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THE DEVELOPMENT OF NEW BUILDING VULNERABILITY RELATIONSHIPs USING THE CEQID DATABASE

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Abstract: In literature, different vulnerability relationships exist which provide the probability of exceedance of a damage state given an intensity measure. Relationships can be obtained in different ways, using actual data or using mechanical models. This paper provides empirical vulnerability relationships starting from observed data that have been collected after different earthquakes and grouped in the Cambridge Earthquake Impact Database (CEQID). Relationships have been obtained for different building classes and for two different intensity measures (macroseismic intensity and peak ground acceleration). Moreover, analyses have been conducted considering two different probability density function distributions (binomial and beta) to define the probability of occurrence of a damage state given the intensity measure.

Introduction

Vulnerability relationships express the probability of damage or loss to a class of structures as a function of the ground motion excitation causing that loss. It is possible to distinguish between empirical and analytical vulnerability relationships. The former derive from damage observed in past earthquakes and they are assumed to be applicable to future events affecting the same class of buildings, the latter derive from mechanical models considering the response of a typical structure of a given class to increasing levels of ground motion. A third form of relationships derives from expert opinion, which are useful when there are not enough data for either of the two primary approaches, or when the goal is to extrapolate available data to other levels of ground shaking, or to other classes of structures (e.g. Jaiswal et al., 2011).

In this paper, attention is focused on empirical vulnerability relationships obtained through data assembled in the Cambridge Earthquake Impact Database (CEQID). This database has been developed at Cambridge Architectural Research Ltd with the support from the Coburn Foundation. Data refer to events which happened in different parts of the world; therefore they refer to different building classes and different damage states.

The purpose of this study is to utilize data present in CEQID, to obtain vulnerability curves in terms of probability of exceedance of different damage states. Because of the vastness and the huge differences of data in the database, the first goal was to group buildings as well as damage levels into homogeneous classes. Seven building classes and six damage levels, from 0 (no damage) to 5 (collapse) have been defined, corresponding to the damage states defined in EMS-98 (Grünthal, 1998).

To describe the probability that a certain class reaches a damage level given an earthquake of a certain intensity, different probability density functions may be used. In this work, both the binomial and beta distributions are considered while the intensity measures adopted to describe the ground shaking are the macroseismic intensity measure (MMI) and the peak ground acceleration (PGA).

The CEQID database

The Cambridge Earthquake Impact Database (CEQID) has been developed at Cambridge Architectural Research Ltd with the support from the Coburn Foundation. The Cambridge University Centre for Risk in the Built Environment (CURBE) has been involved in post-

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earthquake reconnaissance missions for over 25 years through the EEFIT UK group (www.eefit.org), and it has assembled documents recording damage surveys (its own and those of others) throughout this time.

Historically the data were made available through the mission-specific publication reports and through the research articles that discuss the observed damage and vulnerability of selected building classes (e.g., Spence et al. 2007). The CEQID database aims to assemble data referring to the post-earthquake building damage and casualty surveys which have been carried out all over the world since the 1960's into a single, organized, expandable and web-accessible format. Location maps and images of damage are provided for each earthquake event. The Database links to the U.S. Geological Survey (USGS, http://www.usgs.gov/) ShakeMap archive to add data on local macroseismic intensities and other measures of ground shaking.

The database is structured around 4 levels for web dissemination. At the top level the homepage shows a global map indicating epicentres of all earthquakes for which data are available, and lists the earthquakes by country and date. Currently the database includes data from 64 events, out of which, 24 were prior to 1990, 16 between 1990 and 2000, and 24 since 2000.

At the second level, by choosing a specific earthquake, some information such as date, time, magnitude, epicentral location and the USGS ShakeMap ID become available. These data are provided from the USGS National Earthquake Information Center (NEIC). In addition, this level provides a record of the total number of casualties caused by the event and a list of separate damage and casualty studies that are available within the database.

By choosing one of the studies listed, it is possible to access the third level. For each study the details of the damage level and building typology classification systems used during the survey are provided. The survey locations are also listed for quick assessment of geographic coverage of the study. Selected photographs (originally taken by the survey team) showing typical damage for that event are displayed. Documentation and reference material for the study is also provided.

At the fourth (final) level there are the detailed survey data for a particular location. Each survey is defined by the number of buildings suffering different levels of damage and it is presented in tabular form showing the number of buildings or as a fraction of total building stock that have exceeded a specific damage state. The latitude and longitude of the location (and an indication of its accuracy) and the observed or calculated ground shaking at that location are also shown. The survey data are accompanied by images showing examples of the damage at that location. A fuller description of CEQID is given in Spence et al. (2011).

Selection of data and events for analysis

The damage data assembled in CEQID are derived from a wide range of damage surveys in many different countries. Since inspections are conducted for different purposes, many different approaches are used both for classifying the types of buildings and the damage levels. The first step to carry out analyses was to assemble data both in terms of building typology and damage into homogeneous classes.

A total of 634,500 buildings have been considered and 7 different vulnerability classes (reported in Table 1) have been defined. Each class refers to a particular building typology. Class A refers to adobe (earth brick), fieldstone and rubble stone. Class B refers to simple stone or unreinforced masonry; class C considers unreinforced masonry with RC floors and RC structures with frame without earthquake-resistant design (ERD); class D1 considers structures with confined or reinforced masonry and RC structures with frame characterized by a moderate level of ERD; class D2 contains timber structures; in class E there are RC buildings with a high level of ERD; finally RC class contains all buildings where the only information available is that they are RC buildings, while no information is provided on their ERD. Classes A to E correspond to the vulnerability classes which are identified as most probable for each building typology in EMS-98.

Also damage data are very different, because post-earthquakes forms are very different for each country, and inspections are usually conducted for different purposes. For example, in some cases the grade D0 corresponds to a damage level null, in others D0 unifies structures undamaged with those with a slight damage; D5 sometimes considers only collapsed buildings while in other cases it refers to very heavy damaged structures. For this reason it is very important to read the description of each damage grade considered for the different post-earthquake surveys in order to create homogeneous damage classes. Moreover, many forms have as a goal the definition of the usability of the building and not the collection of damage typology therefore it should be difficult to associate the usability result to a damage level. In this work 6 damage classes have been defined referring to structural damages: 0 (no damage), 1 (negligible to slight), 2 (moderate damage), 3 (substantial to heavy damage), 4 (very heavy damage) and 5 (collapse), again following EMS-98.

It is important to note that it was not possible to use all data present in the database as in some cases the information on damage data was not associated to any damage grade. In fact, sometimes it was indicated that the structure was burned or tilted or the damage was not recorded rendering impossible an association between the information and the damage level of the structure. Moreover, in other cases the damage grade was not indicated or the building was already demolished before the survey, therefore its damage level was unknown. Among buildings, mixed structures and structures without a specific typology indicated in the database with the acronym “all” have been removed. Table 1 summarizes the different building types considered for the analyses and the number of buildings belonging to each class.

Table 1. Building type and number of buildings for each vulnerability class.

Class	**Building type**	**Number of buildings**
A	adobe (earth brick), fieldstone and rubble stone	68750
B	simple stone or unreinforced masonry	71007
C	unreinforced masonry with RC floors and RC structures with frame without earthquake-resistant design (ERD)	15347
D1	structures with confined or reinforced masonry and RC structures with frame characterized by a moderate level of ERD	9972
D2	timber structures	411712
E	RC buildings with a high level of ERD	7964
RC	are RC buildings, while no information is provided on their ERD	49748

Alternative ground motion parameters

An important aspect of vulnerability relationships is how the causative ground shaking is defined. For empirical vulnerability relationships, the ground motion is more commonly expressed in terms of macroseismic intensity (MMI). This is a useful measure of the ground motion intensity, because for I>6 it is defined largely through the average effect of the ground motion on building damage over an area. It can also be used to estimate ground motion from past data, when instrumental measures of ground shaking were unavailable. However, the use of macroseismic intensity involves three important difficulties. First, that ground motion intensity is defined in macroseismic intensity scales at discrete values (deliberately allocated Roman numerals VII, VIII, IX etc.). Secondly that there are many different macroseismic intensity scales in use, and also local variations in practice in applying these scales, meaning that vulnerabilities defined in terms of one scale are not necessarily transferable to others. Moreover, in the upper range of the scale (intensity VI or above on EMS-98), the mapping of intensity is derived primarily from observations of building damage. This means that the probability of damage (vertical scale) is not independent of the measure of ground motion (horizontal scale); and indeed empirical vulnerability functions based on observed macroseismic intensity as the ground motion parameter consist of no more than an elaboration of the intensity scale definitions of damage.

A way of avoiding this difficulty is to define MMI through correlation with instrumental ground motion values. The USGS PAGER group using MMI from the earthquake source parameters and existing GMPEs (e.g., Wald et al. 2011) has produced rapid post-event MMI maps. A ShakeMap is a near real-time map of ground motion and shaking intensity produced by an earthquake. They have been produced for all significant earthquakes worldwide since 2006, and more recently an archive of ShakeMaps for earlier events has been produced. These data have been used in conjunction with the earthquake damage data collected in the Cambridge Earthquake Impact Database to construct a new generation of empirical vulnerability relationships, as described below.

The ShakeMaps are also produced in terms of: peak ground acceleration (PGA); peak ground velocity (PGV) and 5% critically damped pseudo-spectral acceleration (PSA) at periods of 0.3s, 1s, and 3s.

The methodology used to produce the maps involves a systematic process to combine data acquired from seismic recording stations where available, with site geology and ground motion attenuation for the distance to the epicenter of causative fault. A uniformly spaced grid of "phantom" stations are created and peak ground motions are calculated for each station using Ground Motion Prediction Equations (GMPE) based on the magnitude and distance from the epicenter of causative fault. Site corrections and amplification factors are then applied to the stations based on geological or topographic maps and interpolation is carried out using the grid stations.

The ShakeMap methodology has adopted the use of MMI in two ways. Firstly, where there are adequate seismic recording stations, the peak ground motion values are converted to MMI and then interpolated. Secondly, in areas that lack ground motion recordings, macroseismic observations are obtained through various sources including USGS's Did you Feel It? (DYFI?) program; the observations are added to the ShakeMap intensity map. In addition, the intensity values are converted to peak ground motions using the inverted equations of Wald et al. (1999) and are used in the peak ground motion maps. A subsequent revision to this ground-motion and intensity interpolation scheme allows the combined use (through a weighted approach) of: direct observations of measured ground motions or reported intensities; converted observations (intensity to ground motion or vice versa); and estimated ground motions and intensities from GMPEs or intensity prediction equations (IPE) (Worden et al. 2010).

Alternative measures of damage and loss

Data collected from earthquakes that have caused significant damage give the opportunity to understand the performance of different types of structures. Empirical vulnerability curve derivations rely on post-earthquake surveys that are carried out in different locations and times, and the survey methods and forms vary accordingly, therefore, when data from different earthquakes are combined, they need to be converted or calibrated to a single damage scale.

When a destructive event occurs, buildings are in a range of damage states. After surveys it is possible to record damage state for each one and present results in the form of histograms showing the damage distribution for each building type. Such distribution is related to the intensity of ground motion and its mean value (the mean damage ratio, μ_D) can be evaluated using Equation 1, where $P\left[D=k\right]$ represents the probability of occurrence of a certain damage state, k .

$$\mu_D = \sum_{k=0}^{5} P\left[D=k\right]\cdot k \tag{1}$$

From the past earthquakes it has also been observed that for well-defined classes of buildings the damage distribution reasonably closely follows a binomial distribution (Equation

2). This distribution was successfully used for the statistical analysis of data collected after the 1980 Irpinia (Italy) earthquake (Braga et al., 1982).

$$P_K(k) = \frac{5!}{k!(5-k)!}\left(\frac{\mu_D}{5}\right)^k \left(1-\frac{\mu_D}{5}\right)^{5-k} \tag{2}$$

However, the simplicity of this distribution, which depends on only one parameter, μ_D, does not allow defining scatter of the damage grades around the mean value. Moreover, observations suggest that some building classes need a more complex description, that is, a more varied distributions, such as the beta distribution (Equation 3) that using two parameters (r and t) allows a more flexibility in the shape of the distribution to fit different circumstances (e.g. Coburn and Spence, 2002). In the equation, *Γ(x)* is the gamma function.

$$P_\beta(x) = \left(\frac{\Gamma(t)}{\Gamma(r)\cdot\Gamma(t-r)}\right)\cdot\frac{(x-a)^{r-1}\cdot(b-x)^{t-r-1}}{(b-a)^{t-1}} \quad a \le x < b \tag{3}$$

The mean value of the continuous variable x is expressed from the Equation (4) and it ranges between a and b.

$$\mu_x = a + \frac{r}{t}\cdot(b-a) \tag{4}$$

Considering that the damage grade is a discrete variable (5 damage grades plus the absence of damage) and as the mean value of the variable x ranges between a and b, it is advisable to assign 0 to parameter a and value 6 to the parameter b.
According to Olivera et al., (2006) the mean value μ_x (Equation 4) can be correlated to the mean damage grade through the following third degree polynomial expression (Equation 5).

$$\mu_x = 0.042\mu_D^3 - 0.315\mu_D^2 + 1.725\mu_D \tag{5}$$

Thus, by using Equations (4) and (5) it is possible to correlate the two parameters of the beta distribution, r and t, with μ_D (Equation 6) where the parameter t affects the scatter of the distribution; if $t=8$ is used, the beta distribution looks very similar to the binomial distribution.

$$r = t\cdot(0.007\cdot\mu_D^3 - 0.0525\cdot\mu_D^2 + 0.2875\cdot\mu_D) \tag{6}$$

Hence, it is possible to evaluate the probability of having each damage level setting $x = 0,1,2,3,4,5$ in Equation 3.

Alternative mathematical expressions of vulnerability relationships

The proposed form of the vulnerability curves in terms of probability of exceedance of a damage level is a cumulative normal distribution when the MMI is considered as intensity measure (Equation 7).

$$P[D \ge k \mid I] = \Phi(\alpha(I - I_0)) \tag{7}$$

While, when PGA is used, a cumulative lognormal distribution is adopted (Equation 8).

$$P[D \ge k \mid I] = \Phi(\alpha \ln(I/I_0)) \tag{8}$$

In the last two equations, k is a specific damage level, I is the intensity measure at the location, Φ is the standard normal cumulative distribution function, I_0 is the value of I

corresponding to the 50% damage state probability, α is a "slope" parameter specific to the vulnerability class. For each class and for each damage state, a set of parameters α, I_0, representing the average performance of a specific building type is determined using a regression process described below.

Regression analysis

The regression analysis is used to define parameters (α and I_0) of each vulnerability curve (Porter et al., 2007). Data are grouped into ranges of intensity measures. For each bin, the mean value of the probability of exceedance of each damage state is evaluated. This value is calculated weighting the probability of exceedance of each damage state with the number of surveys observed in each event belonging to that range.

The following step is to convert Equations 7 and 8 to a linear regression problem by taking the inverse Gaussian cumulative distribution function of each side and fitting a line to the data (Equation 9).

$$y = sx + c \tag{9}$$

In the above equation, s is the slope of the trend line and c is the value of y where the line has a x-value of 0 (the intercept). Parameters of vulnerability curves in Equations 7 and 8 are related to the fitting line; in fact, the α value correspond to s, while $I_0 = -c/s$.

It is to note that when Equation 7 is used, the I value is reported on the horizontal axis; whereas its logarithm is reported when Equation 8 is adopted.

Results

Vulnerability curves were carried out for the Super-building classes and the damage levels defined in Table 1. In fact, selecting a Super-building class, the CEQID analysis module gives the probability of exceedance of a specific damage grade from buildings belonging to that class, i.e. the number of cases where a given damage grade was exceeded as a ratio of the total number of buildings in the survey.

Considering the number of surveys present in each bin of the considered intensity measure, the mean value of the probability of exceedance of each damage level is evaluated and this value is associated to the mean value of the intensity measure of that bin. The result is a damage probability matrix (DPM) for that class. Hence, it is possible to calculate the probability of having each damage state (Equation 10) and the mean damage ratio (using Equation 1).

$$P[D = k] = P[D \geq k] - P[D \geq k+1] \tag{10}$$

As an example, Table 2 reports for the Super-building class "A", the different bins considered for the macroseismic intensities, the representative MMI value for each bin (MMI*), the number of surveys belonging to that range, the probability of exceedance of each damage grade and the corresponding mean damage ratio.

Table 2. MMI ranges, representative MMI value of each bin (MMI*), number of surveys for each bin, the probability of exceedance of each damage level and the mean damage ratio for the Super-building class “A”.

MMI range	MMI*	surveysIMMI	P(D>=D1)	P(D>=D2)	P(D>=D3)	P(D>=D4)	P(D>=D5)	μD
4.0-4.4	4.41	75	0.973	0.668	0.345	0.108	0.041	2.135
4.5-4.9	4.78	1282	0.964	0.587	0.228	0.103	0.039	1.921
5.0-5.4	5.25	5049	0.959	0.617	0.251	0.128	0.033	1.988
5.5-5.9	5.71	13949	0.933	0.606	0.273	0.13	0.044	1.986
6.0-6.4	6.23	15168	0.91	0.568	0.292	0.171	0.056	1.997
6.5-6.9	6.77	7343	0.935	0.643	0.372	0.154	0.054	2.157
7.0-7.4	7.16	7048	0.925	0.688	0.501	0.264	0.062	2.440
7.5-7.9	7.79	10658	0.851	0.537	0.383	0.179	0.033	1.983
8.0-8.4	8.22	1001	0.94	0.59	0.481	0.311	0.072	2.394
8.5-8.9	8.71	533	0.795	0.549	0.438	0.249	0.03	2.062
9.0-9.4	9.31	1833	0.964	0.824	0.71	0.499	0.151	3.147
9.5-9.9	9.9	4811	0.963	0.794	0.684	0.514	0.219	3.174

Once the mean damage grade has been calculated using the observed data, parameters of the binomial and beta distributions can be obtained (for the beta distribution $t = 8$ has been adopted) as well as the probability of exceedance of each damage state.

Hence, the regression process is used to obtain the parameters of the vulnerability curves. A synthesis of the results is shown in Tables 3 and 4, where the parameters of vulnerability curves at collapse are reported for the different building classes having used MMI and PGA as intensity measure respectively. Results are reported for both the binomial and beta distributions.

Table 3. Parameters of the vulnerability curves at collapse for the different Super building classes. The MMI is used as intensity measure.

MMI, DS=5				
Class	**Binomial**		**Beta**	
	α	**I_0**	**α**	**I_0**
A	0.16	19.78	0.18	19.92
B	0.18	21.21	0.2	20.86
C	0.22	21.19	0.23	21.3
D1	0.59	14.34	0.47	16.45
D2	0.67	13.42	0.47	15.68
E	0.43	16.03	0.39	17.4
RC	0.3	18.17	0.28	19.92

Table 4. Parameters of the vulnerability curves at collapse for the different Super building classes. The PGA is used as intensity measure.

PGA [g], DS=5				
Class	**Binomial**		**Beta**	
	α	**I_0**	**α**	**I_0**
A	0.6	2.67	0.7	2.54
B	0.48	4.75	0.61	4.03
C	0.63	4.32	0.79	3.61
D1	2.42	1.15	1.85	1.74
D2	0.89	3.20	0.98	2.97
E	2.63	0.76	2.43	0.92
RC	0.97	2.43	0.98	2.67

Figure 1 illustrates the vulnerability curves in terms of probability of exceedance of each damage state as a function of MMI. When this intensity measure is used, data were collected into half-intensity unit bins (e.g. 6.0≤I<6.5). Results show that differences between the vulnerability curves obtained using the binomial (solid lines) and beta distributions (dotted lines) are negligible. The same result is also found for the other building classes.

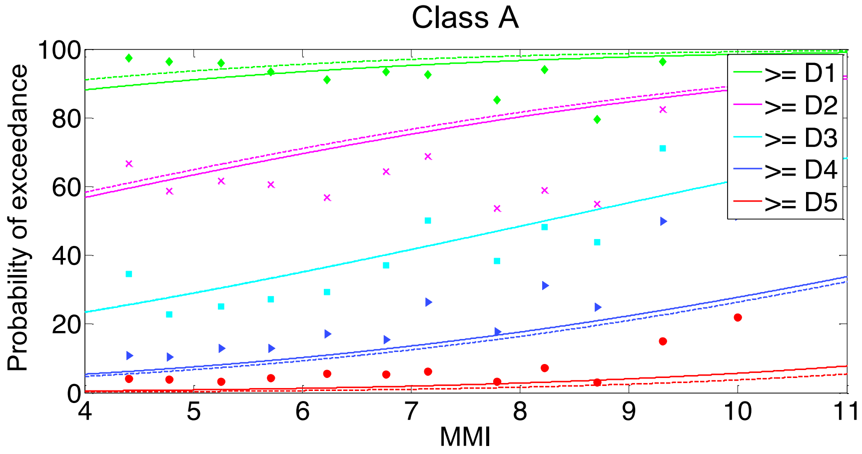

Figure 1. Vulnerability curves for the super-building class “A” as a function of MMI. The solid lines refer to vulnerability curves obtained using a binomial distribution while the dotted lines to a beta distribution. Points scattered represent the mean probability of exceedance of each damage level calculated for each bin using actual data.

Figure 2 shows the vulnerability curves in terms of PGA; data were grouped into bins of 0.05g. Also in this case small or negligible differences between the results corresponding to the probability distributions used in this study are detected.

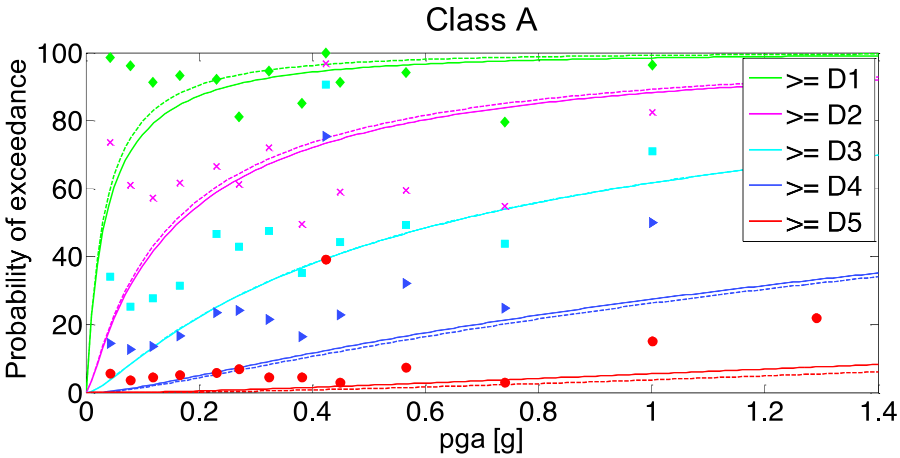

Figure 2. Vulnerability curves for the super-building class "A" as a function of PGA. The solid lines refer to vulnerability curves obtained using a binomial distribution while the dotted lines to a beta distribution. Points scattered represent the mean probability of exceedance of each damage level calculated for each bin using actual data.

However, it is to note that, both the distributions tend to underestimate the probability of exceedance of the highest damage states (D4 and D5). In fact, for both the intensity measures (MMI and PGA), the probability of exceeding one of these damage state is lower than the probability of exceedance calculated using the actual data. This behavior might depend on the choice of the regression process adopted to calculate the parameters of vulnerability curves, or, on the intensity value considered as representative for that bin.

Conclusions

Vulnerability curves are used to describe the probability of exceeding specific damage states as a function of the seismic intensity parameter. Relationships can be obtained in different ways, using observed data or mechanical models.

A methodology for deriving vulnerability curves using an empirical approach has been presented in this study. Analyses have been conducted on the basis of data referring to the post-earthquake building damage and casualty surveys which have been assembled in the Cambridge Earthquake Impact Database (CEQID). The analysis module present in it allows data defining Super-building classes and different damage states to be assembled. This operation permits all data present in the database to be homogenized. Hence, selecting a specific intensity measure, the number of buildings belonging to a specific class exceeding a specific damage level after each event, is provided. In this study 7 Super-building classes and 6 damage levels, from 0 (undamaged) to 5 (collapse) have been defined.

Vulnerability curves have been developed for both macroseismic intensity measure (MMI) and peak ground acceleration (PGA) and they were derived by using two analytical functions: cumulative normal and cumulative lognormal distributions. In particular, the former was used when the MMI is considered as intensity measure, while the latter was used when the PGA is adopted.

Starting from the number of buildings that have exceeded a specific damage state, a discrete distribution that represents the probability of reaching each damage level can be evaluated and the corresponding mean value (the mean damage ratio) can be assessed.

Hence, for all classes, the parameters of both binomial and beta distributions have been calculated and distributions have been used to evaluate the probability of exceedance of each damage level. Finally, a regression process is used to obtain the parameters of the vulnerability curves.

Results show that, binomial and beta distributions provide similar results even if they tend to underestimate the probability of the very heavy damage and collapse. This behavior may depend on the choice of the regression process adopted to calculate the vulnerability curve parameters, or, on the choice of the intensity value adopted to represent the bin of a range of intensity measures, and is to be investigated further.

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