REALISTIC VULNERABILITY AND DISPLACEMENT FUNCTIONS FOR MASONRY STRUCTURES DERIVED FROM DAMAGING EARTHQUAKES IN CENTRAL EUROPE

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ABSTRACT :

Numerical studies of the earthquake behavior of masonry buildings in Central Europe based on national building codes acc. to the Eurocode 8 lead to pessimistic damage prognoses, which are in contradiction to the observed behavior. In order to eliminate this discrepancy realistic experience-based vulnerability and displacement functions for typical masonry constructions are developed. Because of the rather limited number of earthquake damage observations, the Magnitude M_L 5.7 Albstadt earthquake from September 3, 1978 (intensity VII–VIII) in South Germany also based on its excellent documentation is reconstructed with the building stock existing at that time. The prevailing building types and for these the characteristic damage cases are investigated in close cooperation with the local authorities. The vulnerability of the building types is determined. Vulnerability curves as a function of damage degrees and seismic intensity as well as capacity curves are presented; the effect of local site conditions is considered.

KEYWORDS: masonry, Central Europe, damage grades, vulnerability function, displacement function

1.   REINTERPRETATION OF THE SEPTEMBER 3, 1978 ALBSTADT EARTHQUAKE

Due to the lack of strong earthquakes, there are almost no data or experiences available concerning the behavior and vulnerability of common buildings in the low to moderate seismicity regions of Central Europe. The consideration of their earthquake resistance or vulnerability is still outside the scope of official policy and long-term investigations. A scale is missing to calibrate results of seismic risk assessment and prove their reliability. In this context, an outstanding importance has to be attested to the Albstadt earthquake in the Western Swabian Alb, the strongest one in Germany over the last 50 years.
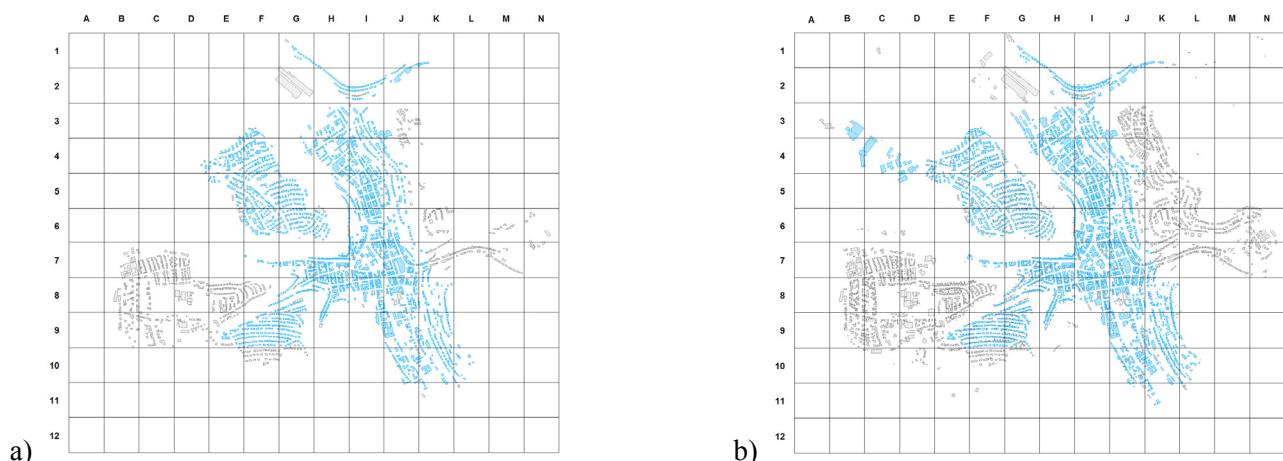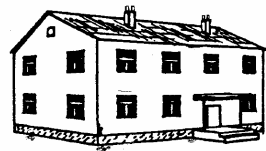

Figure 1 Comparison of existing building stock a) 1978 and b) 2001 [ALK BW © LVA Baden-Württemberg, State 2001] with the ■ study area (building survey 2003/2004)

Table 1.1 Definition of damage degrees acc. to EMS-98 [Grünthal *et al.*, 1998] for masonry buildings and damaged residential buildings due to the Albstadt earthquake 1978 [Schwarz *et al.*, 2005]

Di	Damage description[*]	Scheme	Example
D1	Negligible to slight Hair-line cracks in very few walls. Fall of small pieces of plaster Fall of loose stones from upper parts of buildings in very few cases.		
D2	Moderate Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.		
D3	Substantial to heavy Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).		
D4	Very heavy Serious failure of walls; partial structural failure of roofs and floors.		
D5	Destruction	not observed	

The existing building stock at time of the earthquake (1978) and (2001), at the time of a more recent comprehensive building survey in 2003/2004 are given by Figure 1. The study area is indicated by the blue ▩ elements, and is covering all zones where damage was reported. The quality of the reinterpretation is validated by the comparison of the ratio of damaged building (D_R) within a mesh of raster elements (cf. Figure 2).

The 1978 Albstadt earthquake provides an impression of the severity of design earthquakes defined by German code [DIN 4149, April 2005] for the highest zone 3. Accordingly, the epicentral intensity of $I_0 = 7.5$ is viewed as standard event in zone 3. As a whole, 1.300 damage cases are evaluated. As an outcome of the archive research and the re-documentation of the damage situation, the existing verbal descriptions of observed effects are translated into damage grades acc. to the European Macroseismic Scale EMS-98 (see Table 1.1).
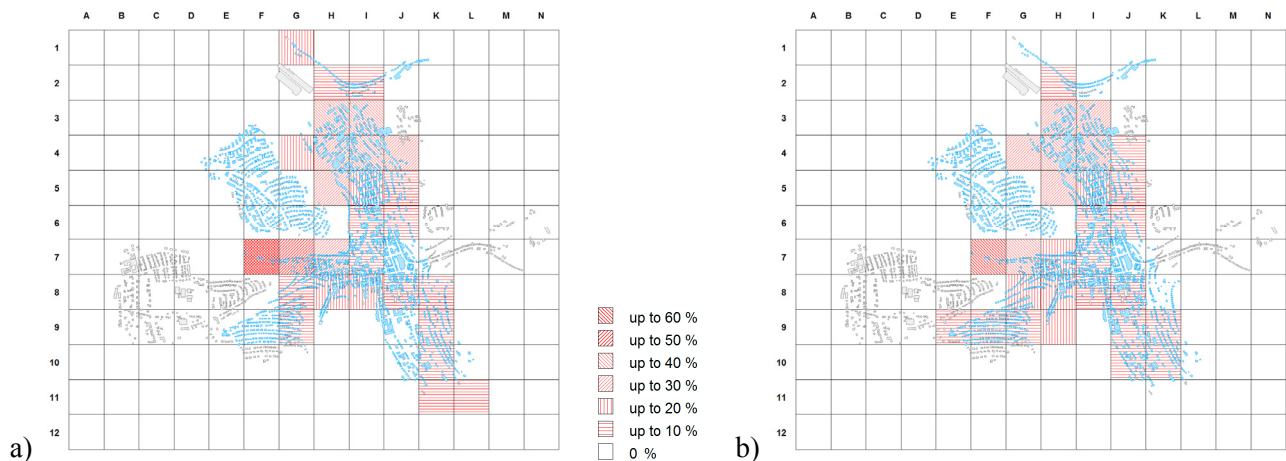

a) b)

Figure 2 Ratio of damaged buildings ($D_R \geq D2$) in Albstadt – Tailfingen: a) compiled immediately after the shaking in 1978 [Hiller, 1985]; b) re-interpreted damage situation [Schwarz *et al.*, 2005]
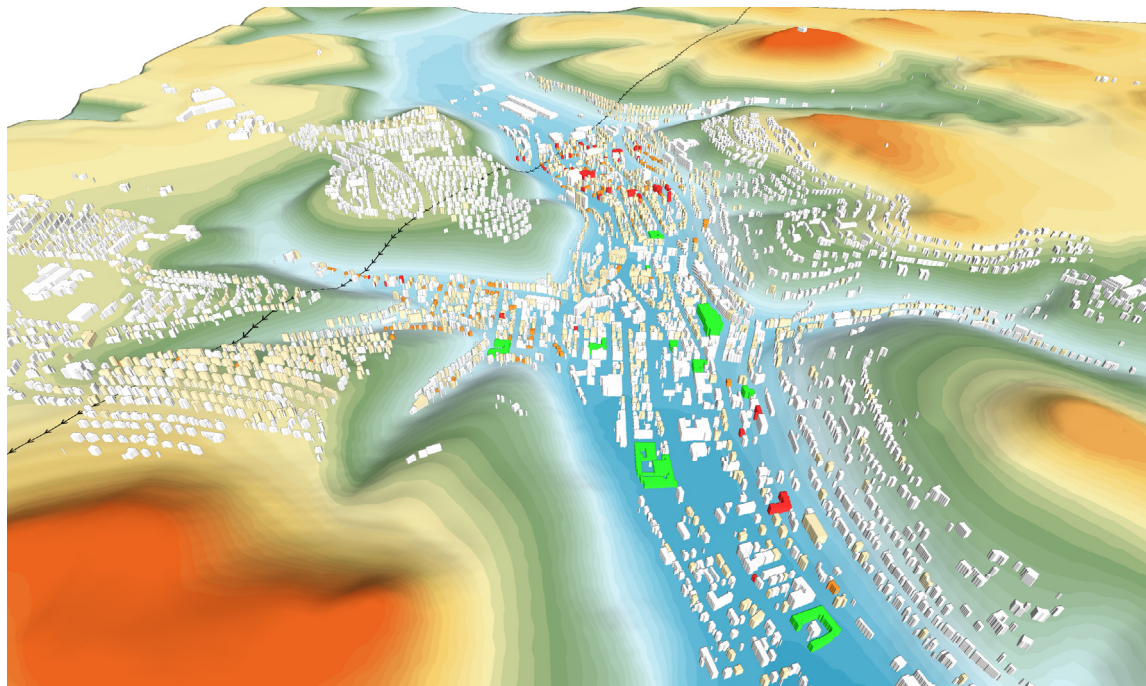
Figure 3 Observed damages in Albstadt – Tailfingen and projection of the rupture surface of the Albstadt earthquake of September 3, 1978 [map prepared on basis of data from ALK BW © LVA Baden-Württemberg, State 2001]

The reconstruction of the about 1.300 damage cases [Schwarz *et al.*, 2005] for the Albstadt earthquake was assisted by the observations of the local authorities and several photo documentations ([Landesstelle für Bautechnik: Landesgewerbeamt Baden-Württemberg, 2002], [Bauamt Albstadt, State 2004]). The examples in Table 1.1 show damage grades D1 to D4. Only in a few cases damage grade D4 could be observed. In general the majority of affected buildings suffered moderate damage due to diagonal cracks between the openings as well as out-of-plane failure of non-anchored gable walls. Walls in danger of collapsing were mostly supported by wooden beams (D4). Due to the small focal depth of the earthquake source, heavy damages in the building stock were concentrated in a narrow zone of a few kilometers length [Hiller, 1985], which basically is a projection of the focal line onto the ground surface of the community of Albstadt (Figure 3).

2. VULNERABILITY OF MASONRY BUILDINGS IN CENTRAL EUROPE

The town of Albstadt in Baden-Württemberg is considered a rather typical small-scale town for the region of Southern Germany, with a mixed building stock dating from different periods mainly of the 20ᵗʰ century. As in most German towns and villages, masonry dominates as construction type, though many varieties exist: Masonry houses from the 1920s to 1930s mostly had comparatively weak mortar and full clay bricks or stones taken from local quarries (for instance 'purnice', the German term being "Bimsstein", a porous stone with volcanic origin, was frequently used in Albstadt). In these houses all floors were timber beam constructions [Schwarz *et al*., 2008a]. The building stock is classified into representative building types accepting the predominance of unreinforced masonry constructions and the need of further differentiation. The vulnerability of the building types is determined in three different ways:

(1) Empirical-statistically, on the basis of the observed damage and the assignment of the most likely and still probable vulnerability classes according to EMS-98 principles [Schwarz *et al*., 2005, 2008a];
(2) Experience-based, using a hybrid approach combining the evaluation by constructional parameters and torsion susceptibility with the determined capacity curves [Schwarz, 2008];
(3) Analytically, with the help of a FEM computational program, where a recently developed plastic masonry wall element is implemented [Schwarz *et al.,* 2008b].
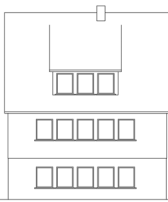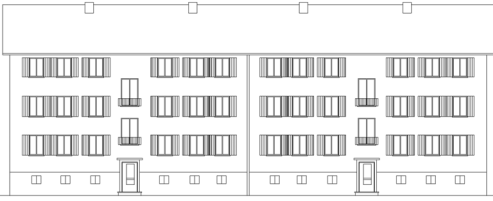
Subsequently results from (1) are presented (section 3); an outlook is given emphasizing the importance and the need of experience-based approaches in case of masonry buildings under horizontal action (section 4).

3. EMPIRICAL–STATISTICAL STUDIES

3.1 *Subdivision of building types and ranges of vulnerability classes*

From the statistics [Schwarz *et al*., 2008] it can be concluded that the building stock at time of the earthquake in 1978 (as well as today) consisted mainly of masonry buildings, mixed types of masonry with timber framework and masonry with RC-frame elements. The *unreinforced masonry structures with floors of timber beam constructions* are here introduced as Type 1-2 and *unreinforced masonry structures with RC floors* as Type 2-1. The defined building types can be differentiated more specifically by means of number of stories n and time of construction. Within the building survey the appropriate vulnerability class is assigned to each building. The red and blue lines in Table 3.1 describe more precisely the vulnerability class for typical masonry buildings in Albstadt. The expected vulnerability classes according to European Macroseismic Scale EMS-98 (without any refinement or adaption to the local building types) are displayed in black. It is one of the inherent advantages of the EMS-98 that the scatter within the earthquake resistance of buildings is reduced to the essential parameters, to their main structural system (expressed by generalized building types) and the ranges of their most likely, probable or exceptional vulnerability classes (see explanation in Table 3.1).

Table 3.1 Representative building types of masonry buildings and vulnerability class VC acc. to EMS-98

Type	Representative building	Example	VC					
			A	B	C	D	E	F
unreinforced masonry with wooden floors		EMS-98	├·········O·········┤					
1-2 A			├—O─┤					
1-2 B			├·O·┤					
unreinforced masonry with RC floors		EMS-98	├——O·······┤					
2-1 A			├·O·┤					
2-1 B			├·O·┤					

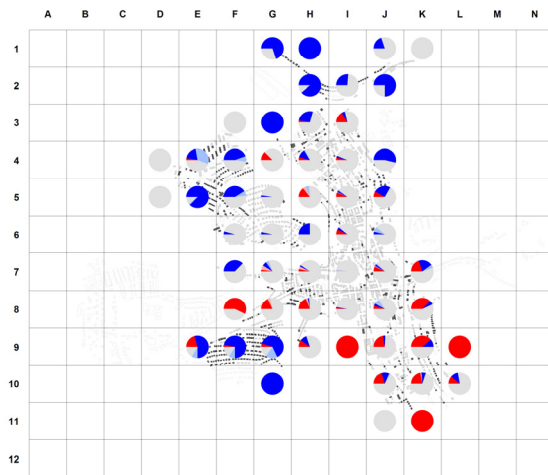O most likely vulnerability class ─ probable range ···· range of less probable, exceptional cases

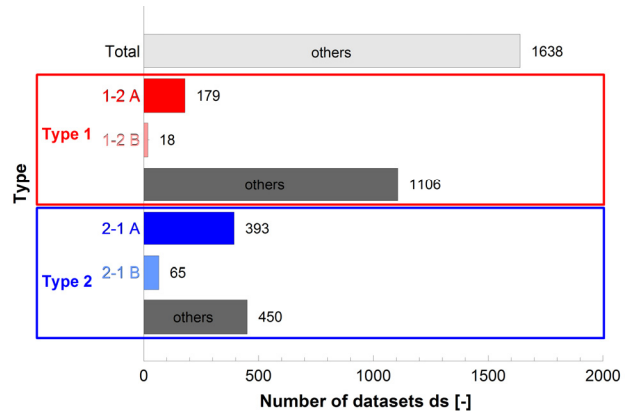Figure 4 Distribution of Types 1-2 A, 1-2 B and of Types 2-1 A, 2-1 B

Figure 5 Number of damage cases for masonry building types (cf. Table 3.1)

3.2 Damage statistics and calibration of macroseismic (shaking) effects

The vulnerability class of B is typical for Type 1-2 A (n = 2, 1920 – 1939, 179 datasets (ds)) and 1-2 B (n = 3, 1920 – 1930, 18 ds). Vulnerability class C is characteristic for Type 2-1 A (n = 2, 1949 – 1965, 389 ds) and 2-1 B (n = 3, 1955 – 1965, 65 ds) (Table 3.1). The quality of classification is consecutively validated by the observed damages. The derived sub-types are justified by their occurrence rate and regional distribution. The percentage of masonry type houses within a mesh of the raster elements is shown on the map in Figure 4 and in total numbers in Figure 5.

Particularly, in regions of low or moderate seismicity, empirical data are missing to derive vulnerability functions, i.e. the percentage of individual damage grades and their shares in the whole sample group is unknown. From the September 3, 1978 Albstadt Earthquake, the already mentioned about 1.300 damage cases are reinterpreted and statistically investigated for the sub-divided building types [Schwarz et al., 2008a]. The occurrence rate of the various damage grades leads to empirical vulnerability functions if for each building type the observed or re-assigned damage grades are plotted. The curves of Figure 6 compare the damage distribution for the four masonry building types. The slightly increased percentage of higher damage grades indicates the higher vulnerability of Type 1-2 masonry buildings.

Following the EMS-98 with respect to the (verbal) descriptions of quantities (Table 3.2), it can be concluded that the observed shaking effects with respect to quality and quantity of damage cases (I_{obs}) refer to a calculational value of intensity I_{EMS} = 7.0 to 7.25 being lower than that one which is given in recent earthquake catalogues (VII-VIII), or, otherwise, that the resistance of the masonry buildings is underestimated by the assigned vulnerability classes.
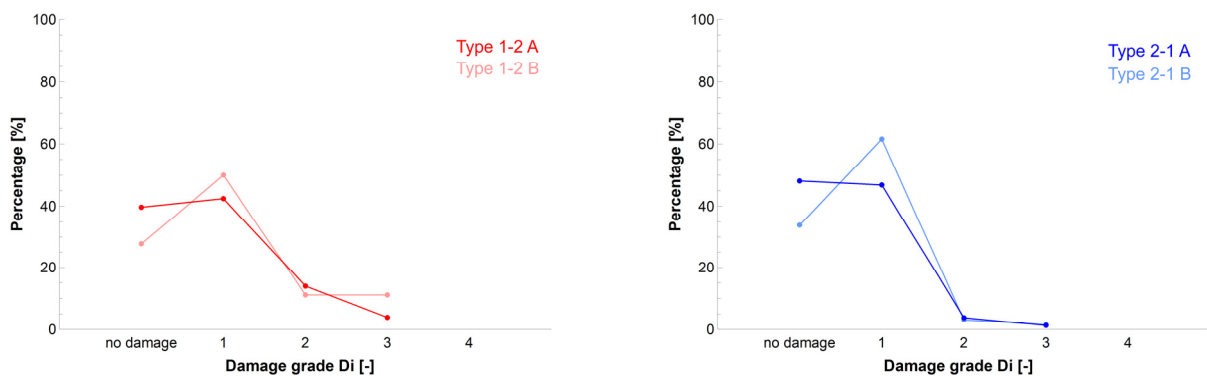

Figure 6 Distribution damage grades for masonry buildings: a) Types 1-2 A, 1-2 B; b) Types 2-1 A, 2-1 B

Table 3.2 Quantity of intensity based damage description for vulnerability classes VC of B and C
acc. to EMS-98 [Grünthal *et al*., 1998] compared with the observed damage

Type	VC	I_EMS	Damage grade Di					I_obs
			no damage	D1	D2	D3	D4	
	B	VII			*many*	*few*		
		VIII				*many*	*few*	
1-2 A	(AB) **B** (BC)		*many*	*many*	*many*	*(very) few*		7.0
1-2 B	(AB) **B** (BC)		*many*	*most*	*many*	*many*		7.25
	C	VII			*few*			
		VIII			*many*	*few*		
2-1 A	(BC) **C** (CD)		*many*	*many*	*(very) few*	*(very) few*		7.25
2-1 B	(BC) **C** (CD)		*many*	*most*	*(very) few*	*(very) few*		7.25

3.3 Local site effects

The local damage distribution, the ratio of damaged buildings and the differently pronounced level of damage grades for similar building types indicate that besides the vulnerability (and level of earthquake resistance) the effects of site amplification have to be considered, too. On the basis of instrumental and analytical site studies ground classes could be assigned (Figure 7). In addition, the local intensity increments (site correction factors) are derived. The intensity correction factors [ΔI_S] account for the effect of local site conditions (subsoil, deep geology, topography; see Figure 3). Repeating the damage statistics and by further subdividing the samples of one building type into the shares of those belonging to different zones/locations of the intensity correction increments [ΔI_S], the damage enforcing or reducing effect of the ground conditions can be quantified for each damage case (see Figure 8). By this innovative procedure the empirical functions of Figure 6 can be replaced by a set of more refined functions representing the vulnerability for reference site conditions and a range of intensities.
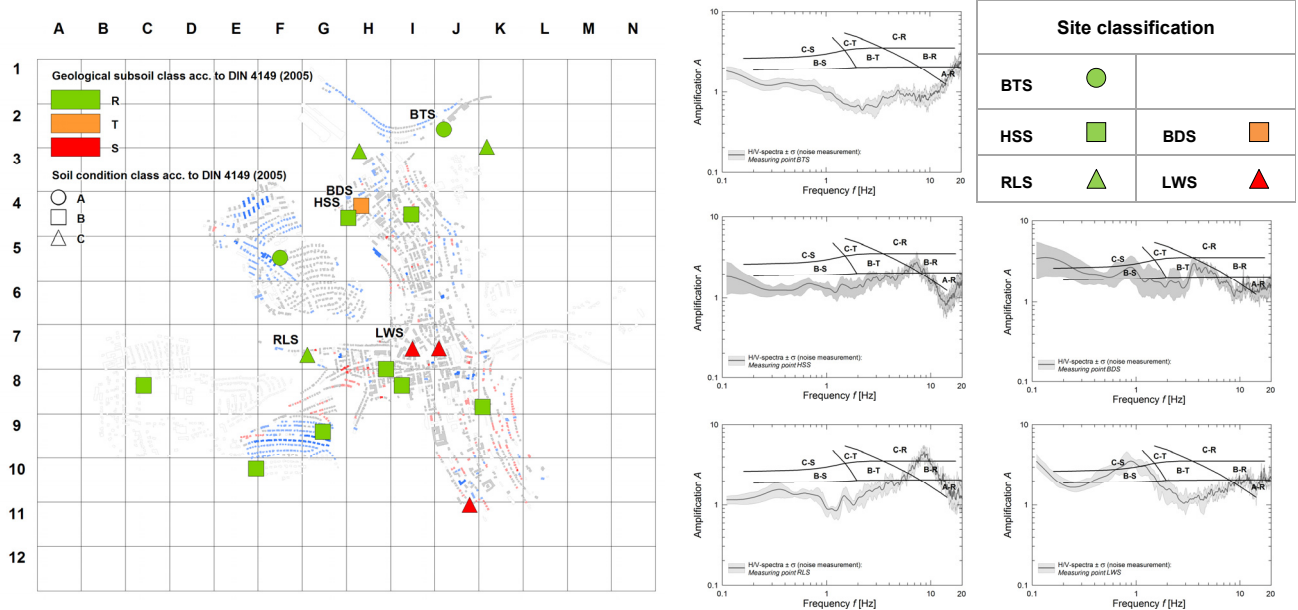

Figure 7 Underground classes [DIN 4149, April 2005] and
results of instrumental site classification scheme by [Lang & Schwarz, 2006]
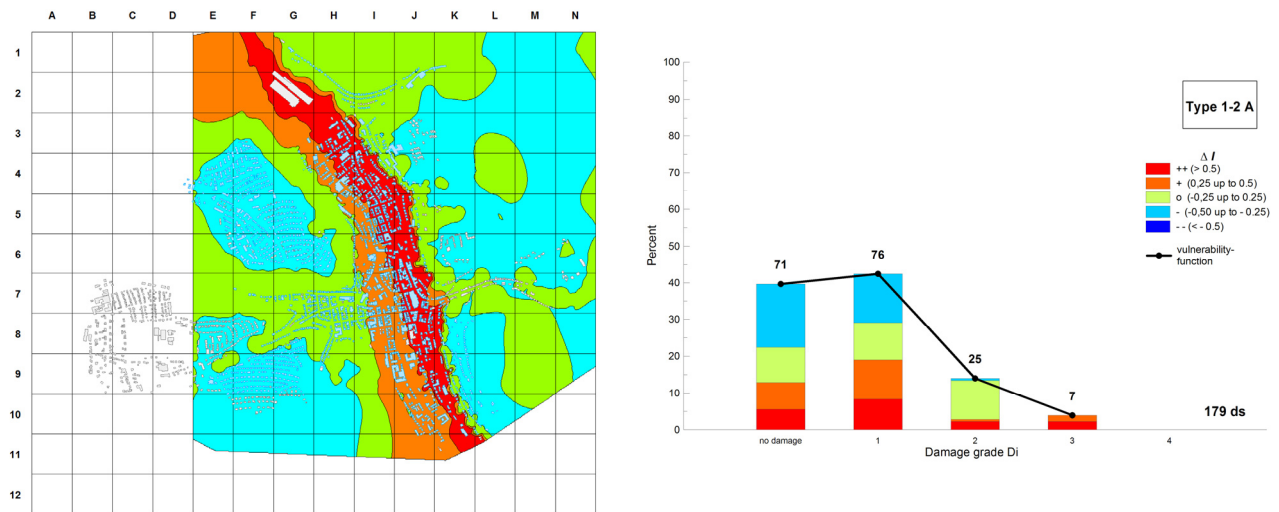
Figure 8 Intensity correction increments [ΔIs] and its effects on the observed damage cases;
example for masonry structures of Type 1-2 A

4.   ANALYTICAL INVESTIGATIONS

For typical representatives of all building types, archive material was studied. Construction plans and information of the building materials as well as the details of the damage pattern are elaborated (cf. Figure 9). Material and other information (about damage, retrofitting measures etc.) are taken from the existing historic documents and building plans. For about 30 sample objects the floor and vertical section elevation plans are digitized (see examples in Table 3.1) and subsequently used as input files for the BLM-tool [EDAC, 2002]. An example of Type 1-2 A is displayed in Figure 9 with the damage pattern observed after the earthquake of 1978. On the basis of the capacity curve, the predicted damage grades [Schwarz *et al*, 2008b] can be compared with the observed damage pattern in the four (load-bearing) front walls of the building (Figure 10).
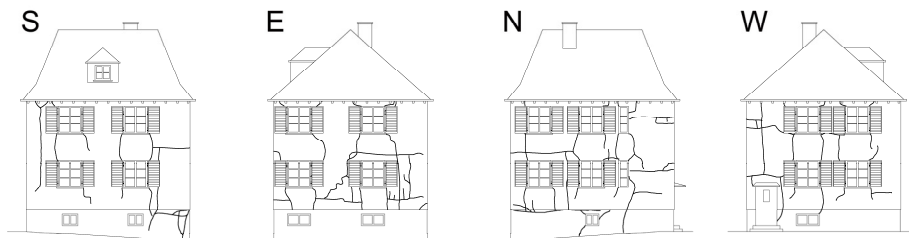

Figure 9 Damage pattern and cracks for a masonry building of Type 1-2 A [Bauamt Albstadt, State 2004]
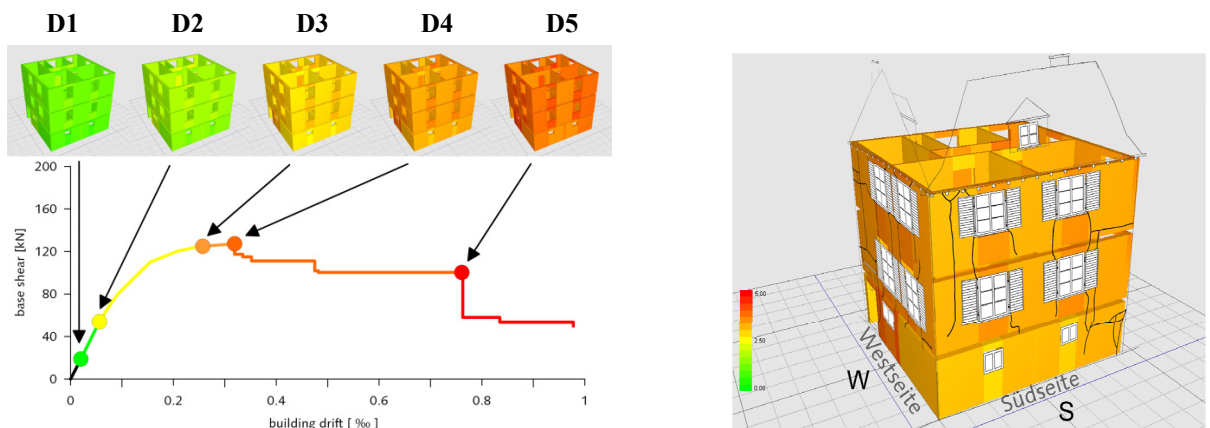

Figure 10 Capacity curve for the Type 1-2 A building of Figure 9; comparison of the observed damage with the determined one by BLM [EDAC, 2002]

The subsoil conditions at the building site were classified on the basis of instrumental site response studies. For the assigned subsoil category, the analytical model enables the correlation between observed damage grade and analytically required ground accelerations to fit the damage situation. It is the purpose of ongoing studies to use the comparison of these experience-based results with the observed damage grades to calibrate existing tools and correlations [Schwarz *et al.*, 2008b]. For risk assessment, damage prognosis and practical applications, a building factor will be defined accounting for the contradictions between modeling (analysis) and reality (reinterpretation, experience).

5. CONCLUSIONS

The 1978 Albstadt earthquake provides an impression of the severity of design earthquakes (in lower range of design ground motion). Due to the representative reflection of the building stock with respect to the composition of building types, their construction and age, the observed behavior and damage describe the vulnerability of the still existing masonry type buildings. The excellent documentation of the damage cases enables a reliable reinterpretation of the situation after the earthquake and the elaboration of empirical vulnerability functions which can be scaled to unified (reference) subsoil conditions. Results provide the calibration basis of recently published studies, and can be transferred to unreinforced masonry buildings in countries with similar construction tradition (e.g. Austria, Switzerland, etc.).

ACKNOWLEDGMENT

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