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Simulative Earthquake Damage Modeling Based on EMS-98 – Reliability and Predictability

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Abstract

Internationally, various damage models exist to quantify the structural damage to the structure and the resulting losses due to seismic action. The application of the different types of damage functions for a realistic assessment of damage requires a detailed knowledge of the structure and its vulnerability and site-specific conditions. The article refers to the internationally exemplary synopsis of natural hazards (earthquake, flood, wind) for the city of Cologne and the results of the German Research Network on Natural Disasters (DFNK) as part of the methodological basis for the quantification of damage potentials in German earthquake areas were derived on the basis of the European Macroseismic Scale 1998 (EMS-98). This intensity-based damage model for general building stock, developed at the Earthquake Damage Analysis Center of the Bauhaus-Universität Weimar within the framework of the DFNK, was validated on the mean damage grades D_m and the reported losses of the 1978 Albstadt earthquake. A consideration of the spreads and uncertainties in the distribution of damage grades D_i as well as the mirroring of comparable damage models was still pending. The validation and evaluation of the investigated model approaches is carried out in the paper on the basis of the distribution of the actually occurred structural damages of the seismic events characterized by different site intensities (e.g. Albstadt 1978, L'Aquila 2009). Consideration is given to the vulnerability and the dynamic behavior of the structures, both depending on the building types and the number of floors. Site effects as a function of subsoil conditions are described by the concept of Delta(Δ) intensities. The spreads in the damages are determined and compared with the observed damage distributions. Looking back at the DFNK study, the results for the metropolitan area of Cologne will be examined again with new building data and the extended updated damage model. The building vulnerability, aggregated in the DFNK, is transferred to the individual building stock and the influence on the earthquake scenarios is examined. The scatter of structural damages and losses are taken into account by Monte Carlo simulations. The changes in the results compared to the DFNK study are identified and discussed.

Keywords: Vulnerability; Simulation; Damage data; Damage prognosis; Re-interpretation

1. Motivation and objectives

The synopsis of natural hazards for the city of Cologne [1] within the framework of the German Research Network for Natural Disasters (DFNK) has proven to be a paradigm for the consideration of multiple natural hazards. A starting point can be seen in the provision of the methodological basis for the quantification of damage potential in German earthquake areas by explicitly referring to the European Macroseismic Scale 1998 (EMS-98) [2].

The intensity-based damage model for the general building stock developed by the Earthquake Damage Analysis Center (EDAC) at the Bauhaus-Universität Weimar offers in principle the possibility of showing the range of scatter and uncertainties regarding to the prognosis of the structural damages and the resulting losses. The article focuses on the outstanding simulative damage predictions, their validation based on real damage events and the mirroring of comparable damage models. The building properties (use, reconstruction values, building vulnerability) described in aggregate form in the DFNK are now available on a microscale level (individual objects). The influence on the damage scenarios is illustrated.

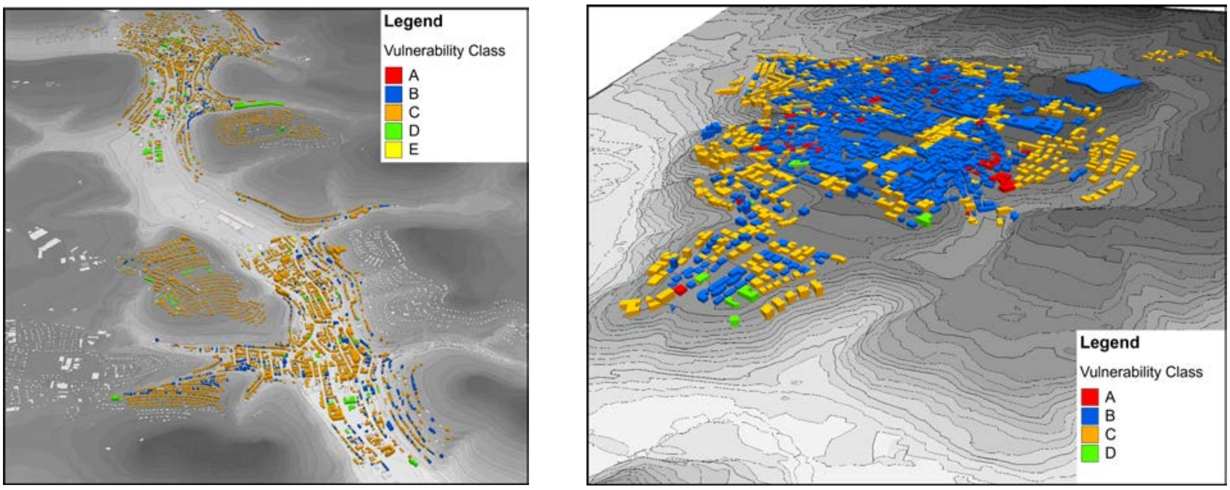
2. Study areas

Three study areas are considered for the re-interpretation of real earthquake events and for the quantification of damage potentials (Table 1).

The town Albstadt in the south of Baden-Wuerttemberg was affected by the strongest earthquake on September 3, 1978, which has occurred in the Federal Republic of Germany over the past 65 years. The earthquake was extensively evaluated from various sides (e.g. [3]) and re-interpretations of the event effects on the existing buildings were made taking into account local site effects [4], [5]. The mean damage grades D_m and the losses are evaluated in [4] on the basis of the observed damage grades and losses proven by the insurance company. The validation of the previously not considered simulative damage prognosis procedures in this paper focuses on the most affected sub-communities - Onstmettingen and Tailfingen. In addition to a detailed classification of the damage into the damage grades according to EMS-98 [2], the parameters of the building stock were elaborated object-specific and the buildings were assessed with regard to their vulnerability (Fig 1a). The replacement values of the surveyed buildings were determined using the *“normal construction costs”* (NHK 2000) [6] and scaled with the building price index of the Federal Statistical Office to the reference year 1978. The *“normal construction costs”* [6] neglect the regional and temporal fluctuations in market prices of the building sector; however, they have been proved in flood damage potential studies [7] as a robust assessment basis for the replacement values. It can be concluded that they can also be regarded as applicable for the prediction of earthquake damage potentials in Germany.

The second study area L’Aquila in Abruzzo in Italy was affected by an earthquake with a magnitude M_W = 6.3 [8] on April 6, 2009 and was heavily damaged. After the earthquake, 1.700 damage cases were documented in detail in [9]. The damage grades and the vulnerability classes (Fig. 1b) of the affected buildings were assigned in accordance with EMS-98 [2], which form the basis for the subsequent investigations. Missing building parameters (like the number of floors or height of the building) could be obtained via Google Street View. The local amplification characteristics of the subsoil (based on the information in [10]) were considered by the concept of the delta (Δ) intensities and applied simplified in the whole study area (see e.g. [11]).

In the (for the DFNK) selected study area Cologne (in the Federal State of North Rhine-Westphalia) the earthquake damage potential was quantified on the basis of a geo-statistical extrapolation of the vulnerability-relevant building parameters which were derived from of a detailed surveyed test area in the city of Cologne (including about 630 objects) [12]. The recent study is based on an extended data collection with Google Street View including 3,000 buildings, which were inspected from an engineering viewpoint (cf. [13]). For the current investigations, the digital real estate cadastral map of the city of Cologne provides a microscale database.



a) Albstadt b) L'Aquila (c.f. [9])

Fig. 1 –Vulnerability in the study areas

On the basis of the information provided by the cadastral map regarding the use categories, the number of floors and roof shapes, the replacement values of the approximately 300,000 individual buildings in Cologne for the reference year 2018 can be approximately determined using the *"normal construction costs"* [6]. The comparison of these microscale derived values with the mesoscale one derived in the DFNK shows a good agreement in [13]. The further basics regarding the earthquake hazard and the local site effects are taken from the DFNK (cf. [1], [12], [14]).

Table 1 - Overview of the study areas.

Parameter / Content	**Albstadt**	**L'Aquila**	**Cologne**
Location	Baden-Wuerttemberg (D)	Abbruzzo (I)	North Rhine-Westphalia (D)
Scenarios	Earthquake 03.09.1978	Earthquake 06.04.2009	Scenario E3 [14]
Moment magnitude	$M_W = 5,1$	$M_W = 6,3$	$M_{W(TR)}$
Focal depth	h = 6,5 km	h = 8,8 km	h = 10 km
Intensities	I_{EMS}=7,0 - 7,5	I_{EMS}=8,0 - 9,0	I_{epi}= variable
Data basis	according to [3], [4], [5]	according to [8], [9], [10]	according to [1], [12], [14]
Building survey	on-site inspection	on-site inspection [9], Google Street View	on-site inspection, Google Street View
Structures considered	4615	2114	298.718
Damage data collection	archive research, damage documentation	on-site inspection [9]	not applicable
Damage data	4599 [4], [5]	1696 [9]	not applicable
Vulnerability according to EMS-98	according to [4], [5]	according to [9]	in extension of [12]
Building values	NHK 2000 [6]	-	NHK 2000 [6]

3. Methodical basics

3.1 Earthquake damage modeling

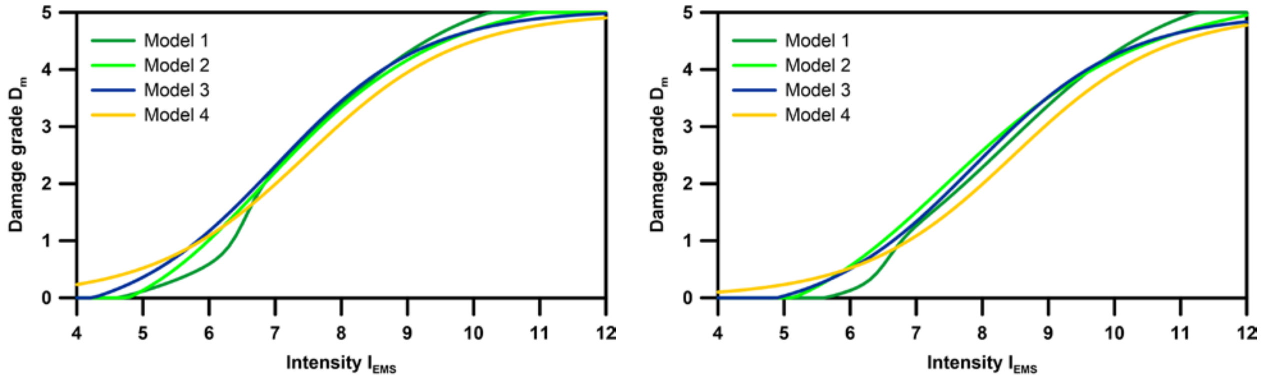
Basically, two possibilities are available for earthquake damage modeling.

Type 1 - Vulnerability functions, which establish the connection between the effects and the structural damage via mean damage grades D_m.

Type 2 - Fragility functions, that describe the probability of exceedance of the individual damage grades D_i or damage states depending on the impact.

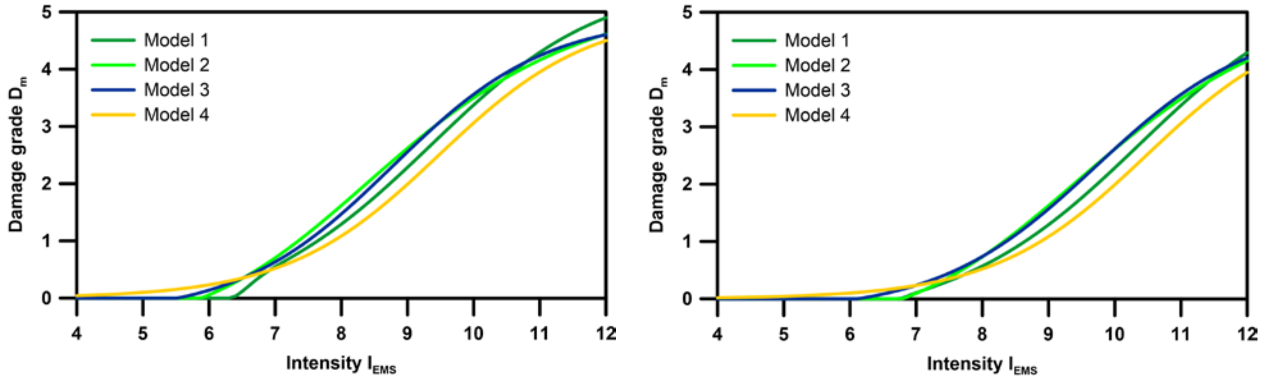
In this paper, four damage models (type 1) are utilized to predict the structural damage via the mean damage grade D_m based on the intensity and the vulnerability classes according to EMS-98 [2].

In order to quantify damage potential for large areas, an intensity-based damage model was developed at the Earthquake Damage Analysis Center within the framework of the DFNK. This model was also successfully used in a further developed form for the analysis of earthquake events [4] and in other model studies e.g. [15]. The vulnerability of the buildings is taken into account in accordance with the vulnerability classes of EMS-98 [2] and the number of storeys. The seismic impacts are differentiated for the associated ranges of the characteristic building periods with the concept of delta (Δ) intensities based on site specification. Topography effects can also be taken into account.



Vulnerability class A

Vulnerability class B



Vulnerability class C

Vulnerability class D

Fig. 2 - Comparison of the vulnerability functions of the considered models

Following models are considered in the paper:

- **Model 1** uses the approaches derived from the evaluation of real damage observations from [11] to determine the mean damage grade D_m.
- **Model 2** that regarded as a preliminary stage of model 1 (and was the basis in the DFNK to determine structural damage in the city of Cologne [12]).
- In **model 3**, the approaches for the vulnerability functions of models 1 and 2 were modified again. It was used for the re-interpretation of the damage caused by the Albstadt earthquake [4] and in the Baden-Württemberg model study [15].
- **Model 4** is based on the approaches presented in [16], which are technically very similar to models 1 to 3 with regard to the vulnerability functions and scattering of structural damage. The vulnerability functions and models developed for damage scattering were not derived directly from real damage data or realistic analytical calculations, but are based exclusively on a complex fuzzy logic analysis of the quantitative information on structural damage in the EMS-98 [2]. The model is used to mirror and evaluate the results.

The comparison of the qualitative shape of the vulnerability functions for vulnerability classes A to D according to EMS-98 [2] can be seen in Fig. 2, whereby these in application were more differentiated according to the number of storeys (cf. [11], [16]).

The scatter around the predicted mean damage grades D_m is described mathematically according to the corresponding damage models using a beta distribution. The models are used for the damage prediction with the Monte Carlo simulation method. The damage grades D_S obtained for each simulation can be used for the loss estimation.

3.2 Loss modeling

Suitable damage functions or so-called damage matrices are required to determine the financial losses due to earthquakes. These convert the determined structural damage (Section 3.1) into a relative loss statement (damage rate or damage ratio - DR). The absolute financial loss is then determined from the DR and the replacement value of the building.

In the DFNK, a simple power function according to Eq. (1) is used to calculate the total loss for Cologne [14].

$$DR\ [\%] = 0.969 \cdot D_S^{\ 3.0756} \tag{1}$$

DR – Damage Ratio

D_S – Calculated damage grades (here from the simulations)

Further damage matrices can be found in the literature (e.g. [17], [18]). They differ considerably with regard to the range of damage rates for the individual damage grades. Following the proposed ranges of damage rates in these sources, three different variants (SBS 1 – SBS 3) are derived as basis for further study purposes (see Table 2).

In addition, SBS 4 is defined as a next variant which implements a discussion initiated by [19], recognizing the fact that buildings with damage grade D3, which are completely replaced after an earthquake, have to be categorized as a damage rate of 100%. Therefore, the maximum damage rates for damage grades D1 and D2 are increased.

Table 2 - Scatter of the damage rates (SBS)

Damage grade	**Range of the applied damage rate [%]**			
	SBS 1 (minimal)	**SBS 2 (extended)**	**SBS 3 (SBS 1 + SBS 2)**	**SBS 4 (Maximum extended; expert based)**
D0	0	0	0	0
D1	0 - 1	0.3 - 5	0 - 5	0.3 - 25
D2	1 - 7.5	5 - 20	1 - 20	5 - 50
D3	7.5 - 20	20 - 60	7.5 - 60	20 - 100
D4	20 - 60	60 - 100	20 - 100	60 - 100
D5	60 - 100	100	60 - 100	100

To quantify the uncertainties, the relative losses following a beta (ß) distribution are simulated using an mean value at 50% and a standard deviation of 20% based on the associated ranges of scatter of the damage rates (SBS) for the respectively determined damage grades D_S.

4. Validation of the models on real events

The results for vulnerability, damage and loss assessment in the two study areas of Albstadt and L’Aquila are re-interpreted based on the defined models in section 3.1. In the process of optimization, a further attempt was necessary to approximate the real observed damage grades in investigated zones.

The mean damage grades D_m in the study areas and the deviation for the individual damage grades are assumed as criteria. Fig. 3 shows the damage distribution for both areas with optimal assessment of the mean damage grade D_m. Table 3 gives an overview of the resulting intensities in each study area. For Albstadt, it was found that all models determine the structural damages at a little too low intensity levels (cf. Albstadt VC1). It was concluded that the vulnerability of individual building types was overestimated. Therefore, the vulnerability classes of these types of buildings were calibrated slightly. So the Albstadt VC2 variant leads to more plausible intensities.

Table 3 - Site intensities with optimal assessment of the mean damage grade D_m in the study area

Study area	**Site intensity**			
	Model 1	**Model 2**	**Model 3**	**Model 4**
Albstadt VC1	6.9	6.5	6.6	6.8
Albstadt VC2	7.1	6.8	6.8	7.0
L‘Aquila	8.6	8.4	8.4	9.2

Table 4 shows the total, maximum absolute deviation of the distribution for each damage grade.

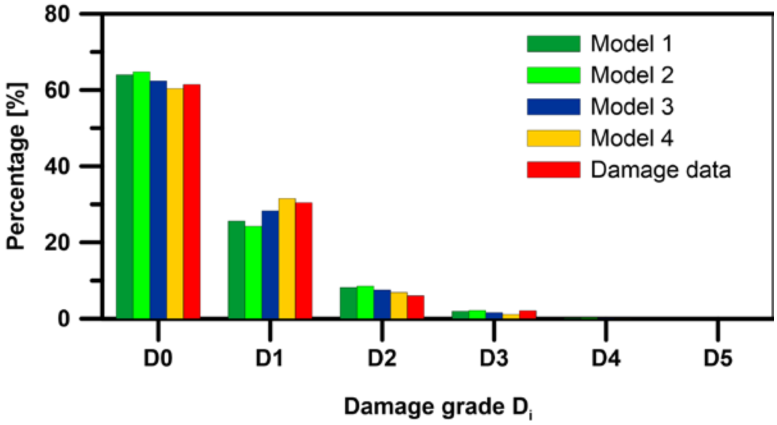
Table 4 - Summed, maximum absolute deviation of the distribution per damage grade with optimal assessment of the mean damage grade D_m

Study area	**Summed, maximum absolute deviation [%]**			
	Model 1	**Model 2**	**Model 3**	**Model 4**
Albstadt VC1	11.9	10.7	5.4	3.1
Albstadt VC2	9.8	12.3	5.3	4.1
L‘Aquila	30.7	27.7	29.5	35.2

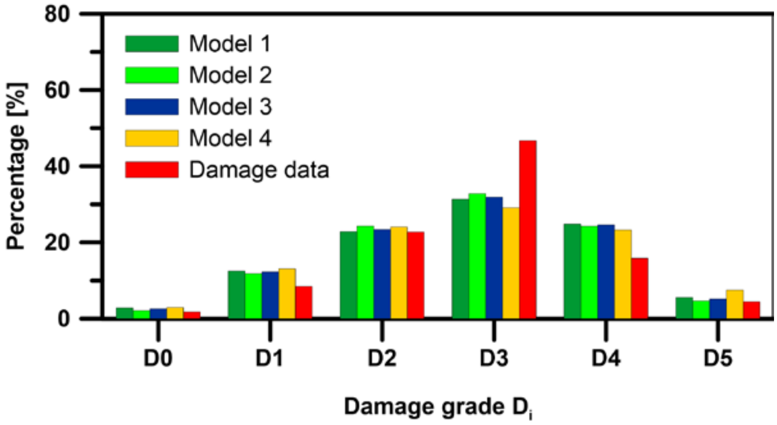
The following conclusions can be derived:

Models 1 and 4 lead to the most plausible intensities in combination with the deviations from the real damage distribution for the Albstadt scenario. Fig. 4 illustrates the distribution of losses (with n = 10000 simulations) derived from model 1 for the four approaches (SBS 1 to 4) explained in section 3.2 (Table 2).

For the considered sub-municipalities of Albstadt, a total loss (structural and expansion damage) of EUR 45.2 million can be taken from the information in [20] as reference basis. Since these evaluations also include damage to the machine inventory of industrial buildings in the expansion damage, a total loss of EUR 42.4 million seems to be a realistic value for the damage assessment of buildings alone. The amount of expansion damages for industrial buildings was taken into account with 50%.



a) Albstadt VC2 (VC modified)

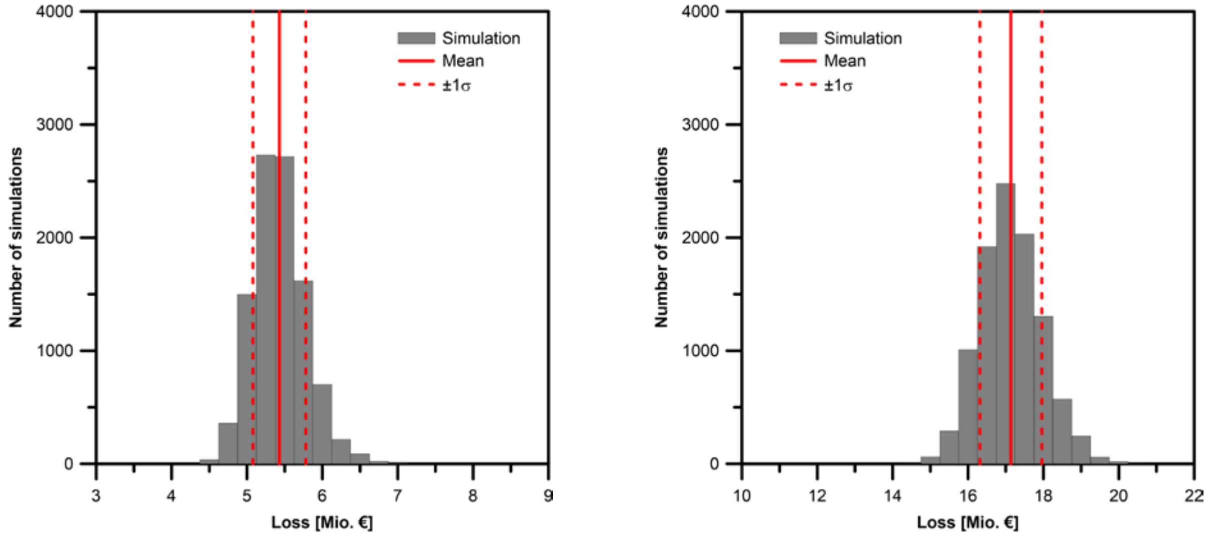


b) L’Aquila

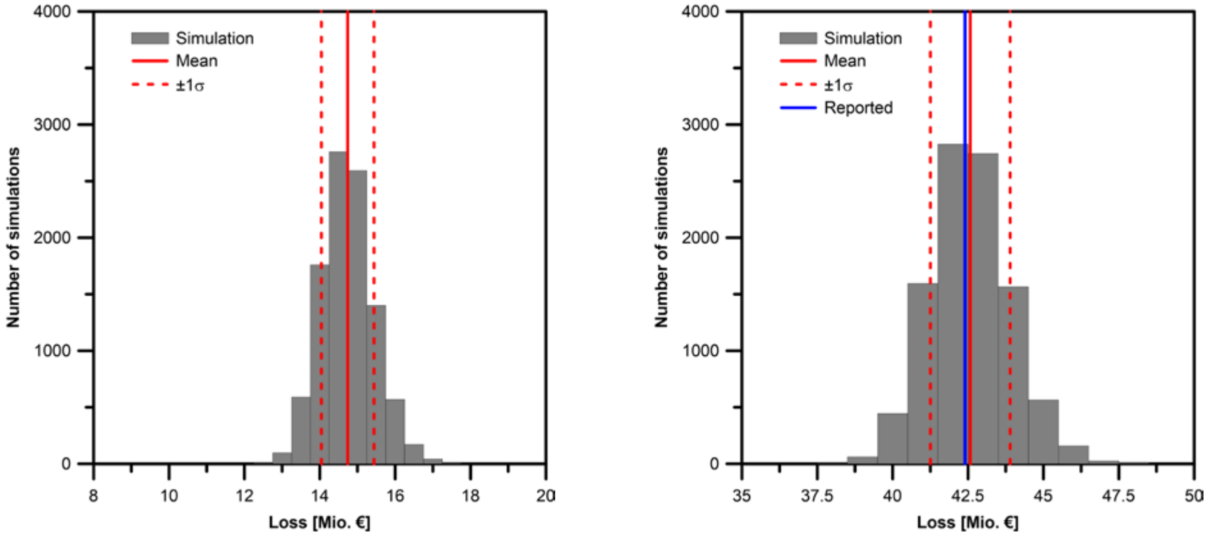
Fig. 3 - Distribution of damage grades D_i by optimal assessment of Mean Damage Grade D_m

Compared to the determined damage distribution (see Fig. 3a), [20] shows significantly more damage cases with insured losses. This can be explained in such a way that in the case of an EMS-98-compliant damage assessment, damage cases which are not visible from the outside are assigned to the damage grade D0. This fact is taken into account in the calculation procedures by interpolating the damage rates between D0 and D1 (corresponding to the simulated damage grades D_S). Thus, for buildings with $D_S < 0.5$, which are assigned a damage grade D0, are also assigned (minor) losses.

It can be seen that the calculated variants SBS 1 to SBS 3 underestimate the reported losses (Fig. 4a - c). However, by application of SBS 4 variant, these results can be easily comprehended (Fig. 4d).



a) Losses according to SBS 1 b) Losses according to SBS 2



c) Losses according to SBS 3 d) Losses according to SBS 4

Fig. 4 - Results of damage grade and loss simulation for Albstadt (Model 1, n=10000)

Note: 1. For a) to c), the reported loss is outside of the displayed range.

2. Consider the different unit ranges of the losses.

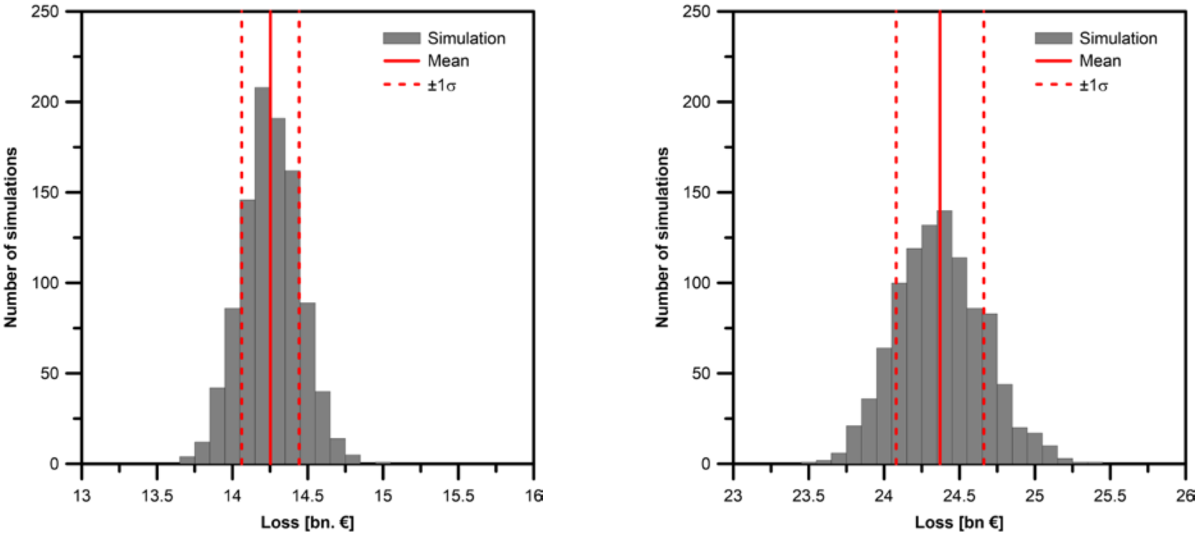
For the L'Aquila study area, none of the models can optimally reflect the damage distribution from the field study [9], since the dominant formation of damage grade D3 cannot be determined by the very flexible beta (ß) distribution (Fig. 3b). This can also be concluded from the comparatively high total absolute deviations (Table 4). A first closer examination of the data according to [9] shows some inconsistencies between the damage distributions of the individual vulnerability classes, so that the assignments of the vulnerability classes and damage grades would have to be checked firstly.

For model 4, a significantly higher intensity required to determine the mean damage grades in the area (Table 3) and an even greater deviation (Table 4) in comparison with models 1 to 3 can be determined, which is already evident from the qualitative shape of the vulnerability functions (Fig. 2)

5. Reflection on event scenarios: Cologne model study

Looking back to the DFNK study, the defined scenarios for Cologne in [14] for the epicenter of the model earthquake E3 (south-west of the city center, distance approx. 14 km) are repeated with the microscale building data and the extended vulnerability assignments.

Fig. 5 shows an example of the distribution of the losses determined with Model 1 and SBS 2 (reference year 2018) for the epicentral intensities I_{epi} = 8.5 and I_{epi} = 9.0, in all cases on the basis of n = 1000 simulations. Fig. 6 shows the damage grades for the individual buildings for that of the random scenarios with I_{epi} = 8.5 (corresponds to an average site intensity $I_{Site} \approx 7.9$) which represents the loss amount in the range of the mean value from Fig. 5a.



a) I_{epi}=8,5 b) I_{epi}=9,0

Fig. 5 - Results of damage grade and loss simulations for Cologne for the epicenter E3

(see [11]; model 1, SBS 2, n=1000).

The loss curves from the mean values of the simulations illustrate the range of the considered damage models (see Fig. 7). The simulative procedure combined with the microscale building data and the slightly lower vulnerabilities resulted for models 1 to 3 in higher loss values in comparison with those are determined in the DFNK for scenario E3. Due to the functional characteristics, Model 4 determines lower losses with longer return periods (Fig. 7a).

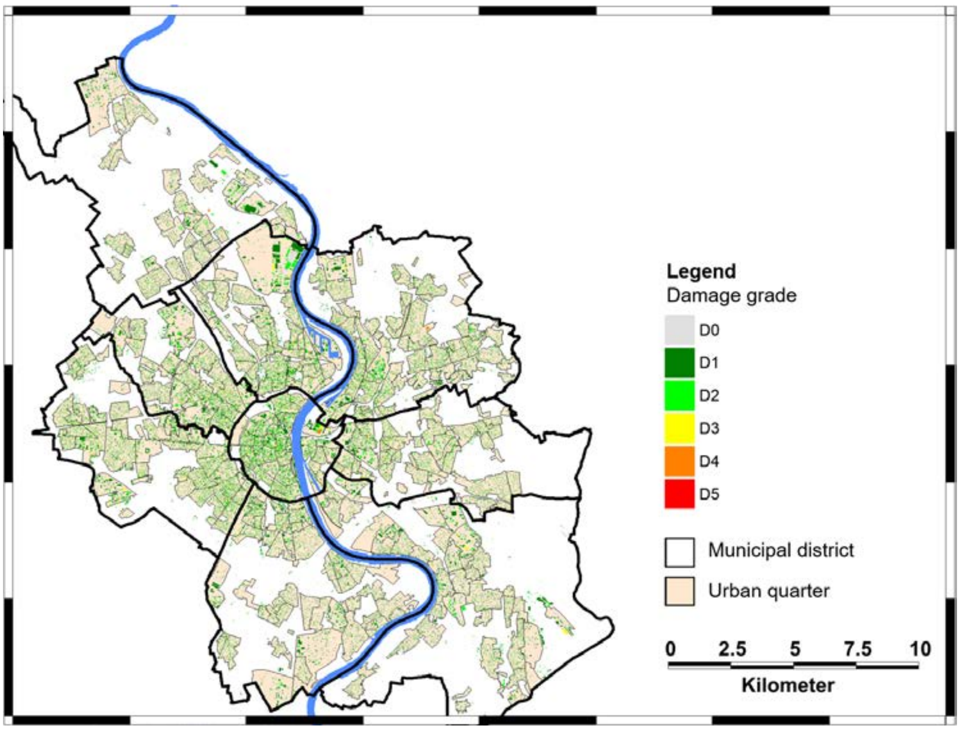
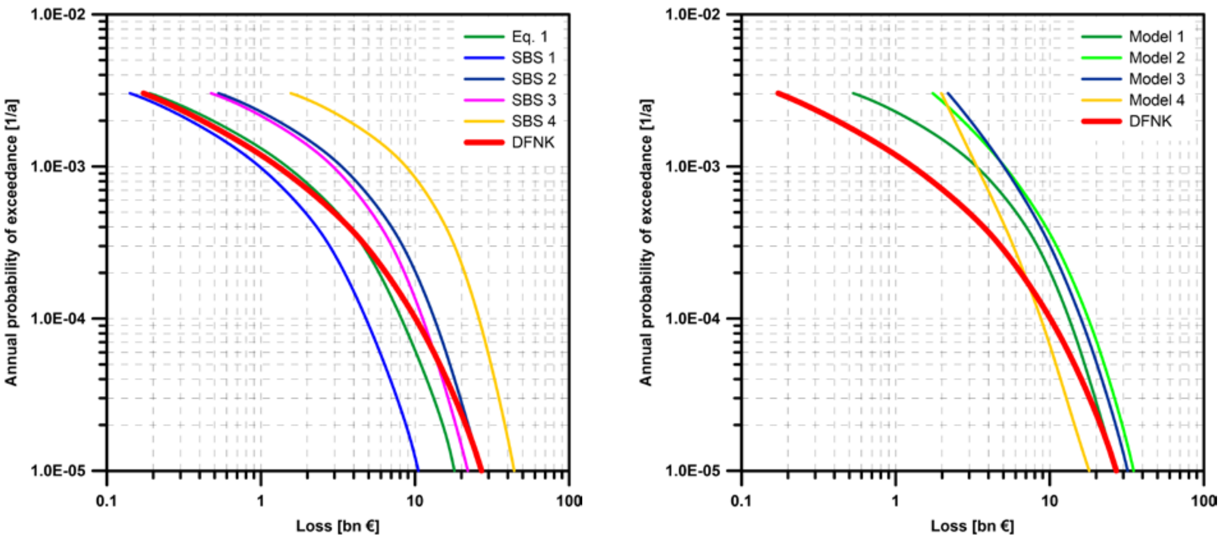


Fig. 6 – Damage grades grades for random scenario $I_{Epi}=8.5$ ($I_{Site} \approx 7.9$), Epicenter E3 (Model 1)

In particular, in the range of the return periods (or annual probabilities of exceedance) relevant to codes for general buildings, the models show larger differences. The loss prediction for the four SBS variants is shown in Fig. 7b for model 1, only. Here, the results from the DFNK are well reproduced, particularly in the case of high return periods for the SBS 2 and SBS 3 variants. The variant SBS 4 specifies an upper limit, its reliability has to be verified in further investigations.



a) Scenario epicenter E3 (SBS 2)

b) Scenario epicenter E3 (model 1)

Fig. 7 - Comparison of the loss curves for the scenarios of the individual calculation variants with reflection of the results from the DFNK

6. Conclusions and Outlook

The investigations show that the existing damage models lead to different results by the same impacts. A realistic assessment of the distribution of the damage grades after a real event is possible with all damage models, but with different, partially less realistic (deviating in diametrical tendencies) intensities.

With the presented simulative methods, the reported losses of the Albstadt earthquake of 1978 can also be re-interpreted. Nevertheless, the basic difficulties would be admitted here in correlating insurance-related information with the engineering-related damage description (in the form of the damage grades) according to Table 2. In the combination of empirical data (observations) with the loss functions determined synthetically on the basis of the damage characteristics; it seems that the applied method has capability to present these relationships based on the building type.

The investigations for the L'Aquila study area show a discrepancy in the description of the scatter of structural damage compared to the observations. Therefore, and in a first step, the quality of the building and damage documentation [9] have to be checked. Next, it has to be clarified why the assigned damage grades indicates such an unusual distribution that it cannot be adequately described by a beta (ß) distribution.

Comparison of damage models with calculated results for Cologne according to DFNK [1], [12] and [14], shows the significant differences between them. In the case of using the same damage model as in the DFNK, the obtained results show some differences and changes due to the availability of microscale building data associated with vulnerability distribution and extending to the simulative prediction methods.

The realistic and time-efficient assessment of the vulnerability-relevant parameters continues to be a challenge for large building stocks in the microscale level, which can only be successfully achieved through interdisciplinary research. Promising methods are new technologies such as deep learning-based AI techniques, which should make the possibility to extract the necessary information from aerial and satellite images in the medium term.

On this basis, the reliability of the risk assessments, which related to the actual building stock and the engineering description for the vulnerability of representative building groups, will ultimately increase as a result. One of the major outcome of this context can be related to the application of non-linear calculation methods to obtain more precise and accurate mapping of damage based on the concept of local damage grade. This also allows entry into multi-hazard considerations [13], [21].

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