STATISTICAL MODELLING OF SEISMIC VULNERABILITY OF BUILDINGS FOR SOUTH ICELAND CONSIDERING THE SPATIAL CORRELATION OF GROUND MOTION INTENSITY

Moosapoor Mojtaba – Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavik, Iceland, e-mail: mom12@hi.is

Darzi Atefe – Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavik, Iceland, e-mail: atefe@hi.is

Bessason Bjarni – Faculty of Civil and Environmental Engineering, University of Iceland, Reykjavik, Iceland, e-mail: bb@hi.is

Rupakhety Rajesh– Earthquake Engineering Research Centre – University of Iceland, Selfoss, Iceland, e-mail: rajesh@hi.is

Erlingsson Sigurður– Faculty of Civil and Environmental Engineering – University of Iceland, Reykjavik, Iceland, e-mail: sigger@hi.is

Abstract:

An Mw6.30 earthquake occurred in south Iceland in May 2008. The epicentre and fault rupture occurred close to small villages and farms, affecting over 5000 residential buildings. Despite significant damage, no residential buildings collapsed. It is desirable to know the ground motion intensity at various locations in order to develop an empirical vulnerability model; however, ground-motion observations are only available for a limited range of sites. Classical Ground Motion Prediction Equations (GMPEs) are commonly used to predict desired ground motion intensity measures (IM) at a given site. There are several interpolation methods available to improve the predictions if local ground motion data for the study event is available. Since IMs or their logarithms are normally distributed, spatially correlated, and correlated with each other at a given location, the conditional multivariate normal (MVN) distribution can be used for this purpose. This paper uses the MVN-based approach to perform PGA interpolation using local GMPE. We specifically present: 1- spatially correlated PGAs using MVN formulation and 2- an advance empirical vulnerability model based on zero-inflated beta regression calibrated for five building typologies in south Iceland.

Keywords: Seismic vulnerability, Beta regression, Multivariate normal distribution, Cross-correlation

1. Introduction

During the last 25 years, three destructive earthquakes have struck in the South Iceland Seismic Zone (SISZ). Two, similar size, Mw6.52 and Mw6.44 earthquakes, occurred in SISZ on 17th and 21st of June 2000 (Jónasson et al., 2021), respectively. Nearly 5000 low-rise residential structures were impacted by them. On 29th of May 2008, an Mw6.31 earthquake occurred further west in the zone, damaging roughly 5000 houses once more (Jónasson et al., 2021; Sigbjörnsson et al., 2009). Registers Iceland has a complete property database with specific information on all building units in Iceland ("Icelandic Property Registers"). The combination of the property database and estimated repair cost for damaged structures results in a total loss dataset that gives unique opportunities to research many elements of seismic vulnerability (Pitilakis and Crowley, 2014). Previous research focusing on losses in residential buildings have analysed and simulated the datasets to some extent (Bessason et al., 2022, 2020, 2016, 2014, 2012; Ioannou et al., 2018). Darzi et al. (2022) employs empirical Bayesian kriging geostatistical analyses for the same area to generate high-resolution shakemaps for various intensity measures of Olfus earthquake and consequently performs seismic risk analyses in building-by-building spatial resolution.

To the best of our knowledge, the first application of the zero-inflated beta regression model (ZIBRM) to post-earthquake loss data was in Ref. (Bessason et al., 2022, 2020). The most significant innovation of the ZIBRM is that it considers no-loss structures differently and assists in lowering the vulnerability curves down towards zero loss at low intensity. As a result, the models more accurately represent the majority of no-loss data in that intensity range. Presenting the possibility of applying this sort of advanced statistical tool in empirical vulnerability assessment is thus seen to be a significant contribution in the area.

Empirical research has shown that ground motion IMs are spatially correlated (Bradley, 2012, 2010; Jayaram and Baker, 2009). It is also feasible to assume ground-motion IMs or their logarithms to be normally distributed when rupture characteristics such as magnitude and distance are considered. These characteristics allow the conditional multivariate normal (MVN) to be used in the IM estimation. In certain circumstances, observed IMs may be accessible at a targeted site, but we want to estimate IMs that are not among the reported IMs. Baker (2011) presents the conditional spectrum technique, in which the distribution of SA at any frequency is conditioned on the availability of a SA value at the same location. Bradley (2012, 2010) modified the technique to account for the dependency of seismic response on non-spectral-acceleration IMs, such as those related to ground motion duration or energy. Here, we used the method of Worden et al. (2018) that accounts for the uncertainty of the conditioning data for the MVN.

The main goal of this research is to propose a vulnerability model based on the zero-inflated beta regression model developed in (Bessason et al., 2022, 2020) while taking into account the spatial correlation of IMs. This model is based on building-by-building loss data collected. Furthermore, an independent model is proposed for each of the three building typologies with consideration of the year of construction.

2. The earthquake and building exposure data

2.1. The May 2008 Ölfus earthquake

On the 29th of May 2008, the most recent destructive earthquake in Iceland, with Mw 6.3, struck in the SISZ (Figure 1). It consisted of north-south running strike-slip ruptures, almost simultaneous, on two closely spaced faults. The highest PGA recorded in the nearest towns, Hveragerdi and Selfoss, was as high as 0.88g and 0.54g, respectively (Halldórsson and Sigbjörnsson, 2009; Sigbjörnsson et al., 2009). While this earthquake caused the most damage in Iceland to date; no casualties or collapse of residential buildings was reported.

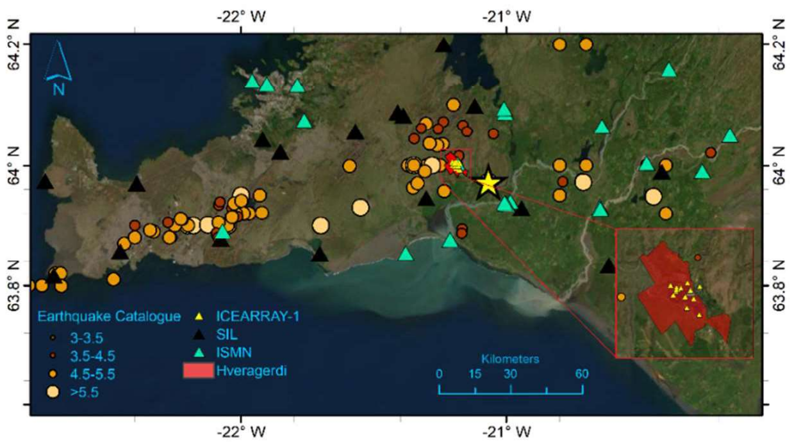

Fig. 1: Earthquake occurrences (circles) from 1904-2019 in Southwest-Iceland. Yellow star shows the epicentre of the May 2008 Ölfus earthquake. The triangles show monitoring systems in SW Iceland

2.2. Property database

The official building property database contains comprehensive information regarding each building such as construction year, construction material, floor area, number of storeys, geographical coordinates, etc. ("Icelandic Property Registers"). The fire insurance value for each building is also included in the database, and it has been used as the replacement value herein. Most properties in the SISZ are one-storey residential buildings; however, there are also duplexes, townhouses, and apartment blocks. In this database, the "building" and "dwelling" units are the same for single-storey buildings; however, multistorey buildings can contain many dwellings. In the 2008 Ölfus earthquake dataset, the losses are reported dwelling-by-dwelling.

Based on the construction year, Crowley et al. (2021) grouped the status of seismic design codes into four categories (Table 1).

Table 1: Status of seismic design codes for the Icelandic building

Period	Seismic Design Code	Code Classification	Comment
< 1958	No code	CDN	No seismic design code
1958 – 1975	Only hazard map (Tryggvason et al., 1958)	CDL	First generation of seismic codes
1976 – 2001	ÍST 13 (1989, 1976)	CDM	Second generation of seismic codes
>2002	Eurocode 8 (Standard, 2005; Sveinsson and Halldorsson, 2010)	CDH	Latest generation of seismic codes

In this study, datasets are grouped by construction material and year based on GEM taxonomy (Brzev et al., 2013). In this regard, the dataset is classified into three main typologies, and then, they are subclassified based on the seismic codes defined in Table 1. The result of this classification and subclassification is presented in Table 2.

In the dataset, 45% of buildings are built of reinforced concrete (RC), including concrete and precast concrete classes, 48% timber (W) and 7% unreinforced masonry buildings, including cinderblock, bricks and concrete's combination with blocks/bricks (MUR). Also, more than 97.5% of buildings are low-rise with one or two stories.

The concrete strength of buildings built before 1976 was low (fck=16 MPa). After 1976 it was increased to C20 or C25 concrete. Nowadays, only ribbed high-grade steel bars with fyk=500 MPa are used for reinforcement, but before 1965, non-ribbed low-grade bars with fyk=235 MPa were the only option. From 1965 until 1976, using reinforcement bars generally increased around all openings, and after 1976, all structural walls had reinforcement grids (Bessason et al., 2012).

Table 2: Classification of residential buildings based on the GEM building taxonomy and seismic code status

Code Classification	RC (Reinforced Concrete)		W (Timber)		MR (Masonry)	
	Number of Buildings	%	Number of Buildings	%	Number of Buildings	%
CDN	253	12.4	262	12	231	68.7
CDL	809	39.6	366	16.7	100	29.8
CDM	618	30.2	788	36	5	1.5
CDH	364	17.8	770	35.3	0	0
	2044	**100**	**2186**	**100**	**336**	**100**

2.3. Loss data

Only residential buildings are considered in this study. For each dwelling that the landlord reported damage after the Ölfus earthquake, a repair cost was estimated by expert people who prepared a detailed report for each building. Considering that each property has compulsory hazard insurance provided by the Natural Catastrophe Insurance of Iceland ("Natural Catastrophe Insurance of Iceland"), we assumed that all damaged buildings were considered as it is financially beneficial for the owners to file a claim. Then the damage factor DF for each property was calculated by dividing the repair cost by replacement value taken from the official property database.

$$DF = \frac{\text{Estimated repair cost}}{\text{Replacement value}} \tag{1}$$

The replacement values, which are equal to the depreciated replacement value plus the cost of removing the destroyed building, is the same as the fire insurance value of the property.

2.4. Intensity measure

An intensity measure (IM) that can be associated with the observed damage is required in a vulnerability assessment. At typical structural periods, it is most practicable to employ single parameter IM that can be generated using existing GMPEs, such as PGA, PGV, or spectral acceleration or spectral displacement (Rossetto et al., 2014). Because the impacted buildings in this study were low-rise, stiff, and had low natural periods, the intensity measure was stated in terms of the PGA, which is indicative of the shorter period component of a response spectrum. A local GMPE proposed by Kowsari et al. (2020) was used. The functional form of the GMPE is:

$$log(PGA) = C_1 + C_2\mathrm{M_w} + C_3\mathrm{R} - \log(\mathrm{R} + C_4\exp\,(C_5 M_w)) + C_6 S \tag{2}$$

Where R is the distance to surface trace of the fault in km, S is a site factor that takes the value 0 for rock sites and 1 for stiff soil sites. The unit of PGA is in m/s^2. Moreover, the coefficients are based on Table 3:

Table 3: The median model parameter values

Period	C_1	C_2	C_3	C_4	C_5	C_6	τ	φ
0	-0.10706	1.24848	-0.02233	0.00543	0.98714	0.90146	0.08572	0.39353

2.4.1. Observed intensity measure

Recorded ground motion data from a total of 19 stations are available from the Ölfus earthquake (Table 4). Most of them are from the strong-motion array ICEARRAY I stations (IS6xx IDs) (Halldórsson and Sigbjörnsson, 2009) and some from the Icelandic Strong Motion Network (ISMN) (triangles in Fig.1). In this study, the horizontal components of PGAs (H_1 and H_2) are combined to the average rotation-invariant (ARI) component, which gives the expected values of PGA for all possible orientation of accelerometer axes in the horizontal plane (Rupakhety and Sigbjörnsson, 2013).

Table 4: values of recorded peak ground acceleration (PGA)

Station ID	**Distance R_{JB} (km)**	**PGA (g)**			**Calculated (ARI) PGA (g)**
		H1	H2	Z	
'IS105'	34.85	0.05	0.04	0.02	0.05
'IS113'	0.82	0.58	0.59	0.54	0.58
'IS306'	5.38	0.13	0.11	0.07	0.12
'IS402'	31.68	0.02	0.01	0.01	0.01
'IS403'	29.47	0.03	0.04	0.02	0.03
'IS112'	3.52	0.54	0.34	0.27	0.43
'IS101'	4.23	0.51	0.22	0.17	0.33
'IS502'	20.80	0.08	0.10	0.03	0.09
'IS601'	0.36	0.64	0.83	0.82	0.73

'IS602'	1.73	0.86	0.88	0.50	0.87
'IS603'	1.38	0.42	0.61	0.62	0.51
'IS604'	1.48	0.38	0.50	0.47	0.44
'IS605'	1.46	0.45	0.67	0.54	0.55
'IS607'	1.58	0.48	0.87	0.79	0.65
'IS608'	0.94	0.55	0.62	0.61	0.59
'IS609'	0.82	0.64	0.47	0.47	0.55
'IS610'	0.40	0.84	0.71	0.74	0.77
'IS611'	1.04	0.45	0.44	0.29	0.45
'B3Clp17'	3.49	0.54	0.49	0.37	0.52

3. Spatial correlations

The well-known correlation features observed in ground motion intensity measures (IMs) may not always be adequately captured within vulnerability modelling. Weatherill et al. (2015) showed that considering spatial cross-correlation of IMs into the seismic risk analysis often results in observing larger (and in some cases smaller) losses compared to simulations in which the cross-correlation of IMs is ignored.

3.1. Modelling spatial correlation

The general form of GMPEs is:

$$log(IM_{ij}) = f(M_i, R_{ij}, \theta_{ij}) + \tau\vartheta_i + \varphi\epsilon_{ij} \tag{3}$$

IM_{ij} is the value of the earthquake IM of interest at location j at a distance of R_{ij} from the source of ground motion with the magnitude of M_i. Parameter θ_{ij} represent the terms of site effects and style of faulting. The inter-event ($\tau\vartheta_i$) term in the ground motion model represent the variability of the median of IM from one earthquake to another of the same magnitude and rupture mechanism, and the intra-event ($\varphi\epsilon_{ij}$) term represents the variability of the ground motion value from one site to another at the same distance with the same site characterisation (Bommer and Crowley, 2006). The τ and φ constants represent the standard deviations of the inter- and intra-event variability, and the terms of ϑ_i and ϵ_{ij} are standard normally distributed random variables.

Previous studies have shown the strong spatial correlation between intra-event residual terms, in a way that the coefficient of correlation (ρ_h) observed at two sites separated by a distance, h, will decrease by increasing the distance. Most of these studies (Esposito and Iervolino, 2012, 2011; Jayaram and Baker, 2009) showed that the exponential function form is preferred. In this study, the Jayaram and Baker (2009) model has been considered.

$$\rho_h = \exp\left(-\frac{3h}{b}\right) \tag{4}$$

The b constant has been assumed to be 8.5 based on Jayaram and Baker (2009) for the soil type of south Iceland.

3.2. The Conditional Multivariate Normal Distribution

Usually, one or estimates of mean and variance of a variable is known, also there would be some observed data, and we intend to estimate the value of the parameter some distance away from the observation. In this case, the distance might refer to any variable, such as spatial separation, separation in the spectral period, time, or any other parameter for which the correlation among observed data can be determined (Worden et al., 2018).

Considering we have N observations (Y_2) of variable Y, and we intend to calculate predictions (Y_1) at M target location. The MVN is summarized as a function of a random vector partitioned into these two components (Johnson and Wichern, 2014):

$$Y = \left\{-\frac{Y_1}{Y_2}\right\} \tag{5}$$

With mean of: $\mu_Y = \left\{-\frac{\mu_{Y_1}}{\mu_{Y_2}}\right\}$ (6)

And matrix of covariance of:

$$\Sigma_Y = \begin{bmatrix} \Sigma_{Y_1Y_1} & \Sigma_{Y_1Y_2} \\ M \times M & M \times N \\ \Sigma_{Y_2Y_1} & \Sigma_{Y_2Y_2} \\ N \times M & N \times N \end{bmatrix} \tag{7}$$

In which $M \times M$, $M \times N$, $N \times M$ and $N \times N$ are the dimension of partitioned matrixes.

The matrix of residuals equal to:

$$\xi = y_2 - \mu_{Y_2} \tag{8}$$

So Y_1, given $Y_2 = y_2$ is MVN with mean and covariance of:

$$\mu_{Y_1|y_2} = \mu_{Y_1} + \Sigma_{Y_1Y_2}\Sigma_{Y_2Y_2}^{-1}\xi \tag{9}$$

$$\Sigma_{Y_1Y_1|y_2} = \Sigma_{Y_1Y_1} - \Sigma_{Y_1Y_2}\Sigma_{Y_2Y_2}^{-1}\Sigma_{Y_2Y_1} \tag{10}$$

$\Sigma_Y$in above equations is equal to:

$$\Sigma_{Y_iY_j} = \rho_{Y_iY_j}\sigma_{Y_i}\sigma_{Y_j} \tag{11}$$

μ_Y, σ_{Y_i} and σ_{Y_j} are derived from a GMPE model calculated based on Equation 2 and $\rho_{Y_iY_j}$ is the correlation of *i*th and *j*th element of Y which is calculated using Equation 4. Then by using Equations 9 to 11, we could calculate the spatially correlated PGA (PGA_{cor}).

4. Development of statistical vulnerability model

This section explains the ZIBR modelling based on a two-step regression analysis of the empirical loss data. Herein, the random variable (X) is expressed by the predefined DF. The first regression provides a logistical model representing the probability of experiencing damage for a given ground motion intensity level. The second regression provides a beta distribution representing the extent of loss conditioned on its occurrence. The final vulnerability model is constructed by combining a logistical regression model and a conditional beta regression model commonly called the zero-inflated beta regression (ZIBR) model (Ospina and Ferrari, 2012). Then, it can be used to predict average loss and the desired prediction limits. This subsection briefly explains the underlying structure and formulas behind the ZIBR model and introduces the model parameters.

In the first step, the logistical regression model is used to predict the probability of incurring loss (DF>0), p_j, as a function of ground motion IM $(Y) = PGA_{cor}$:

$$log\left(\frac{p_j}{1-p_j}\right) = \beta_{0,j} + \beta_{1,j} \cdot Y \tag{12}$$

where $\beta_{0,j}$ and $\beta_{1,j}$ are the regression coefficients; and j is the building typology.

In the second step, a conditional probability model for the loss is being modelled by a beta distribution limited in the unit interval (0, 1), given that DF > 0 (Ferrari and Cribari-Neto, 2004). For buildings with complete loss (DF=1), which only occurred in a very few cases, DF is treated with a value less than a unit, herein 0.85. The probability density function (PDF), expected value, and variance of the model are respectively given as:

$$f(x|DF>0)=\frac{\Gamma(\varphi)}{\Gamma(\mu\varphi)\Gamma(1-\mu)\varphi}x^{\mu\varphi-1}(1-x)^{(1-\mu)\varphi-1} \qquad 0<x<1 \qquad (13)$$

$$E[X|DF>0]=\mu \qquad 0<\mu<1 \qquad (14)$$

$$\mathrm{Var}[X|DF>0]=\frac{\mu(1-\mu)}{1+\varphi} \qquad \varphi>0 \qquad (15)$$

Where μ is the mean value and φ is the precision. The μ is connected to η_1, a function of the explanatory variable PGA_{cor}, via the logit link function of $g_1(.)$ which is expressed as below:

$$\mu=g_1^{-1}(\eta_1), \text{ and } g_1(\mu)=logit(\mu)=log\left(\frac{\mu}{1-\mu}\right) \qquad (16)$$

Similarly, the precision, φ, which was considered as a constant intercept, is related to η_2, through a link function, g_2:

$$\varphi={g_2}^{-1}(\eta_2), \text{ and } g_2(\varphi)=log(\varphi) \qquad (17)$$

Exploring the various combination of explanatory variables, the corresponding functions are chosen based on the logarithm of ground motion PGA_{cor} and the building typology as follows:

$$\eta_{1j}=\theta_{0,j}+\theta_{1,j}\times log(Y), \text{ while } Y=PGA_{cor} \qquad (18)$$

$$\eta_{2j}=\theta'_{0,j} \qquad (19)$$

where $\theta_{0,j}$, $\theta_{1,j}$ and $\theta'_{0,j}$ are the regression coefficients of the conditional beta regression model. The parameter set for each building typology consists of five regression coefficients, namely $\beta_{0,j}$, $\beta_{1,j}$, $\theta_{0,j}$, $\theta_{1,j}$ and $\theta'_{0,j}$. To determine the expected loss value, $E\left[DF_j\right]$, the logistical regression model and the conditional beta model are combined and given as follows (Ospina and Ferrari, 2012):

$$E[DF_j]=\mu_j.p_j \qquad (20)$$

where μ_j is computed from Equation 16 to Equation 19 and p_j is obtained from Equation 12. The desired predictions interval can be computed using:

$$P[X<x]=1+p_j.\left(F_X(x,\mu_j,\varphi_j)-1\right) \qquad (21)$$

Where $F_X(x,\mu_j,\varphi_j)$ is the conditional beta cumulative distribution function for a given building typology j. To determine the 90% upper bound for DF predictions, assume $P[X<x]$= 90% in Equation 21. Computed prediction interval that corresponds to ± one standard deviation in the standard normal distribution, through solving Equation 21 considering $P[X<x]$~0.16 and 0.84, as well as the mean curve plus one standard deviation given by Equation 21, are also shown. It should be noted that mean minus one standard deviation can provide negative DF, especially at low PGA, which has no meaning (negative loss). This fact explains why the beta model is preferable to

construct the statistical loss estimation model. For a detailed explanation about the ZIBR models and beta regression models and application on loss data, refer to (Bessason et al., 2022, 2020) and Ioannou et al. (2018).

5. Result and discussion

Following the ZIBR modelling instruction described above, the average vulnerability curves are developed statistically. In this regard, we fit the model to the building-by-building loss data of each identified building group. Overall, five ZIBR models are developed for two seismic code-based classes for RC and timber (W) buildings and one Masonry (M) building class, namely: RC-CDNL (CDN+CDL), RC-CDMH (CDM+CDH), W-CDNL, W-CDMH, and M-CDNL. Since most buildings experienced losses of less than 20%, and to remove outliers in the beta regression, all buildings with a loss exceeding 85% are assigned a maximum value of 0.85.

Figure 2 presents the average vulnerability curves as functions of PGA_{cor} for five building groups along with the distribution of observed data. In Figure 3, the developed models associated with different building groups are compared.

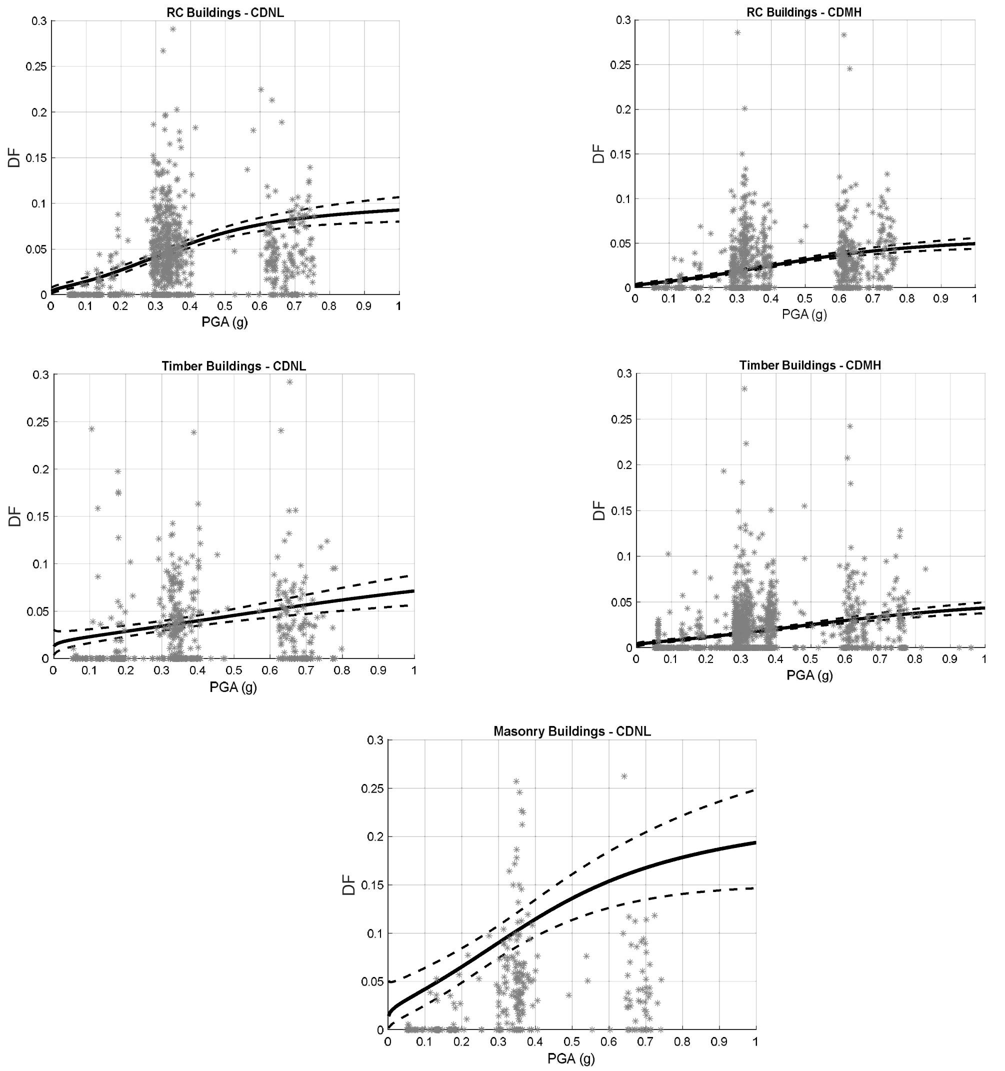

Fig. 2: Mean vulnerability curves (back solid line) and its 95% confidence intervals (dashed lines) as a function of PGA (g) obtained for 5 building groups (see the header) based on zero-inflated beta regression methodology. gray data points present the observed DF values versus their associated inferred

For PGA of 0.6g, the mean DF is estimated in the range of 4 to 8% for almost all building classes except for M-CDNL, which shows a larger DF. At a PGA of 0.6g, the average loss of newer buildings in CDMH class in the affected area is around 4% of the building replacement value, while this increases to an average of 7% for CDNL classes.

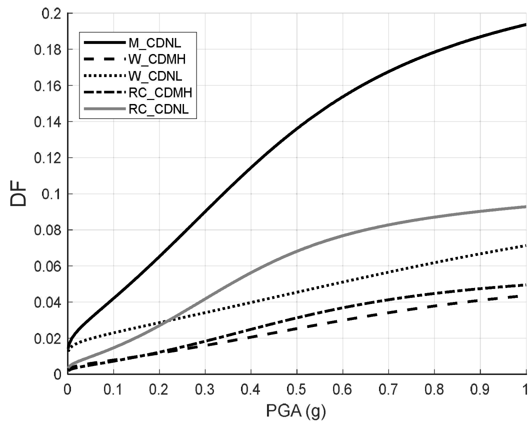

Fig. 3: comparison of vulnerability curves developed for the identified building groups

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