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VULNERABILITY ASSESSMENT OF MULTI-HAZARD EXPOSED BUILDING TYPES –AN EMS-98 BASED EMPIRICAL-STATISTICAL METHODOLOGY

H. Maiwald[(1)], J. Schwarz[(2)]

[(1)] *Senior Researcher, Earthquake Damage Analysis Center (EDAC), Bauhaus-Universität Weimar, Germany, holger.maiwald@uni-weimar.de*

[(2)] *Head, Earthquake Damage Analysis Center (EDAC), Bauhaus-Universität Weimar, Germany, schwarz@uni-weimar.de*

Abstract

The European Macroseismic Scale EMS-98 provides robust tools for the damage classification and evaluation of the vulnerability of buildings under earthquake action.

The vulnerability table of the EMS-98 is an attempt to categorize the strength of structures in a manageable and simple way, taking into account both, building type or structural system and other vulnerability affecting factors (e.g. quality of workmanship, state of disrepair, irregularities of shape, layout, design “defects”). Based on the engineering experience from real observed damage cases characteristic vulnerability classes are defined for different building types; whereas most likely, still probable and exceptional cases have to be considered

The basic methodology of the EMS-98 is also transferable to other natural hazards such as flood, tsunami and storm. This allows a unified approach for the consideration of the building vulnerability in the sense of a multi-hazard approach.

For the transfer of this concept to other natural hazards and also in the context of development of the "International Macroseismic Scale (IMS)" a (still missing) mathematically supported approach is required to classify the individual building types into their characteristic vulnerability classes as well as to define the range of scatter of assignments for the individual building types provided by empirical-statistical relationships. At international level, regional variations of building types are known; their vulnerability, however, has not been evaluated in a systematic manner.

This paper presents the refinement of a methodology which allows the specification of the most likely vulnerability classes for the different building types on the basis of damage data and existing observations. As an extension to former studies the "probable range of scatter" and the ranges for the "exceptional cases" are determined by applying beta distributions.

The developed methodology enables the assignment of previously unclassified building types into the system of vulnerability classes with the related range of scatter. The basic elements of the procedure are stepwise methodically developed. Practical application is demonstrated for the natural hazards earthquake and tsunami. The differentiation of individual building types into vulnerability classes (in form of vulnerability tables) is presented for both natural hazards in a comparative way.

Keywords: vulnerability classes; vulnerability table; vulnerability function; beta distribution

1. Introduction

The vulnerability tables included in the EMS-92 [1] and EMS-98 [2] are the basic element for evaluating the vulnerability of the individual building types. Following this intensity based concept developed for earthquake impacts, the method of vulnerability tables can be transferred as a tool to analyze multiple natural hazards. The assignment and adjustment of vulnerability classes are based in an empirical basis and the more or less generalized observations of the damage to different building types. Differences in the observations are maintained and indicated by a rough description of a comprehensive statistical diagnosis in terms of the "most likely" vulnerability classes and the "probable" or "less probable, exceptional" ranges of their occurrence.

The objective of this paper is the development of a unified analytical (mathematical justified) concept for determining the scatter of the vulnerability classes for the individual building types taking into consideration that characteristic differences in the damage progression with the increase of impact level might require an intensity-dependent reference system of vulnerability assignments.

Table 1 gives an overview of possible combinations of symbols for identifying the range of scatter and characterizes those actually included in the EMS-92 [1] and EMS-98 [2]. The presence and the size of the different ranges of scatter by the individual building types depend on several factors. However, the issues discussed in the following are also applicable to the (still to be determined) assignment of vulnerability classes of new building types [3]; in particular, they are transferable to other natural hazards.

- A non-existing range of scatter (No. 1 in Table 1) indicates very homogenous damage patterns (equal damage grades) of the individual damage cases under similar impact. Building types where the same damage levels can be observed for most damage cases have small ranges of scatter of (± 1) vulnerability class (No. 2 to 9 in Table 1). Variations in some cases to higher or lower damage grades can occur due to differences in the building construction.
- Large ranges of scatter from ± 2 vulnerability classes (No. 10 to 21 in Table 1) stand usually for roughly classified building types (e.g.: masonry in general). Consequently, within the EMS-98 [2] some building types (e.g. adobe, wood) would benefit from a further sub-classification and require a more detailed consideration of the existing (regionally different) construction techniques. These wide ranges of scatter are also typical for building types with larger uncertainty in the buildings construction. Thus, according to the EMS-98 [2] for example reinforced concrete frame systems can have in the worst case a similar behavior like adobe building types.
- However, these large ranges of scatter may also be a result of a partially inaccurate assignment of building types, which cannot be avoided, for example in air-frame-based or satellite photo-based damage surveys. A good example for these can be found in the behavior of the documented damage cases by the 2004 tsunami in the Indian Ocean. Some of the building classes introduced by the SCHEMA-Project [4] show $\pm 1\sigma$- standard deviations up to two damage grades with respect to the mean damage grade D_m. This would result in very large ranges of scatter in the (still to be defined) tsunami vulnerability classes. The originally resistant assessed building class D shows in [4] also a higher vulnerability (higher damage states) as the buildings of class B and C. In this case a reclassification of the vulnerability classes would be required. This indicates very clearly the demand for a coherent concept for the differentiation between building type classes and vulnerability classes as defined in the EMS-98 [2].

Based on empirical data, it was explained in [5] and [6] how vulnerability classes can be assigned and how the concept can be transferred to other natural hazards. In this study, the proposed concept is extended to determine the ranges of scatter in the vulnerability classes of the individual building types; it is practically further refined on the basis of damage data gained from field survey of recent earthquake and tsunami events.

In the paper the necessary statistical parameters for a suitable distribution function (beta distribution) are derived, which allow the specification of the ranges of scatter in the vulnerability classes of the individual building types. This unified (mathematically justified) concept for the description of the building vulnerability enables in perspective simulative risk analyses considering the ranges of scatter in the vulnerability with respect to the individual natural hazards.

Table 1 – Possible elements of vulnerability table

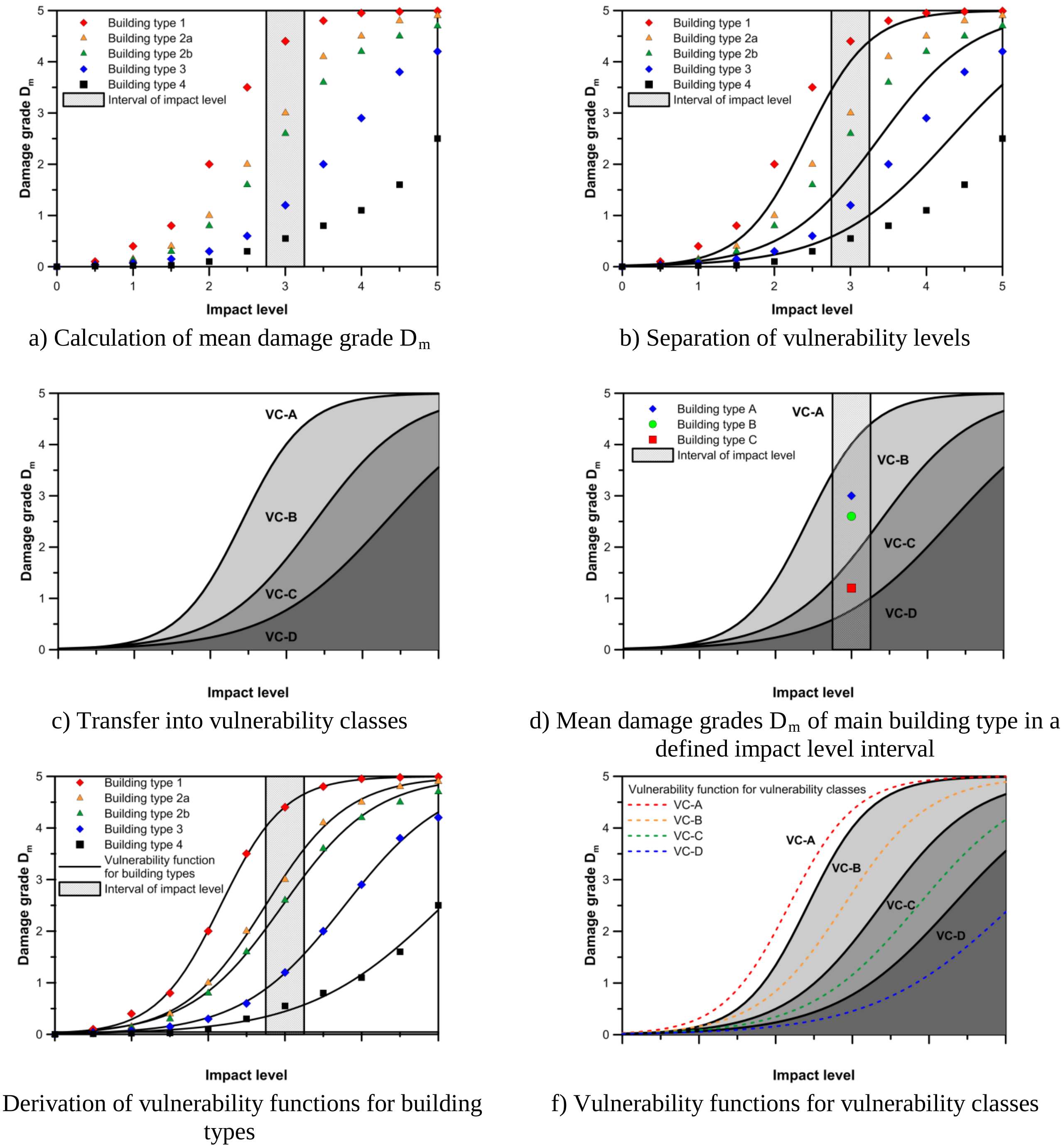
No.	Ranges of scatter in Vulnerability Classes					Earthquake		Tsunami (see proposal in Table 3)
	-2	-1	0	+1	+2	EMS-92 [1]	EMS-98 [2]	
1			○			Masonry, rubble stone, fieldstone	Masonry, rubble stone, fieldstone	-
2			○	···|		Masonry, adobe (earth brick)	-	-
3			○	—|		-	Masonry, adobe (earth brick)	-
4		|···	○			Masonry, simple stone	Masonry, simple stone	-
5		|—	○			Masonry, unreinforced brick with RC floors RC with high level of ASD	-	-
6		|···	○	···|		Masonry, unreinforced brick / concrete blocks	Masonry, unreinforced, with manufactured stone units	-
7		|···	○	—|		-	Masonry, reinforced or confined RC walls: without ERD with moderate level of ERD with high level of ERD	-
8		|—	○	···|		Masonry, massive stone	Masonry, massive stone Masonry, with RC floors	-
9		|—	○	—|		-	-	Steel structures
10			○	——	···|	-	-	-
11			○	——	—|	-	-	-
12	|···	——	○			RC with minimum level of ASD RC with moderate level of ASD	-	-
13	|——	——	○			-	-	-
14	|···	——	○	···|		-	RC frame: without earthquake resistant design (ERD) with moderate level of ERD with high level of ERD	RC structures
15	|···	——	○	—|		RC without antiseismic design (ASD)	Steel structures, Timber structures [RC, see Table 2]	-
16		|···	○	——	···|	Masonry, reinforced brick (confined masonry)	-	Wooden structures
17		|—	○	——	···|	-	[Masonry, see Table 2]	-
18	|···	——	○	——	···|	-	-	-
19	|···	——	○	——	—|	Wooden structures	-	Lightweight steel frame
20	|——	——	○	——	···|	-	-	-
21	|——	——	○	——	—|	-	-	-

○ most likely vulnerability class; — probable range; ···· range of less probable, exceptional cases

2. Definition of vulnerability classes and range of scatter – basic procedure

2.1 Separation of vulnerability levels

The developed procedure to determine vulnerability classes and classify the various building types on the basis of empirical damage data was first introduced in [5] for the flood impact and generalized in [6] and [7] for different natural hazards. The differences in the mean damage grades D_m of the individual building types (Fig. 1a) are used to separate vulnerability levels (Fig. 1b). Those can be regarded as expectation ranges for the mean damage grades D_m of the individual vulnerability classes (Fig. 1c).



a) Calculation of mean damage grade D_m

b) Separation of vulnerability levels

c) Transfer into vulnerability classes

d) Mean damage grades D_m of main building type in a defined impact level interval

e) Derivation of vulnerability functions for building types

f) Vulnerability functions for vulnerability classes

Fig. 1 – Concept for the classification of vulnerability classes and the derivation of vulnerability functions (on the basis of a fictitious dataset; c.f. [5], [6], [7])

2.2 Definition of the most likely vulnerability class

Still not assigned building types can be classified into the corresponding vulnerability class by the position of sufficiently statistically based data points of D_m (Fig. 1d). For the prediction of the mean damage grade D_m the vulnerability functions for the different building types are described according to Eq. (1) and (2). They can be derived by the regression of the data points (Fig. 1e). These functions define by their location or their progression also the "most likely vulnerability class". Finally vulnerability functions for vulnerability classes (Fig. 1f) can be specified for a unified damage prognosis.

2.3 Definition of the probable and the less probable range using the beta distribution

The proposed method in [6] uses the ±1σ standard deviation for the definition of the "probable range" in the vulnerability of the individual building types. However, the "range of less probable, exceptional cases" cannot be determined. Therefore, it seems more target-orientated, to use the quantiles of a suitable distribution function for this purpose.

According to [8] and [9] the beta distribution is an appropriate distribution function for the description of the scatter in structural damage due to earthquakes. The variance σ_D^2 and the expected value E(x) of the considered random variable x are required for the calculation of the moment estimators of the beta distribution [10].

The expected value E(x) will be described here with the mean damage grade D_m. It can be determined from the damage data for appropriate impact intervals respectively with vulnerability functions. In this study the general mathematical formulation of the vulnerability functions using a hyperbolic tangent function follows Eq. (1) and (2).

$$D_m = \left(\frac{D_{ub} - D_{lb}}{2}\right) \cdot \tanh(f(x)) + \left(\frac{D_{ub} + D_{lb}}{2}\right) \tag{1}$$

D_{lb} – lower bound of Damage grade (D_{lb}=0 for earthquake, D_{lb}= 1 for tsunami)

D_{ub} – upper bound of Damage grade (D_{ub}=5 for earthquake, D_{ub}= 6 for tsunami)

D_m – Mean damage grade

x – impact parameter (acceleration, water level h, indicator for flow force h x v^2)

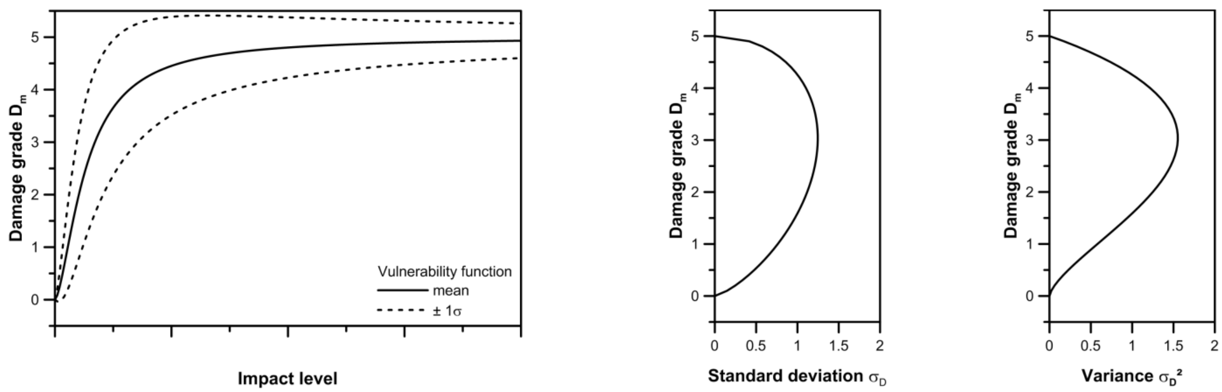
$$f(x) = A \cdot \log_{10}(x) + B \tag{2}$$

A, B – control parameters

The regression variants (as presented in [8]) enable the derivation of a prediction model for the variance σ_D^2. The variance σ_D^2 can be determined for the same impact intervals from the damage data in dependence on the corresponding mean damage grade D_m. In the present study, an asymmetrical power function according to Eq. (3) was selected. For the lower and upper limits of the damage grades (D_{lb} and D_{ub}), the variance has to be fixed by $\sigma_D^2 = 0$ to cover the boundary conditions [8]. It allows also a more flexible assignment of the variances to the corresponding mean damage grades D_m as other applicable regression models like a sine function or a symmetrical power function.

$$\sigma_D^2 = C_1 \cdot (D_m - D_{lb})^{C_2} \cdot (D_{ub} - D_m)^{C_3} \tag{3}$$

C1, C2, C3 – control parameters



a) Vulnerability functions for building types (estimation of expected value - mean damage grade D_m)

b) Estimation of standard deviation and variance (asymmetric power function c.f. [8])

Fig. 2 – Prognosis of the control parameter of the beta distribution

The transformation of the damage grades and the associated variance σ_D^2 from the domain $\{D_{lb}, D_{ub}\}$ into the domain of the beta distribution {0, 1} follow the procedure in [8] und [9]. The corresponding quantiles can be determined for the complete considered range of impact. These quantiles can be used to distinguish the range of scatter in the vulnerability.

However, the quantiles of the beta distribution are calculated in domain {0, 1}. As displayed in Fig. 5a and 9a, the transformation back to the domain of discrete damage grades leads to values above or below the upper and lower boundaries $\{D_{lb}, D_{ub}\}$. This behavior leads especially for values close to D_{lb} or D_{ub} to difficulties in the interpretation of the ranges of scatter. For avoiding these problems, specified limits of vulnerability areas, the vulnerability functions for calculating D_m and the quantiles are discretized to integer values for D_i. Fig. 5b and 9b display the evidence to assign the ranges of scatter respectively.

3. Application to a multi-hazard approach

3.1 Model for earthquake

The presented concept in chapter 2 should be applied to a well distributed comprehensive data base for earthquake damages covering different building types related to a large impact range.

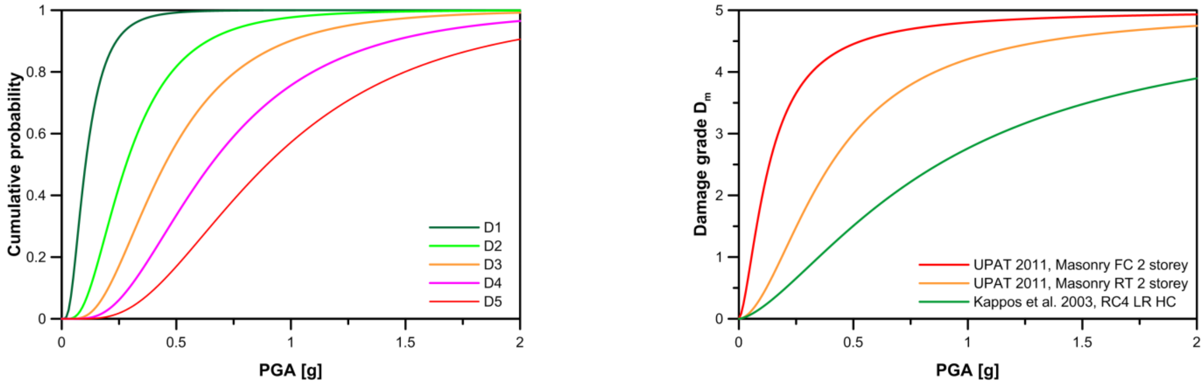
In absence of such a comprehensive damage data base, in the majority of studies analytically determined "fragility functions" are used (Figure 3a). These functions represent in the best sense the distribution of damage grades of an equivalent (synthetic) damage database.

Three types of functions [11], [12] are selected, taking into account the same number of damage grades (D0-D5) and the same impact parameter (here: PGA in [g]). According to the EMS-98 [2] the considered building types of these fragility functions are typical for the vulnerability classes B to D. In further investigations also fragility functions, which represent the vulnerability classes A, E and F should be applied.

The cumulative probabilities for each damage grade D_i are converted with Eq. (4) into mean damage grades D_m. These are the basis for the derivation of vulnerability functions with Eq. (1) and (2) for the prediction of D_m (Fig. 3b).

$$D_m(PGA) = \sum_{i=1}^{5} P(D_i(PGA)) \cdot i \tag{4}$$

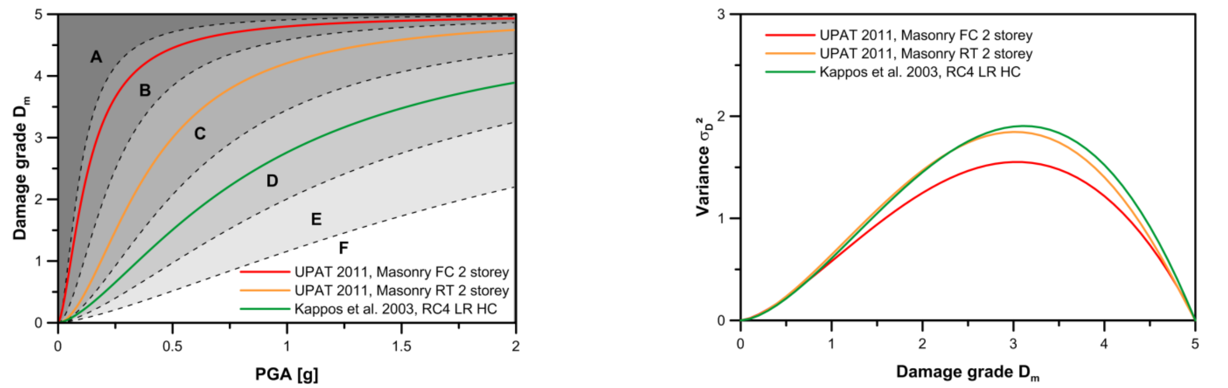
Based on the selected building types (fragility functions) Fig. 4a shows the derived expectation ranges for the mean damage grades D_m of the different vulnerability classes. The boundaries between the vulnerability classes A/B, D/E and E/F are considered as engineering-based assumptions and require a careful evaluation of their plausibility.



a) Fragility function for Masonry RT, 2 stories buildings according to UPAT2011 [11]

b) Transformation of fragility functions into vulnerability functions (cf. Eq. (1) and (2))

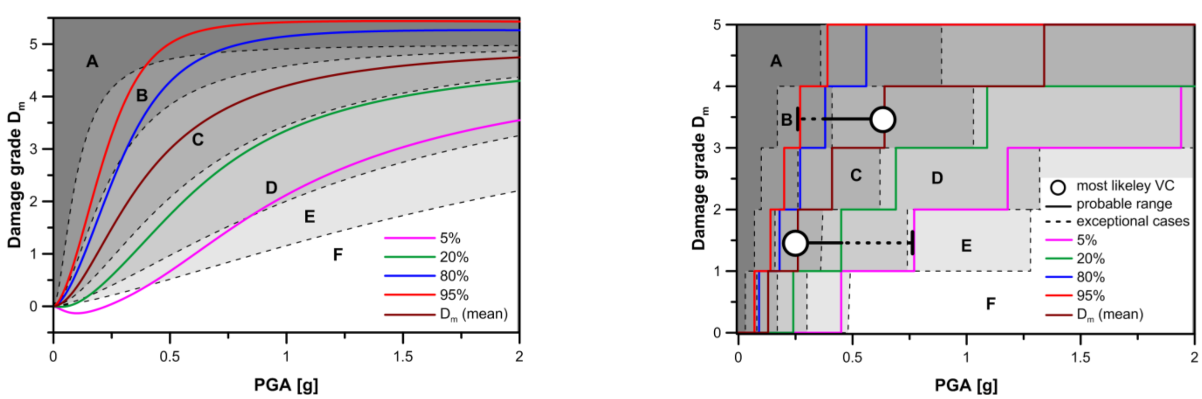
Fig. 3 – Fragility function and corresponding mean damage grades D_m



a) Definition of vulnerability levels/classes

b) Model for variance σ_D^2 from different fragility functions following Eq. (3)

Fig. 4 – Assignment of building types into vulnerability classes and modelling the scatter parameter

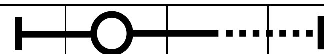
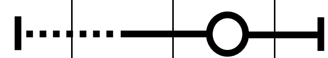


a) Functional representation

b) Representation by discrete damage grades D_i

Fig. 5 – Quantiles of the beta distribution for Masonry RT, 2 storeys, rigid floors: UPAT2011 (see Table 2)

Table 2 – Assignment of vulnerability classes and ranges of scatter

Type of structure	**Vulnerability class**					
	A	B	C	D	E	F
Masonry FC, 2 stories, flexible floors: UPAT2011						
Masonry RT, 2 stories, rigid floors: UPAT2011						
RC Frames and walls, Low Rise, High Code: RC4 LR HC, Kappos *et al*. (2003)						

The derived mean damage grades D_m (Fig. 3b) and variances $\sigma_D{}^2$ (Fig. 4b) enable the calculation of the quantiles of the beta distribution. Fig. 5a shows the assignment of ranges of scatter for the considered building type of the fragility functions UPAT2011, Masonry RT, 2 stories [11].

In Fig. 5b the ranges of scatter in the vulnerability according to the symbolism of the EMS-98 [2] are derived on the basis of discretized integer damage grades (see also Table1). In this study the 20% and 80% quantiles characterize the "probable range" and the 5% and the 95% quantile are used for the identification of the "range of less probable, exceptional cases". Thus, in this study the "probable range" includes 60% and the "range of less probable, exceptional cases" 30% of the damage cases. These preliminary assumptions should be verified in detail in further investigations.

For the characterization of the ranges of scatter those vulnerability areas are recognized, in which the corresponding quantiles are farthest from the "most likely vulnerability class". This explains that (on the basis of the assumed borders for the vulnerability classes) the "range of less probable, exceptional cases" reaches in Fig. 5b up to vulnerability class E in direction of lower vulnerability. On the other hand, the "probable range" as well as the "range of less probable, exceptional cases" are reaching classes of higher vulnerability (up to vulnerability class B). For this building type an asymmetrical scatter of vulnerability classes has been assigned. Other examples of building types where the deviation from the most likely class indicates similar tendencies (of rather different ranges) can be taken from Table 2.

It should be noted that a certain impact level is necessary for a clear differentiation (i.e., strong enough to cause damage to buildings of the high vulnerability classes D, E or even F). In an intensity-based context the impact level would be selected in a way that distinguishable structural damages occur for all building types. A maximum level of damage, which is representative for the most earthquakes, is required to justify the concept of vulnerability classes for practical applications. Otherwise a plausible assignment for building types with lower vulnerability (class D, E and F) would be impossible.

The selected approach allows the differentiation of the ranges of scatter in the vulnerability of the individual building types. Based on an extensive empirical damage data base the methodology is therefore suitable to classify the different building types into the vulnerability table of the EMS-98 [2] or future scales such as the planned International Macroseismic Scale - IMS [13], [14].

3.2 Model for tsunami

A comprehensive damage database is available for the tsunami after the 2011 “Tohoku Earthquake” in Japan [15]. The database was revaluated for the purpose of this study, not at least to transfer the proposed methodology and to develop a vulnerability table of buildings types for tsunami action. Based on this database "fragility functions" are derived for different building types in correlation to the water level h at the building in [16] and [17]. Six damage grades have been defined in analogy to the scheme of the EMS-98 [2]. The additional damage grade D6 has been assigned for building being completely washed away or total overturned (see [17]). Buildings in an area which were not affected by the tsunami have to be excluded from the investigations. Therefore, the lowest damage grade is D1 (see also [5], [18]).

Flow velocities were estimated in [19] and [20] using video recordings. In [20] also the differences between "Plain coast" and "Ria coast" were highlighted. In this study the affected areas [15] were separated with respect to the classification of the coast. The estimated flow velocities in [19] and [20] enable the derivation of average values of the Froude number in Eq. (5).

The flow velocities v and the product h x v² as an indicator of the flow force according to Eq. (5) have been determined based on the observed water levels of the damage cases in [15]. Fig. 6a show for the building types according to [15] and [16] the mean damage grades D_m calculated with Eq. (4) in dependence of the indicator of the flow force. This relationship and the derived vulnerability function for wooden buildings can be taken from Fig. 6b. The determined vulnerability functions for all considered building types can be found in Fig. 7a.

$$v = F \cdot \sqrt{g \cdot h} \tag{5}$$

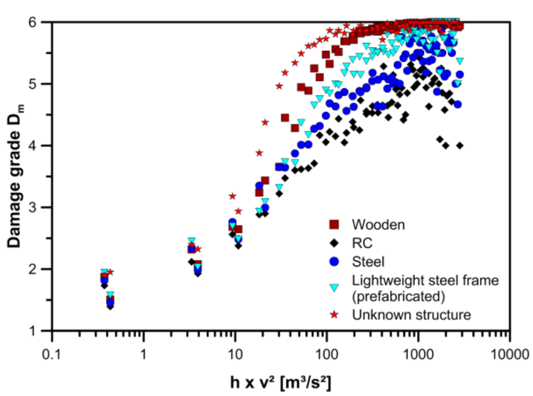
v- flow velocity, F- Froude number, g - acceleration of gravity, h - water level

As noted already in [16], Fig. 7a displays that the steel and concrete structures have higher damage at low impacts and lower damage at higher impact intensities than the other building types. An explanation for such overlaps can be found in a nonlinear material behavior under the impact of higher intensities; they can vary for the different building types. Basically, this abnormal behavior would be explainable by misallocations of the building types and the impact sizes. However, this peculiarity in the behavior can only be clarified if the database could be taken under a re-evaluation.

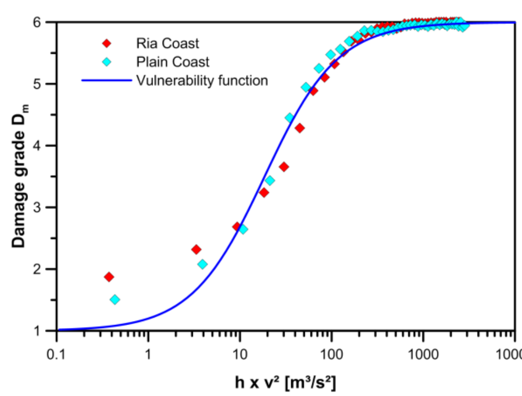
However, this leads for the study in this paper to difficulties to separate resilient vulnerability levels. Therefore, the plausibility of the preliminary assessed vulnerability level in Fig. 7b has to be validated in further studies. Initially 5 tsunami vulnerability classes (A to E) are considered.

Fig. 8 shows the procedure for determining the variance σ_D^2 according to Eq. (3). The visible differences between "Ria" and "Plain Coast" are neglected. Thus, the input parameters are available for the moment estimators of beta distribution [9], [10], which are necessary for the calculation of the quantiles over the observed impact range. The corresponding quantiles (see also section 3.1) for wooden structures as continuous relationships can be found in Fig. 9a. These quantiles and also the corresponding regions of scatter in the assignment of vulnerability classes were discretized in Fig. 9b into integer damage grades D_i.

The "most likely vulnerability class" and the "most probable range" in direction higher vulnerability have to be assigned here in vulnerability class B and the upper bound of "most probable range" in direction lower vulnerability is found in vulnerability class C. The corresponding limits for the "range of less probable, exceptional cases" can be found in vulnerability class A and D. An asymmetrical distribution of vulnerability classes according to Table 3 seems to be the appropriate for wooden structures.



a) Mean damage grades of the damage data for the different building types

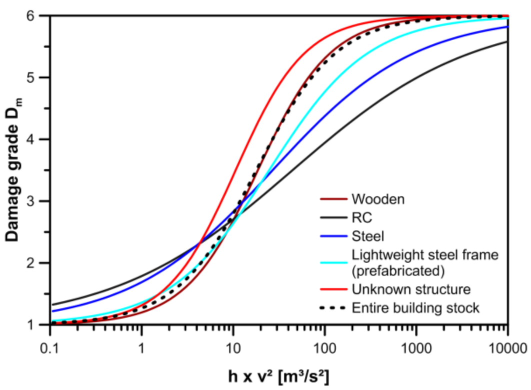


b) Derivation of vulnerability function for wooden structures

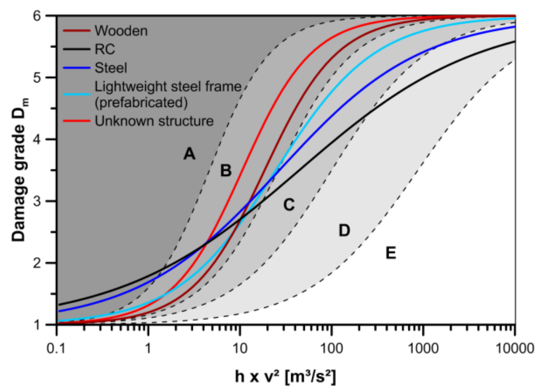
Fig. 6 – Mean damage grades D_m and derivation of vulnerability functions

Due to the abnormal characteristics of the vulnerability functions for steel and reinforced concrete structures (Fig. 7) the jump discontinuities of the quantiles at the higher damage grades are used to classify the ranges of scatter. Similar description seems to be representative for other building types given in Table 3. It should be noted here that also the plausibility of these ranges has to be validated in further studies.

Summarizing the presented results and applied database, it can be concluded that the proposed method enables the specification of a vulnerability table similar to the EMS-98 [2] also for the tsunami action.

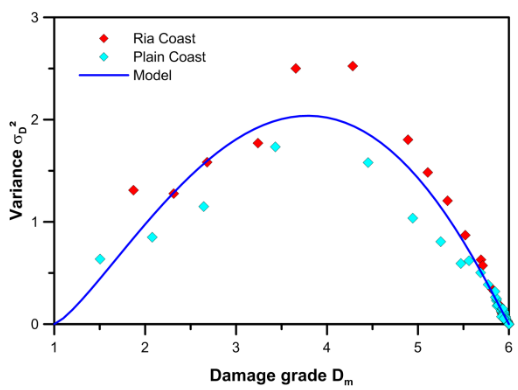


a) Vulnerability functions resulting from different fragility functions (cf. Eq. (1) and (2))

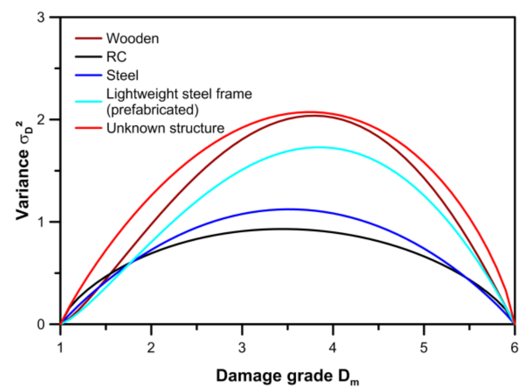


b) Definition of vulnerability levels/classes

Fig. 7 – Separation of vulnerability level

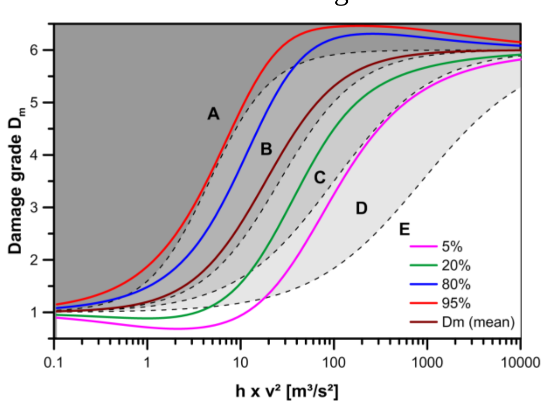


a) Example for wooden buildings

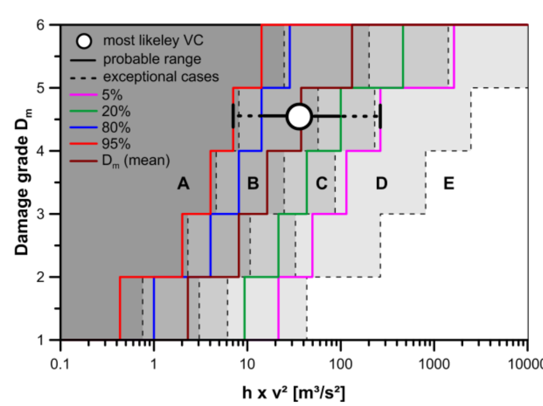


b) Model resulting for different building types

Fig. 8 – Mean damage grades D_m and variance σ_D^2



a) Functional representation



b) Representation by discrete Damage grades D_i

Fig. 9 – Quantiles of the beta distribution for wooden buildings

Table 3 – Assignment of vulnerability classes and ranges of scatter for Tsunami impact

Type of structure	Vulnerability class				
	A	B	C	D	E
Wooden	|····	··O—	—····	····|	
RC		|····	···—	—O···	···|
Steel		|—	—O—	—|	
Lightweight steel frame prefabricated	|····	···—	—O—	—|	

4. Conclusions and outlook

The methodology developed for different natural hazards in [5], [6] and [7] to classify the different building types into vulnerability classes on the basis of empirical damage data was conceptually improved. The ranges of scatter in the vulnerability of the individual building types can now be assigned in plausible way.

Fragility functions were used as a synthetic database for earthquake damages. Vulnerability functions for different building types could be derived for the prediction of the mean damage grade D_m. Based on these functions, ranges are derived, which are typical in its damage expectation for the "most likely vulnerability class" of building type.

A model for the description of the ranges of scatter in the damage grades due to seismic action has been extended. The determined quantiles of the beta distribution are used for the definition of "probable range" and the "range of less probable, exceptional cases".

The study provides the entry how (under which assumptions) the empirical approach and the experience-based determined vulnerability classes and the scatter of the assignments (being quite different for the building types) can be determined in a mathematically justified form, maintaining the symbolism and the elements used by the EMS-98 [2]).

In case of a robust empirical or synthetically determined damage database, the methodology enables the development or the verification of vulnerability tables for scales to be developed in the future, such as the planned International Macroseismic Scale - IMS [13], [14].

On the basis of real observed damage cases of the tsunami after the 2011 ”Tohoku Earthquake” in Japan it was shown that the developed method can be transferred to other natural hazards. Consequently, vulnerability tables can also be derive for a tsunami scale compatible to EMS-98 [2] after a plausibility check and an extension of the data base for further building types.

In further studies, these methods should be transferred to the damage caused by other natural hazards like extreme wind effects to come up with a multi-hazard related, robust evaluation of the vulnerability of complex building stocks taking into account also the occurrence of cascaded events (see [6]).

5. Acknowledgements

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6. References

[1] Grünthal, G. (ed.), Musson, R., Schwarz, J., Stucchi, M. (1992): The European Macroseismic Scale 1992: (up-dated MSK-scale). *Cahiers du Centre Européen de Géodynamique et de Séismologie* **7**, Centre Européen de Géodynamique et de Séismologie, Luxembourg.

[2] Grünthal, G. (ed.), Musson, R., Schwarz, J., Stucchi, M. (1998): European Macroseismic Scale 1998. *Cahiers de Centre Européen de Géodynamique et de Séismologie*, Volume **15**, Luxembourg.

[3] Schwarz, J. (2011): Empirical vulnerability assessment - a review of contributions to the damage description for the European Macroseismic Scale, Proceedings Workshop: *Earthquake Engineering and Engineering Seismology: Past Achievements and Future Prospects, Honoring Polat Gülkan*, Ankara Oct. 2011.

[4] Valencia, N., Gardi, A., Gauraz, A., Leone, F., Guillande, R. (2011): New tsunami damage functions developed in the framework of SCHEMA project: application to European-Mediterranean coasts, *Natural Hazards and Earth Systems Sciences*, **11**, 2835-2846.

[5] Schwarz, J., Maiwald, H. (2007): Berücksichtigung struktureller Schäden unter Hochwassereinwirkung, *Bautechnik* **84** (7), 450 – 46.

[6] Schwarz, J., Maiwald, H. (2012): Empirical vulnerability assessment and damage description for natural hazards following the principles of modern macroseismic scales. *15th World Conference Earthquake Engineering*, Lisboa 2012, Paper 5652.

[7] Maiwald, H., Schwarz, J. (2015): Damage and loss prognosis tools correlating flood action and building's resistance-type parameters, *International Journal of Safety and Security Engineering*, Volume **5** (3), 222 - 250.

[8] Raschke, M. (2003): Die Korrelation zwischen Erdbebenschaden und Erdbebenstärke und deren Anwendung in der Erdbebenrisikoanalyse. *Dissertation*, Bauhaus-Universität Weimar.

[9] Lallemant, D., Kiremidjian, A. (2015): A beta distribution model for characterizing earthquake damage state distribution, *Earthquake Spectra*, **31** (3), 1337-1352.

[10] Rinne, H. (2008): Taschenbuch der Statistik, Harri Deutsch Verlag GmbH.

[11] SYNER-G (2011): Analytical fragility functions for masonry buildings and building aggregates – UPAT methodolgy. Syner-G project internal report.

[12] Kappos, A. J., Panagiotopoulos, C., Panagopoulos, G., Papadopoulos, El. (2003): WP4 reinforce concrete buildings (level 1 and level 2 analysis). RISK-UE.

[13] Spence, R., Foulser-Piggott, R. (2014): The International Macroseismic Scale – extending EMS-98 for global application, *Second European Conference on Earthquake Engineering and Seismology*, Istanbul.

[14] Schwarz, J., Abrahamczyk, L., Leipold, M., Wenk, Th. (2015): Vulnerability assessment and damage description for R.C. frame structures following the EMS-98 principles. *Bulletin of Earthquake Engineering*. Vol. **13** (4), 1141-1159.

[15] Ministry of Land, Infrastructure and transportation (MLIT): Survey of tsunami damage condition: http://www.mlit.go.jp/toshi/toshi-hukkou-arkaibu.html, (28.01.2016).

[16] Suppasri, A., Mas, E., Charvet, I., Gunasekera, R., Imai, K., Fukutani, Y., Abe, Y., Imamura, F. (2013): Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan Tsunami, *Natural Hazards*, **66** (2), 319-341.

[17] Suppasri, A., Charvet, I., Imai, K., Imamura, F. (2015): Fragility curves based on data from the 2011 Tohoku-Oki Tsunami in Ishinomaki City, with discussion of parameters influencing building damage, *Earthquake Spectra*, **31** (2), 841-868.

[18] Maiwald, H. (2007): Ingenieurmäßige Ermittlung von Hochwasserschadenspotentialen im mikroskaligen Bereich, *Dissertation*, Bauhaus-Universität Weimar, Schriftenreihe des Instituts für Konstruktiven Ingenieurbau, Heft 011

[19] Foytong, P., Ruangrassamee, A., Shoji, G., Hiraki, Y., Ezura, Y. (2013): Analysis of tsunami flow velocities during the March 2011 Tohoku, Japan, Tsunami, *Earthquake Spectra*, **29** (S1), 161-181.

[20] Suppasri, A., Imai, K., Imamura, F., Koshimura, S. (2012): Comparison of casualty and building damage between Sanriku Ria Coast and Sendai Plain Coast based on the 2011 Great East Japan Tsunami, *Proceedings of International Sessions in Conference of Coastal Engineering*, JSCE, Vol.**3**, 76-80.