Hazard level	Maximum ground acceleration (g)	Maximum wind velocity (kph)
Low (L)	< 0.10	< 150
Medium (M)	0.10–0.25	150–300
High (H)	> 0.25	> 300

Table 4
Illustrative suggested design level assignment for selected building classes.

Building class ID	Building class description	Country development level																	
		High Complexity level of the city									Low Complexity level of the city								
		High Hazard level			Medium Hazard level			Low Hazard level			High Hazard level			Medium Hazard level			Low Hazard level		
		High	**Medium**	**Low**	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**
C1L	Concrete moment frames low-rise	H	M	M	H	M	M	H	M	M	M	M	M	M	M	L	L	L	L
C1M	Concrete moment frames mid-rise	H	M	M	H	M	M	H	M	M	H	M	M	M	M	M	M	L	L
C1H	Concrete moment frames high-rise	H	M	M	H	M	M	H	M	M	H	M	M	H	M	M	M	M	M
C3L	Concrete frame with unreinforced masonry infill walls low-rise	M	L	L	M	L	L	M	L	L	L	L	L	L	L	L	L	P	P
C3M	Concrete frame with unreinforced masonry infill walls mid-rise	M	L	L	M	L	L	M	L	L	M	L	L	L	L	L	L	L	P
C3H	Concrete frame with unreinforced masonry infill walls high-rise	M	L	L	M	L	L	M	L	L	M	M	L	M	L	L	M	L	L
C4L	Reinforced concrete frames and concrete shear walls low-rise	H	M	M	H	M	M	H	M	M	L	L	L	L	L	P	L	P	P
C4M	Reinforced concrete frames and concrete shear walls mid-rise	H	M	M	H	M	M	H	M	M	M	L	L	L	L	L	L	P	P
C4H	Reinforced concrete frames and concrete shear walls high-rise	H	M	M	H	M	M	H	M	M	M	M	L	M	L	L	M	L	L

Note: design levels: H=high, M=medium, L=low, P=poor; the complete table is available in Annex 16 of Ref. [2].

4. Discussion and conclusions

A general methodology and a set of seismic and cyclonic wind vulnerability curves suitable for a probabilistic global risk assessment are proposed. They have been estimated for each one of the building classes defined in typical global exposure databases. They also consider possible variations according to the design level in different regions of the world which accounts for the expected quality of construction and design code compliance level. The proposed set of vulnerability functions were used for the probabilistic global risk assessment made in the framework of the UNISDR's Global Assessment Report on Disaster Risk Reduction, GAR 2013 [1,2].

The vulnerability assessment process considers the resolution, information and limitations established for both the hazard and exposure models adopted for the global risk assessment. The elastic spectral acceleration for 5% damping and the maximum wind velocities sustained for 5 s were selected as the controlling hazard intensity parameters. A methodological approach based on the Hazus probabilistic risk assessment model was adopted [8,23]. Additional considerations and parameters were included to account for non-engineered building classes and different design levels.

A consistent, expert opinion based methodology is proposed in order to assign vulnerability functions to particular building classes considering the development level of each country, the city complexity level and the hazard level of the region.

The proposed vulnerability assessment approach is consistent with the general goals established for the global risk assessment. Modeling is aimed at capturing only the general vulnerability characteristics at a regional level compatible with the level of resolution used in the exposure database for purposes of obtaining regional relative risk figures. No specific considerations have been made for any particular country, structural system or particular building. The probabilistic approach adopted in the present case allows considering the great uncertainties associated with the vulnerability assessment. It is a main concern to involve in the analysis of the controlling conceptual variables that can affect both the vulnerability function itself and the assignment process, although the treatment of those variables may involve great uncertainties. The vulnerability functions described in this paper have been developed solely for the scope of this project and should not be used for purposes other than the ones set forth herein. In the proposed form, they are to be used only under the risk assessment methodology adopted by the CAPRA platform [9] or by consistent methodologies. Modifications may be required to use these vulnerability functions in other risk assessment software.

Considering the technical framework under which the presented vulnerability functions catalog was developed, it is possible to develop a more detailed vulnerability assessment at regional or country level. The same basic probabilistic assessment approach can be used to obtain more reliable risk figures and down-scale the proposed global model to a particular region under analysis using the same basic principles and arithmetic. Correspondingly, specific consistent vulnerability function may be developed for those more detailed risk assessment processes.

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