A Compendium of Existing Vulnerability and Fragility Relationships for Flood: Preliminary Results

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ABSTRACT: In the last decade, probabilistic approaches for flood risk assessment have emerged, often as an extension of more consolidated methods used in probabilistic seismic risk assessment. Nonetheless, only a few studies deal with best-practice methodologies for flood vulnerability assessment and existing approaches lack of an appropriate guidance for their selection. These concerns underline the need for a rational, integrated and complete compendium of all the existing flood-related vulnerability and fragility relationships to be used in a comprehensive probabilistic flood risk assessment framework. Following the same approach used in the guidelines recently developed by the Global Earthquake Model (GEM) Project, this paper presents a preliminary review of the state-of-art regarding existing empirical vulnerability and fragility curves in the context of flood risk. In particular, a worldwide overview is intended in terms of data sources, assets features and also statistical techniques employed for data collection and fitting. The research aims at providing a complete and flexible guide for selection of vulnerability and fragility curves for building structures. A discussion on data sources, building classification and considered features, and damage scales is presented, in order to evaluate the reliability, and at the same time the limitations, of different approaches and provide recommendation for future studies.

1. INTRODUCTION

One-third of the economic losses due to natural disasters in Europe are due to flooding, which is one of the most frequent natural hazards with wind storms (e.g., Munich Re, 2005; EEA et al. 2008). Quantifying the potential impact of flood on portfolios of properties located in flood-prone regions is of primary interest to property owners, insurance and reinsurance companies, and local government agencies. It is critical that potential loss estimates, on which risk management and possible mitigation decisions are based, are as accurate as possible given the available information.

Probabilistic catastrophe loss models are becoming increasingly popular tools for estimating potential loss due to natural hazards. Such models incorporate detailed databases and scientific understanding of the highly complex physical phenomena of natural hazards and engineering expertise about how buildings and their contents respond to those hazards (e.g., Grossi and Kunreuther, 2005). Until the 1980's, loss estimates to property portfolios associated with natural catastrophes such as earthquakes, storms, and floods were usually extrapolated from historical loss data. Nevertheless, the limited span covered by historical catalogs, the lack of systematically gathered loss data, and the changes in terms of exposure in high risk regions have led to severe underestimation of such losses. As a result, purely actuarial approaches (e.g., based on claims data as in the case of automobile or fire insurance policies) for the estimation of losses generated by rare natural catastrophes were abandoned in favor of models integrating all the relevant science, data, and engineering knowledge. Moreover, as uncertainty lies at the heart of catastrophe risk modeling, it requires an appreciation at all modeling stages. Thus, a probabilistic approach is the most appropriate method to model the complexity of catastrophes. Within catastrophe risk modeling, several different approaches have been developed to link hazard intensities to the expected level of damage (fragility) or, more ambitiously, directly to the level of monetary loss (vulnerability). In particular, vulnerability functions express the likelihood that assets at risk will sustain varying degrees of loss (e.g., in terms of direct damage) over a range of hazard intensities. In some cases, developing vulnerability relationships requires the use of (1) fragility functions, expressing the likelihood of different levels of damage (i.e., damage states) sustained by a given building class over a range of hazard intensities, and (2) damage-to-loss functions, which convert the damage estimates to loss estimates.

Vulnerability and fragility functions are both derived from statistical analysis of loss/damage values which are recorded, simulated or assumed over a range of hazard severities. In practice, loss/damage statistics can be obtained from observation of past events (empirical approaches), analytical or numerical studies, expert judgment, or a combination of these (hybrid approach). Empirical approaches based on post-event surveys of the performance of asset classes are commonly regarded to be the most reliable source of loss/damage statistics due to the fact that they are based on real observations. Despite the fact that considerable efforts have been spent and progress has been made on post-flood damage data collection/post-processing and model development in recent years, the main challenge in using available models for future applications is how to identify and, if necessary, combine suitable vulnerability and fragility curves with different characteristics and, often unknown, reliability (Rossetto et al., 2014).

Following the same approach used in the bulk of research developed by the Global Earthquake Model (GEM; e.g., Rossetto et al., 2013, 2014), the study presented here aims at addressing this challenge by presenting a preliminary review of the state-of-art regarding existing vulnerability and fragility in the context of flood hazard with special focus on empirical approaches.

2. FLOOD RISK MODELING

Flood is probably the most challenging to model among all the natural perils because of the complexity at each stage of the flooding process, from the precipitation forcing to the inundation at each locations and the estimation of the damage to buildings and contents and resulting consequences in terms of financial losses and business interruption. This complexity can be tackled with a modular approach comprising four modules (i.e., *hazard*, *exposure*, *vulnerability*, and *loss*; e.g., Grossi and Kunreuther, 2005). The starting point for flood loss assessment is the quantification of the flood hazard in order to produce flood depths, or any other relevant intensity measure (IM) in the flood plain-of-interest. Although different types of flooding (e.g., mainstream, flash, and overland) behave differently, flood-related damage fundamentally results from the depth and duration of inundation as well as the water velocity.

In the hazard module, large catalogs comprising tens of thousands of computer-simulated precipitation events are generated (*event generation* sub-module), representing the broad spectrum of plausible events. For each stochastic event, the total and effective runoff per catchment area is calculated, accounting for topographic and antecedent conditions, by implementing a detailed hydrologic model that converts precipitation to discharge and is calibrated and validated based on the available data. Next, a detailed hydraulic model is used in conjunction with the hydrologic model output to define a flow versus depth relationship, i.e. a rating curve, for each location of interest (*local intensity* sub-module). Typically, one-dimensional or two-dimensional hydraulic models are used for flood hazard mapping in flood risk assessment. In general, the level of suitability of a given assessment method depends on the characteristics of the area under study but also on the study's requirements and the availability of data (e.g., Apel et al., 2004). The vulnerability module estimates damage and downtime caused by flood to assets of interest. The extent of damage, repair and cleaning costs depends on many factors including debris load and silt in the water, house location and its orientation to any flow, spacing of houses (influencing the flow velocity between buildings), materials used and construction detailing, and how quickly the house may be cleaned and completely dried out after a flood. Occupancy classes have an effect as well since they can help determine the design level, the contents of a building and its cellar (if present), and which local standards for flood defenses may apply to the property. Downtime, namely the time window during which the flooded area cannot be used, also depends on the occupancy class of the building.

3. EXISTING METHODS FOR DEVELOPMENT OF VULNERABILITY AND FRAGILITY CURVES RELATED TO FLOODING

Vulnerability and fragility relationships correlate loss and damage, respectively, to flood intensity. In developing flood damage models and vulnerability functions, two main approaches can be distinguished in the literature: (i) empirical approaches which use damage and/or loss data collected after flood events, and (ii) synthetic approaches, which are based on expert judgment and use damage and/or loss data collected via *what-if* questions.

Empirical vulnerability functions can be constructed directly from past flood observations of losses collected over sites affected by different intensities of flood. If the IM level has not been recorded at each site, one can be assigned using a hydraulic model (eventually combined with a hydrological model). Regression approaches are used to estimate the parameters of a chosen functional form to fit the data. The main assumption in the development of empirical vulnerability and fragility relationships is that past damage suffered by a particular asset class is representative of the damage that might happen in the future to a similar asset class subjected to a similar flood event. In practice, this assumption essentially limits the applicability of empirical vulnerability and fragility functions to the assessments of locations and buildings in geographical proximity to where the empirical data was collected. This poses a problem for their use in flood assessments in some countries as there is not an equal distribution of vulnerability and fragility relationships for buildings worldwide. For example in the case of buildings, the vast majority of empirical fragility curves have been derived for Australia, Germany and Japan, as discussed later in the paper.

What-if analyses estimate the damage which is expected in case of a certain flood situation, e.g.: "*Which damage would you expect if the water depth is 1 m above the building floor*?" (Merz et al., 2004).

Recently, analytical approaches based on structural engineering principles (load and resistance approach) have been proposed. Such approaches use a computer-based model of the structure or a structural component of interest to increasingly apply forces due to floodwater while observing the building performance (flood demand). Three main types of forces due to floodwater are usually considered in analytical approaches to damage estimation: (1) hydrostatic forces associated with pressure of still water which increase with depth, (2) hydrodynamic forces associated with pressure due to energy of moving water, and (3) impact forces associated with floating debris moved by water.

The flood demand at a given IM level is compared to the capacity of each structural component of interest and the conditional probability of demand exceeding capacity for the given value of IM is determined. Examples of such a procedure can be found in De Risi et al. (2013) and Kelman and Spence (2003).

3.1. Factors Affecting the Reliability of Empirical Vulnerability and Fragility Curves

Post-flood loss and damage databases can be associated with problems such as incompleteness, misclassification errors, small sample sizes, large aggregated building classes. In empirical vulnerability and fragility relationships therefore, large epistemic uncertainties can be introduced by the low quantity and/or quality of typical post-flood damage databases and the inability to account for the complete characteristics of the flood event in the selection of a particular IM. Furthermore, existing studies typically do not appropriately communicate the overall uncertainty in vulnerability and fragility functions and often cannot distinguish the effect of the two components, i.e. aleatory and epistemic. The main categories of factors affecting the reliability of empirical vulnerability and fragility relationships are summarised in Table 1. The quality of the damage data is the most important determinant for reliability of an empirical vulnerability or fragility relationship. Even large damage databases may contain errors or may be associated with a low degree of refinement in the definitions of damage scales and building classes. Post-flood damage data at a building-by-building level is not always available. Instead, the damage data is presented in aggregated form, often over geographical areas of varied size (e.g. a zip-code, village, district or town). In the latter case, the geographical area is assumed to have a constant flood intensity value, which is typically evaluated at its centroid. However, if the geographical unit is large there is likely to be a large variation in the IM values across the unit which is not typically accounted for. The variation of the selected IM over a geographical unit and uncertainty in the estimation of the IM at a site that arises from the use of hydrological/hydraulic models contribute to the uncertainty associated with the IM determination at a site of damage evaluation. No existing study has yet taken this into account and all adopt statistical models that assume that the IM is known with certainty. The damage scale used to collect the damage data from the field is important in determining the potential for misclassification errors and the usefulness of the developed relationship.

Table 1. Categories of factors determining the reliability of empirical vulnerability and fragility relationships.

Factors	**Description**
Intensity Measure	Hazard parameters and their spatial resolution. IM estimation method (e.g. hydraulic model or recorded).
Damage Characterization	Damage scale; consideration of non-structural damage. Number of damage states (DS).
Class definition and sample size	Sample size (size of database and completeness). Single or multiple building classes.
Data Quality/Quantity	Post-flood survey method. Coverage, response and measurement errors in surveys. Quantity of data (e.g. number of buildings or loss observations). Number of flood events, range of IM and DS covered by data.
Derivation Method	Data manipulation or combination. Statistical modeling. Treatment of uncertainty (sources of uncertainty, quantification).

In general terms, a damage scale that describes unambiguously a number of damage states in terms of structural and non-structural component damages will result in a more reliable and useful empirical fragility curve. Moreover, due to the nature of flood, the empirical data is typically seen to be clustered in the low-damage and low-IM ranges. This means that extrapolations of vulnerability and fragility relationships to the high-IM range may be unreliable. As a matter of good practice, empirical vulnerability and fragility relationships should not be used to estimate damage and loss outside the range of IMs of the data that has been used in their derivation. Finally, different statistical modeling approaches have been used by existing studies to fit parametric functions to their empirical data.

4. COMPENDIUM OF EXISTING EMPIRICAL VULNERABILITY AND FRAGILITY CURVES FOR FLOOD

A number of vulnerability and fragility relationships have been developed from post-flood data, mostly by individual researchers or small research groups rather than a united research community. A preliminary version of a compendium of existing vulnerability or fragility functions has been compiled here and a summary is presented in Table 2. For the developed compendium, there are 26 fields (i.e., columns) related to 6 categories, see Table 3. Each record in Table 3 (i.e., row) provides information regarding the vulnerability or fragility functions obtained by an existing study.

Table 2. Basic information provided in the compendium of existing vulnerability and fragility relationships.

General category	**Field**	**Description**
Existing study	Reference	
	Type of assessment	Type of assessment followed by the study, e.g., fragility or vulnerability.
	Source	The methodology used to obtained the functions, e.g., empirical, or synthetic.
Damage and loss measures	Damage scale	The main damage scale adopted by the study (if applicable).
	No. of DSs	Number of damage states used by the main damage scale.
	Loss parameter	
Building classification	Construction material	
	Structural system	
	Type of foundation	
	Age/Year of construction	
	No. of stories	
	Floor material	
	Walls material	
	Percentage of openings by floor	
	Presence of basement	
	Flood design?	Does the building class account for any flood design?
	Occupancy class	
Flood intensity	Intensity measure	The flood intensity measure used by each study.
	Range of IM	Range of IM values of the data.
	Main IM estimation method	Recorded/surveyed or simulated (hydraulic modeling).
Data quality/quantity	Country/ies	Name of the country of each dataset used.
	Source of the data	Source/s of data, e.g., flood event.
	No. of assets	Number of buildings used for the construction of the relationship.
	No. of data points	Number of data points used for the construction of the regression analysis.
Method	Functional form	Type of function, e.g., mean curve or probability distribution.
	Type of analysis	The analysis used by the examined study, i.e., regression, univariate distribution fitting.

Table 3. Compendium of existing vulnerability and fragility relationships.

REFERENCE	EXISTING STUDY		DAMAGE AND LOSS MEASURES			BUILDING CLASSIFICATION										FLOOD INTENSITY			DATA QUALITY				METHOD	
	Type of assessment	*Source*	*Damage scale*	*No. of DSs*	*Loss parameter*	*Construction material*	*Structural system*	*Foundation*	*Age*	*No. of storeys*	*Floor/Walls material*	*Percentage of openings*	*Presence of basement*	*Flood Design*	*Occupancy class*	*Intensity measure*	*Range of IM*	*IM estimation method*	*Country/ies*	*Source of data*	*No. of assets*	*No. of data points*	*Functional form*	*Type of analysis*
Apel et al. (2004)	V	E	–	–	L	na	na	na	na	na	na	na	na	na	residential industrial	IV	0 - 120×10^6	HD	Germany	Elbe and Danube river basins (2002)	na	na	MC	UDF
Büchele et al. (2006)	V	E	–	–	DR	na	na	na	na	na	na	na	Yes	Yes	residential	WD	0 - 1.5	HD	Germany	Elbe and Danube river basins (2002)	1697	na	MC	R
Chang et al. (2008)	V	E	–	–	L	na	na	na	na	na	na	na	na	na	residential	WD	na	S	Taiwan	Keelung river basin (2001)	302	na	MC	R
Dutta et al. (2003)	V	E S	–	–	DR	C WD	F	na	na	up to 6	na	na	na	na	residential non-residential	WD	0 - 6	HD S	Japan	Ichinomiya river basin (1996)	na	na	MC	na
Gissing & Blong (2004)	V	E	–	–	L	na	na	na	na	na	na	na	na	na	commercial	OFD	0 - 3	S	Australia	Kempsey (2001)	94	na	MC	R
Jonkman et al. (2008)	V	E	–	–	DR	na	na	na	na	low-rise mid-rise high-rise	na	na	na	na	residential commercial	WD	0 - 4.5	HD	Netherland	Meuse river basin (1993)	na	na	MC	na
Herath (2003)	V	E S	–	–	DR	WD nonWD	na	na	na	na	na	na	na	na	residential industrial	WD	na	HD S	Japan	Ichinomiya river basin (1996)	na	na	MC	na
Kreibich et al. (2009)	V F	E	Schwarz and Maiwald (2012)	5	L	na	na	na	na	na	na	na	na	na	residential	WD H	na	HD	Germany	Elbe and Mulde river basins (2002)	na	na	na	na
Merz et al. (2004)	V	E	–	–	DR	na	na	na	na	na	na	na	Yes	na	residential historical	WD	0.5 - 4	S	Germany	Events during 1978-1994	4000	na	MC	R
Nascimento et al. (2006)	V	E	–	–	L	na	na	na	na	na	na	na	na	na	residential	WD	0 - 3.5	S	Brazil	Itajuba' (2000)	469	na	MC	R
Schwarz & Maiwald (2009; 2012)	F	E	Developed by the authors	5	na	C M	F W	na	existing new	na	na	na	Yes	na	residential	WD H	na	S	Germany Chile	Saxony (2002) Dichato (2010)	na	na	MC	R
Smith (1994)	V	E	–	–	L	M	na	na	existing	1	na	na	na	na	residential	WD	0 - 2	S	Australia	Sydney (1986)	71	na	MC	na
Tang et al. (1992)	V	E	–	–	L	WD nonWD	na	na	na	na	na	na	na	na	residential commercial industrial	FD WD	na	S	Thailand	Bangkok (1983)	3522	na	MC	R
Zhai et al. (2005)	V F	E	Developed by the authors	1	DR L	WD nonWD	na	na	existing	up to 3	na	na	na	Yes	residential	WD	0 - 2.1	S	Japan	Tokai area (2000)	3036	na	MC PD	R

Explanatory legend. In "Existing study", Type of assessment: F = fragility or V = vulnerability; Source: E = empirical or S = synthetic. In "Damage and loss measures", DR = Damage Ratio, repair cost vs replacement cost or L = loss, i.e. repair cost. In "Building classification", Construction material: M = Masonry or C = Concrete or WD = Wood; Structural system: F = frame or W = wall. In "Flood intensity", Intensity measure: WD = Water Depth [m] or OFD = Over-floor depth [m] or H = specific energy height [m] or FD = flood duration [days] or IV = inflow volume [m^3]; Main IM estimation method: S = surveyed or HD = hydrological/hydraulic model. In "Method", Functional form: MC = mean curve or PD = probability distribution; Type of analysis: R = regression or UDF = univariate distribution fitting.

The compendium contains 17 functions; vulnerability functions constitute approximately 88% of these functions. Of the included 15 vulnerability relationship, 13 are obtained based on empirical approaches while 2 are derived based on synthetic approaches. As expected, all these functions have been constructed for only a few flood-prone countries, in particular Australia, Germany and Japan. It is worth noting that 'big models' such as Anuflood (Australia), FLEMO (Germany), HAZUS MH (USA) and Multi-Coloured Manual (United Kingdom) have deliberately not been included in this first version of the compendium since (1) they have already been widely reviewed in several similar studies (e.g., Jongman et al., 2012; Merz et al., 2010) and, (2) they require a much broader discussion which contrasts with the space limitation in this paper.

As shown in Table 3, the different relationships have been constructed for building classes defined predominantly (but not always) via construction material and number of stories. Other important factors affecting vulnerability and relevant in an exposure taxonomy for flood are often not properly considered, e.g., type of foundations, type of floors and walls, etc. Moreover, it is possible noting that most relationships are based on data from a single flood event/river basin. As such, those relationships often cover a small range of IM levels and typically contain few observations for high level of loss or damage. Finally, details on the statistical modeling used and the treatment of the uncertainty are often not properly addressed in the existing studies.

5. CONCLUDING REMARKS

This paper presents (1) an overview on catastrophe risk modeling, with emphasis on flood risk assessment and the methods to develop vulnerability and fragility relationships for flood, and (2) a preliminary database of existing relationships found by the authors in the literature. Despite the number of relationships available, it is noted that their quality and geographical applicability may significantly vary. More specifically, existing empirical vulnerability and fragility relationships are typically based on databases associated with important quality issues, which include low level of refinement/details on the building class and damage states (if considered), scarcity of observations, especially at high flood intensities and damage states. Furthermore, there is no consensus in the literature concerning the functional form of empirical vulnerability and fragility functions or on best-practice methodologies for modeling and communicating the uncertainty related to those functions.

These observations highlight the need for improved protocols for the collection of loss and damage data in post-flood scenarios, in order to provide a sound basis for derivation of future empirical vulnerability and fragility relationships. There is also an urgent need for a rational, statistically correct, widely accepted approach to be developed for construction of empirical fragility and vulnerability, which explicitly quantifies and models the uncertainty in the data and clearly communicates the uncertainty in the considered models.

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